ADOPTING MACHINE LEARNING-BASED INTELLIGENT TUTORING SYSTEMS FOR EFFECTIVE CHEMISTRY CURRICULUM IMPLEMENTATION

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Abstract
The study examined the adoption of Machine Learning-based Intelligent Tutoring Systems (ITS) for effective implementation of the chemistry curriculum. Persistent challenges associated with conventional chemistry instruction were identified, including limited instructional personalization, delayed feedback, and students' difficulties in understanding abstract chemical concepts. The integration of Machine Learning-driven ITS was presented as a viable approach to addressing these challenges through adaptive, learner-centered instructional delivery tailored to individual learning needs, learning pace, and cognitive abilities. Key features of Intelligent Tutoring Systems, including real-time feedback, predictive analytics, and automated assessment, were highlighted for their relevance in enhancing teaching and learning outcomes in chemistry education. Evidence from existing literature indicates that ITS improve students' conceptual understanding, increase engagement, and support teachers through data-driven instructional practices. However, constraints associated with the adoption of these technologies were also identified, including inadequate infrastructure, limited digital competence among educators, high implementation costs, and concerns related to data privacy and security. The study concluded that although Machine Learning-based ITS offer significant potential for improving chemistry curriculum implementation, successful adoption depends on strong policy support, teacher capacity development, and sustained investment in digital infrastructure. A phased and context-sensitive approach was recommended to ensure effective integration and equitable access.

Keywords: Machine learning, intelligent tutoring systems, chemistry education, curriculu

Introduction

Chemistry education occupies a strategic position in national development because it provides learners with the scientific knowledge, practical skills, and problem-solving abilities required for industrialization, technological advancement, healthcare innovation, agriculture, environmental sustainability, and economic growth. Chemistry is defined as the area of science that deals with the study of matter; the composition, properties, structure, reactions or transformation that matter undergo under various conditions (such as, heat, light, catalyst etc) and the use of such reactions to solve man's problem or satisfy human needs (Nwankwo, 2025). Chemistry is one of the most important sub-disciplines of science and emphatically, a branch of physical science. The teaching and learning of chemistry as a science subject in senior secondary schools is very important because students can hardly offer most science courses in tertiary institutions without at least, a credit in chemistry at the senior secondary school certificate examination level. Developing an understanding of what chemistry is, and how we can use it, is central to a successful chemistry curriculum. Curriculum is an interrelated set of plans and experiences which a student completes under the guidance of the school (Nation and

Macalister, 2020). The implementation of the chemistry curriculum therefore remains an essential component of science education aimed at preparing students for scientific literacy and active participation in contemporary society.

In many educational systems, the chemistry curriculum is designed to equip learners with knowledge of chemical principles, laboratory competencies, technological and mathematics competency, analytical reasoning, competency in ICT applications that will egender entrepreneurial skills, and the capacity to apply scientific concepts to real-life situations. According to Yusuf and Afolabi (2022), effective chemistry curriculum implementation enhances learners' scientific inquiry abilities and promotes innovation needed for sustainable national development. The growing dependence on science and technology across nations has further increased the need for effective instructional approaches capable of improving students' achievement and participation in chemistry learning. However, the implementation of chemistry curriculum in many schools continues to face several content, instructional and pedagogical challenges. Researchers such as Nwosu and Ugwuanyi (2021); Nwankwo (2025) noted that many students perceive chemistry as difficult because of its abstract concepts, mathematical demands, and symbolic representations. The abstract concepts of chemistry curriculum contents cannot be easily understood and therefore pose difficulties to the students. Available evidence from WAEC Chief examiners' report from 2019 to 2020 revealed that students performed poorly in chemistry due to their weaknesses (difficulties) in chemistry topics such as chemical bonding, periodic table, stoichiometry, cracking of petroleum, electrolysis and chemical reaction. Furthermore, conventional teacher-centered instructional approaches have been criticized for limiting active learner participation and individualized learning experiences. In many classrooms, teachers rely heavily on lecture methods that emphasize memorization rather than conceptual understanding and practical engagement. Jonah, Achor and Adah (2021) found that chemistry students have difficulties in comprehending some concepts such as chemical reaction due to inappropriate learning strategies. According to Adeyemi and Ibrahim (2022), variations in students' cognitive abilities, learning pace, and prior scientific knowledge often make it difficult for teachers to meet individual learning needs using traditional instructional methods alone. These challenges have contributed to poor student achievement, low motivation, examination anxiety, and declining interest in chemistry-related careers among secondary school students. Hence, espousing cutting-edge technologies that will dynamically customize learning experiences to varying cognitive abilities and difficulty levels of the learners has become paramount.

The increasing advancement in digital technologies and artificial intelligence has introduced innovative approaches capable of transforming teaching and learning processes in chemistry education. Authors (Cai, Msafiri & Kangwa, 2024; Sidorkin, 2025; Munenakoppa, Nitin, Rane & Heggond, 2026) propose innovative technologies such as Multimodal AI, Generative AI-driven adaptive content, Virtual/Augmented Reality Simulations and Machine Learning-based Intelligent Tutoring Systems (ITS), for sustainable, personalized and resilient chemistry education. Machine Learning-based Intelligent Tutoring Systems (ITS) are increasingly gaining attention as adaptive instructional technologies designed to support personalized learning experiences. Machine Learning enables computer systems to analyze learner data, identify learning patterns, predict students' performance, and provide customized instructional support without explicit human programming. Intelligent Tutoring Systems integrate artificial intelligence techniques to simulate one-on-one tutoring by offering individualized guidance, immediate feedback, automated assessment, and adaptive learning pathways tailored to learners' academic needs and cognitive abilities. According to Hassan and Lee (2024), Machine Learning-driven ITS improve students' conceptual understanding by continuously adapting instructional content based on learners' responses and progress. Likewise, Chen, Wang and Torres (2023) maintained that ITS enhance learner engagement and retention through interactive learning environments capable of supporting self-paced instruction and real-time monitoring of students' learning difficulties.

In chemistry education, the adoption of Machine Learning-based Intelligent Tutoring Systems has the potential to improve curriculum implementation through enhanced visualization of abstract concepts, personalized instructional delivery, predictive learning analytics, and continuous learner assessment. Recent studies by Kumar and Bassey (2024) revealed that intelligent tutoring technologies significantly improve students' academic achievement and motivation in chemistry by providing immediate corrective feedback and individualized learning support. Furthermore, these technologies assist teachers in monitoring learners' progress and identifying areas requiring instructional intervention. However, despite the numerous educational benefits associated with ITS adoption, several barriers continue to hinder effective implementation, particularly in developing educational environments. Such barriers include inadequate digital infrastructure, poor internet connectivity, limited technological competence among teachers, high procurement and maintenance costs, and concerns relating to ethical use and data privacy in artificial intelligence-supported learning systems.

Based on these developments, there is growing need for educational institutions and stakeholders to explore innovative instructional technologies capable of enhancing effective chemistry curriculum implementation. The paper therefore discusses the adoption of Machine Learning-based Intelligent Tutoring Systems for chemistry curriculum implementation, highlights the relevance of intelligent tutoring technologies in chemistry education, examines associated implementation challenges, and suggests strategies for effective integration within contemporary educational environments.

Machine Learning-Based Intelligent Tutoring Systems

The rapid advancement in digital technology and artificial intelligence has transformed educational practices across different levels of learning. Educational institutions are increasingly adopting technology-driven instructional approaches aimed at improving students' academic performance, participation, and conceptual understanding. Among these technological innovations, Machine Learning and Intelligent Tutoring Systems have gained considerable attention because of their ability to support adaptive, learner-centered, and data-driven instructional delivery. The integration of these technologies into chemistry education has become necessary due to the persistent challenges associated with conventional teaching methods, especially in the teaching of abstract and computational chemistry concepts. The growing demand for effective chemistry curriculum implementation and improved chemistry education outcomes has therefore increased scholarly interest in Machine Learning-based Intelligent Tutoring Systems as modern instructional tools capable of enhancing chemistry teaching and learning processes.

Machine Learning is one of the major components of artificial intelligence that enables computer systems to learn from available data and improve performance over time without direct human programming. The concept has become increasingly important in educational technology because of its capacity to analyze learner behaviour, predict learning outcomes, and provide adaptive learning support. According to Russell and Norvig (2022), Machine Learning refers to a branch of artificial intelligence that allows computer systems to learn patterns from data and make intelligent decisions with minimal human intervention. Similarly, Sharma and Gupta (2023) defined Machine Learning as a computational process through which algorithms identify relationships in data, generate predictions, and continuously improve system performance based on experience and interaction. In another perspective, Li and Zhang (2024) viewed Machine Learning as an intelligent analytical technique that enables educational systems to personalize instructional delivery by monitoring students' learning progress and behavioural patterns. Furthermore, Eze and Nwachukwu (2023) explained that Machine Learning involves the use of intelligent algorithms capable of analyzing students' responses and automatically adjusting instructional activities to suit individual learning needs.

Operationally, Machine Learning in chemistry education may be viewed as the application of intelligent computer algorithms that analyze learners' academic performance, learning pace, and cognitive abilities in order to provide adaptive instructional support for effective chemistry curriculum implementation. The relevance of Machine Learning in chemistry education lies in its ability to facilitate personalized instruction, improve conceptual understanding, support automated assessment, and enhance learner engagement through intelligent instructional processes. Through continuous analysis of students' learning activities, Machine Learning technologies help educators identify students' strengths, weaknesses, and learning difficulties, thereby improving instructional decision-making and curriculum delivery. The intelligent and adaptive nature of Machine Learning technologies has therefore contributed significantly to the emergence and development of Intelligent Tutoring Systems in modern educational environments.

Intelligent Tutoring Systems have become prominent educational technologies designed to simulate the role of human tutors through artificial intelligence-supported instructional delivery. The growing complexity of classroom instruction, combined with the increasing need for individualized learning experiences, has encouraged educational researchers and institutions to explore intelligent systems capable of supporting learners beyond the limitations of traditional classroom teaching. According to Nkambou, Bourdeau, and Mizoguchi (2021), Intelligent Tutoring Systems are computer-based instructional systems that apply artificial intelligence techniques to provide personalized tutoring, adaptive instruction, and immediate feedback to learners. Likewise, Al-Harthy and Al-Mashani (2024) defined Intelligent Tutoring Systems as intelligent educational software designed to diagnose learners' difficulties, monitor academic progress, and provide customized instructional responses that improve students' learning outcomes. In another related view, Anderson and Corbett (2022) described Intelligent Tutoring Systems as interactive digital learning environments capable of mimicking human tutoring processes through continuous learner assessment and adaptive instructional support. Similarly, Hassan and Lee (2024) explained that Intelligent Tutoring Systems are artificial intelligence-driven learning platforms that use predictive analytics and learner data to provide individualized instruction tailored to students' cognitive abilities and educational needs.

For the purpose of this study, Intelligent Tutoring Systems in chemistry education may be regarded as artificial intelligence-supported instructional technologies that integrate Machine Learning techniques to provide adaptive learning experiences, automated evaluation, real-time feedback, and personalized instructional support for effective chemistry curriculum implementation. These systems are designed to support learners through continuous monitoring of their academic progress and by adjusting instructional content according to individual performance levels and learning styles. In chemistry education, Intelligent Tutoring Systems assist students in understanding difficult concepts such as atomic structure, chemical reactions, stoichiometry, thermodynamics, and electrochemistry through interactive and learner-centered instructional processes. The increasing relevance of Intelligent Tutoring Systems in contemporary education is largely associated with their unique characteristics and features that distinguish them from conventional teaching methods.

One important characteristic of Intelligent Tutoring Systems is adaptive learning. Adaptive learning refers to the ability of instructional systems to modify learning content, instructional strategies, and assessment activities according to learners' individual differences, performance levels, and cognitive needs. Intelligent Tutoring Systems continuously analyze students' responses and learning behaviours in order to provide suitable instructional materials capable of improving understanding and retention. This feature is particularly important in chemistry education because students often differ in their comprehension of abstract scientific concepts and laboratory procedures. Adaptive learning therefore ensures that slow learners receive additional support while advanced learners are exposed to more challenging instructional activities. Another significant feature of Intelligent Tutoring Systems is real-time feedback. Real-time feedback enables students to receive immediate responses concerning their academic performance, learning errors, and instructional progress during learning activities. Unlike conventional classroom settings where feedback may be delayed due to large class size and teachers' workload, Intelligent Tutoring Systems provide instant corrective responses that help learners identify mistakes and improve conceptual understanding. In chemistry education, immediate feedback is essential during activities involving balancing of chemical equations, numerical calculations, laboratory simulations, and scientific problem-solving tasks. This continuous reinforcement process improves students' confidence, motivation, and academic achievement.

Predictive analytics also represents an important feature of Intelligent Tutoring Systems. Predictive analytics involves the use of Machine Learning algorithms to analyze learner data and forecast future academic outcomes based on students' behavioural patterns and performance records. Through predictive analytics, Intelligent Tutoring Systems can identify students who are at risk of poor academic performance and recommend appropriate instructional interventions. This feature supports teachers and educational administrators in making informed instructional decisions and improving curriculum implementation processes. In chemistry classrooms, predictive analytics assists educators in identifying difficult learning areas and designing suitable remediation strategies capable of improving students' understanding of chemistry concepts. Automated assessment constitutes another major characteristic of Intelligent Tutoring Systems. Automated assessment allows the system to evaluate students' responses, grade assignments, track academic progress, and generate performance reports automatically with minimal human involvement. This feature enhances assessment efficiency, reduces teachers' workload, and ensures continuous monitoring of learners' academic development. Automated assessment also improves objectivity and consistency in evaluating students' performance. In chemistry education, automated assessment enables rapid evaluation of theoretical questions, objective tests, scientific calculations, and virtual laboratory exercises, thereby supporting continuous assessment practices required for effective curriculum implementation.

Personalized instruction further distinguishes Intelligent Tutoring Systems from traditional instructional approaches. Personalized instruction refers to the provision of customized learning experiences based on learners' interests, abilities, strengths, weaknesses, and learning preferences. Intelligent Tutoring Systems provide individualized learning pathways that allow students to learn at their own pace and according to their unique educational needs. This personalized approach increases learner engagement, promotes independent learning, and enhances academic confidence. In chemistry education, personalized instruction enables students to revisit difficult concepts repeatedly until mastery is achieved, thereby improving conceptual understanding and long-term retention of scientific knowledge. The features of Intelligent Tutoring Systems collectively contribute to effective instructional delivery and learner-centered educational practices. Through adaptive learning, immediate feedback, predictive analytics, automated assessment, and personalized instruction, Intelligent Tutoring Systems provide meaningful learning experiences capable of improving students' academic achievement and participation in chemistry learning. These instructional benefits directly relate to the broader concept of curriculum implementation, which focuses on translating curriculum objectives into practical teaching and learning experiences that promote the attainment of educational goals and desired learning outcomes.

Chemistry Curriculum Implementation

Curriculum implementation is an important aspect of the educational process that focuses on translating planned educational objectives, learning experiences, and instructional contents into practical classroom activities capable of achieving desired learning outcomes. Effective curriculum implementation ensures that educational goals are properly delivered through appropriate teaching methods, instructional materials, learner participation, and continuous assessment processes. In science education, curriculum implementation plays a significant role in improving learners' scientific knowledge, practical competencies, problem-solving abilities, and critical thinking skills necessary for national development and technological advancement. According to Offorma and Nwiyi (2022), curriculum implementation refers to the actual process of putting planned educational programmes, policies, and instructional activities into operation within the classroom environment. Similarly, Okafor and Edeh (2023) defined curriculum implementation as the interaction between teachers, learners, instructional resources, and educational activities aimed at achieving stated curriculum objectives and learning outcomes. In another related view, Yusuf and Adigun (2024) described curriculum implementation as the practical execution of educational plans through instructional delivery, classroom management, learner engagement, and assessment activities designed to facilitate effective learning experiences.

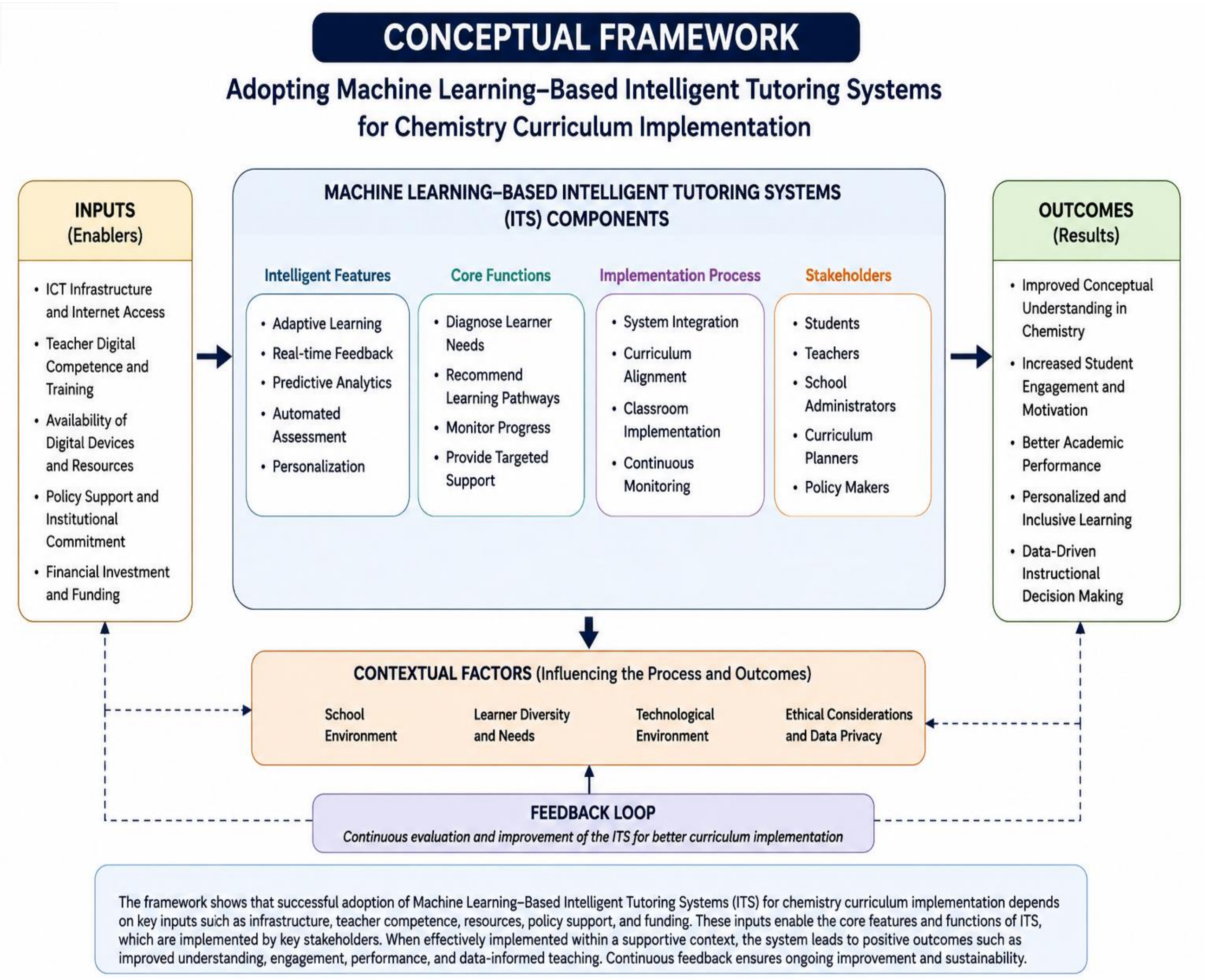
For the purpose of this study, curriculum implementation in chemistry education may be viewed as the systematic process of translating chemistry curriculum objectives, instructional contents, practical activities, and assessment procedures into meaningful teaching and learning experiences capable of improving students' understanding, scientific skills, and academic achievement in chemistry. Effective implementation of the chemistry curriculum requires qualified teachers, appropriate instructional strategies, adequate laboratory facilities, digital learning resources, and supportive learning environments that enhance active learner participation and conceptual understanding. The successful implementation of the chemistry curriculum is therefore essential for achieving the objectives of chemistry education at different levels of the educational system. The chemistry curriculum is designed to achieve several educational objectives that contribute to scientific literacy, technological advancement, and socio-economic development. One major objective of the chemistry curriculum is to equip learners with adequate knowledge of chemical principles, concepts, and scientific processes necessary for understanding the composition, properties, and transformations of matter. Through chemistry education, students develop analytical thinking, problem-solving abilities, and scientific inquiry skills required for addressing real-life environmental, industrial, and technological challenges. Similarly, Bello and Hassan (2022) observed that chemistry education prepares learners for science-related careers such as medicine, pharmacy, engineering, agriculture, environmental science, and biotechnology. According to Ezeudu and Ugwu (2023), the chemistry curriculum aims at developing students' intellectual competence, experimental skills, and ability to apply scientific knowledge to everyday life situations.

Another objective of the chemistry curriculum is to promote practical and laboratory competencies among learners. Chemistry education encourages students to participate actively in laboratory investigations, experimentation, observation, and scientific reasoning processes capable of enhancing creativity and innovation. The curriculum also seeks to develop students' interest in science and technology while fostering positive attitudes toward scientific inquiry and responsible use of scientific knowledge for societal development. Furthermore, the chemistry curriculum is intended to prepare learners for higher education and professional advancement in science-oriented disciplines. The attainment of these objectives depends largely on effective curriculum implementation and the availability of appropriate instructional resources and teaching strategies.

Notwithstanding the importance of chemistry education, the implementation of the chemistry curriculum in many schools continues to face several difficulties that hinder effective teaching and learning outcomes. One major difficulty is the abstract nature of chemistry concepts. Chemistry involves many symbolic representations, microscopic processes, mathematical calculations, and theoretical explanations that students often find difficult to understand. Concepts such as atomic structure, chemical bonding, thermodynamics, equilibrium, and electrochemistry are highly abstract and may not be easily visualized through conventional teaching approaches. According to Nwafor and Adeyemi (2022), the abstract nature of chemistry contributes significantly to students' poor academic performance, low interest, and examination anxiety. Many learners struggle to connect theoretical explanations with practical applications, thereby reducing meaningful learning experiences.

Poor laboratory experiences also constitute a major challenge affecting chemistry curriculum implementation. Laboratory activities are essential components of chemistry education because they provide opportunities for practical experimentation, observation, and skill acquisition. However, many schools lack functional laboratories, adequate chemicals, modern equipment, and safety facilities necessary for effective practical instruction. In some cases, practical lessons are taught theoretically due to inadequate laboratory resources and poor maintenance culture. According to Ibrahim and Okeke (2023), inadequate laboratory exposure limits students' scientific inquiry skills, reduces practical competence, and negatively affects conceptual understanding in chemistry. Poor laboratory experiences therefore weaken the practical orientation of chemistry education and limit the achievement of curriculum objectives. Large class size is another challenge affecting effective chemistry curriculum implementation in schools. Overcrowded classrooms make it difficult for teachers to provide individualized attention, supervise laboratory activities effectively, and monitor students' academic progress. In large classes, teachers often experience difficulties managing instructional activities, conducting practical experiments, and addressing students' learning needs within limited instructional time. The situation becomes more problematic in chemistry education where practical demonstrations and interactive instructional approaches are required for meaningful learning. According to Olatunji and Eze (2024), large class size reduces teacher-student interaction, weakens classroom participation, and contributes to ineffective curriculum delivery in science (chemistry) education.

Inadequate instructional materials also hinder effective implementation of the chemistry curriculum. Instructional materials such as laboratory equipment, charts, models, computers, projectors, digital simulations, and chemistry textbooks are essential for facilitating effective teaching and improving students' understanding of scientific concepts. However, many schools experience shortages of instructional resources due to poor funding, inadequate infrastructure, and limited access to educational technologies. The absence of relevant instructional materials limits teachers' ability to simplify difficult concepts and engage students actively during lessons. According to Akinwale and Musa (2023), inadequate instructional materials negatively affect students' comprehension, retention, and participation in chemistry learning activities. Poor learner engagement further constitutes a major challenge affecting chemistry curriculum implementation. Learner engagement refers to students' active participation, motivation, interest, and involvement in classroom instructional activities. In many conventional classroom settings, chemistry lessons are dominated by teacher-centered instructional methods that limit interaction, collaboration, creativity, and independent learning opportunities. As a result, many students develop negative attitudes toward chemistry and lose interest in science-related subjects. Poor learner engagement often leads to low academic achievement, poor retention of concepts, absenteeism, and reduced participation in practical activities. According to Hassan and Nwosu (2024), ineffective instructional strategies and limited use of interactive learning technologies contribute significantly to low learner engagement in chemistry classrooms. The numerous difficulties associated with chemistry curriculum implementation therefore highlight the need for innovative instructional approaches capable of improving students' understanding, participation, and academic achievement in chemistry education. Addressing these challenges requires the integration of modern educational technologies such as Machine Learning-based Intelligent Tutoring Systems that support adaptive learning, personalized instruction, interactive learning experiences, and effective curriculum delivery in contemporary educational environments.



Relevance of Machine Learning-Based ITS in Chemistry Education

The integration of Machine Learning-based Intelligent Tutoring Systems (ITS) into chemistry education has become increasingly significant due to the persistent challenges associated with traditional instructional approaches and the abstract nature of chemical concepts. In contemporary science education, there is a growing emphasis on learner-centered and technology-enhanced instructional strategies capable of improving understanding, engagement, and academic performance. Machine Learning-based ITS offer adaptive and intelligent learning environments that respond to learners' individual needs, making them highly relevant for effective chemistry curriculum implementation in the digital age. One major relevance of Machine Learning-based ITS in chemistry education is the provision of personalized learning experiences. Personalized learning allows instructional content, pace, and difficulty level to be tailored to meet the unique needs of individual learners. Machine Learning algorithms continuously analyze students' learning behaviours, performance patterns, and interaction data to deliver customized instructional pathways. According to Holmes and Tuomi (2022), AI-driven educational systems enhance learning effectiveness by adapting instructional content to individual learner profiles. Similarly, Luckin, Holmes, Griffiths and Forcier (2023) observed that intelligent tutoring technologies promote equity in learning by ensuring that students with different cognitive abilities receive appropriate instructional support. In chemistry education, personalized learning enables students to revisit complex concepts such as chemical bonding and stoichiometry at their own pace, thereby improving comprehension and retention.

Machine Learning-based ITS also contribute significantly to improved understanding of abstract concepts in chemistry. Chemistry contains many microscopic and symbolic processes that are difficult for students to visualize using conventional teaching methods. ITS also support learners through simulations, visualizations, and interactive representations that make abstract concepts more concrete and understandable. According to Mayer (2021), multimedia and adaptive learning systems improve cognitive processing by reducing cognitive overload and enhancing conceptual clarity. In the same vein, Clark and Mayer (2022) noted that intelligent digital tools enhance learners' ability to connect theoretical knowledge with practical applications. Through these capabilities, ITS help students better understand difficult chemistry topics such as molecular structures, reaction mechanisms, and thermodynamic processes. Another important relevance of ITS is the provision of immediate feedback and error correction. Unlike traditional classroom environments where feedback may be delayed due to large class sizes and workload constraints, Machine Learning-based ITS provide instant responses to learners' inputs. This real-time feedback helps students identify misconceptions, correct errors, and reinforce correct understanding immediately. According to VanLehn (2023), immediate feedback in intelligent tutoring systems significantly improves learning efficiency and knowledge retention. In chemistry education, this feature is particularly useful during problem-solving tasks such as balancing equations, performing calculations, and interpreting experimental data, where timely correction enhances accuracy and understanding.

Machine Learning-based ITS also play a crucial role in increasing student motivation and engagement. Learners often show greater interest when instructional content is interactive, adaptive, and responsive to their needs. ITS incorporate gamified elements, interactive simulations, and adaptive challenges that sustain learners' attention and motivation. According to Ryan and Deci (2021), motivation in learning is enhanced when students experience autonomy, competence, and relevance in their learning environment. Similarly, Chen et al. (2023) emphasized that AI-supported learning systems improve learner engagement by creating interactive and immersive learning experiences. In chemistry classrooms, ITS encourage active participation and reduce learning anxiety associated with complex scientific concepts. Another significant relevance of Machine Learning-based ITS is their support for teachers through data-driven instruction. These systems collect and analyze learner data, providing teachers with detailed insights into students' strengths, weaknesses, progress, and learning patterns. This information enables teachers to make informed instructional decisions and adopt targeted intervention strategies. According to Siemens and Baker (2022), learning analytics generated by intelligent systems enhance instructional planning and educational decision-making. In chemistry education, such data-driven insights help teachers identify difficult topics, monitor student performance, and adjust teaching strategies to improve learning outcomes.

Finally, Machine Learning-based ITS contribute to the enhancement of students' academic achievement in chemistry. By providing personalized instruction, immediate feedback, conceptual visualization, and continuous assessment, ITS improve learners' understanding and retention of chemistry concepts. Studies have shown that students who learn through intelligent tutoring systems tend to perform better academically compared to those taught using traditional methods. According to Ma, Adesope, Nesbit and Liu (2023), AI-supported instructional systems significantly improve academic achievement by promoting active learning and continuous engagement. Similarly, Oke and Adebayo (2024) found that intelligent tutoring technologies positively influence students' performance in science subjects by enhancing conceptual understanding and problem-solving skills. Therefore, the adoption of Machine Learning-based ITS offers a transformative approach to improving chemistry education outcomes. Generally, the relevance of Machine Learning-based Intelligent Tutoring Systems in chemistry education lies in their ability to transform traditional teaching and learning processes into adaptive, interactive, and learner-centered experiences that enhance curriculum implementation and academic achievement.

Challenges Associated with the Adoption of Machine Learning-based ITS

Despite the significant potential of Machine Learning-based Intelligent Tutoring Systems (ITS) in transforming chemistry education, their adoption in many educational settings is still constrained by several infrastructural, human, financial, and ethical challenges. These challenges often limit the successful integration of intelligent technologies into classroom instruction and reduce the extent to which their benefits can be fully realized in curriculum implementation. Understanding these constraints is important for policymakers, educators, and stakeholders seeking to enhance the effectiveness of technology-driven education in chemistry. One major challenge is inadequate ICT infrastructure. The successful implementation of ITS requires functional digital devices, stable electricity supply, computer laboratories, and updated software systems capable of supporting intelligent learning platforms. However, many schools, particularly in developing contexts, lack sufficient ICT facilities needed to support such advanced technologies. According to Alabi and Okoye (2022), inadequate technological infrastructure remains one of the most significant barriers to the integration of digital learning tools in science education. Similarly, Eze and Nwankwo (2023) observed that poor ICT infrastructure limits students' exposure to computer-assisted learning and reduces the effectiveness of technology-enhanced instruction in secondary schools.

High cost of implementation is another critical challenge associated with the adoption of ITS. Machine Learning-based tutoring systems require substantial financial investment for software development, procurement of hardware, system maintenance, and technical support. In addition, schools may incur recurring costs related to licensing, updates, and training of personnel. According to Yusuf and Bello (2023), the high cost of educational technology adoption often discourages schools and governments from fully integrating advanced digital systems into classroom instruction. This financial burden is particularly pronounced in public schools with limited funding, thereby restricting equitable access to intelligent learning technologies. Limited digital competence among teachers also poses a significant challenge to ITS adoption. Teachers play a central role in the effective integration of technology into teaching and learning processes; however, many educators lack adequate training in the use of artificial intelligence tools and Machine Learning-based instructional systems. This lack of digital literacy affects their ability to effectively operate ITS platforms, interpret learning analytics, and integrate system outputs into instructional planning. According to Adeyemi and Ojo (2024), insufficient teacher training in digital technologies reduces the effectiveness of ICT-based instruction and limits classroom innovation. Similarly, Olawale and Ibrahim (2022) emphasized that teacher competence is a key determinant of successful educational technology adoption.

Resistance to technological change is another factor that hinders the adoption of Intelligent Tutoring Systems. Some educators and stakeholders may be reluctant to adopt new technologies due to fear of job displacement, unfamiliarity with digital tools, or preference for traditional teaching methods. This resistance often slows down the integration of innovative instructional systems into the educational process. According to Rogers' innovation diffusion perspective as discussed by Nwosu and Eze (2023), resistance to change is common in educational environments where stakeholders are not adequately sensitized to the benefits of new technologies. Such resistance can limit the acceptance and utilization of ITS in chemistry classrooms. Internet connectivity issues also significantly affect the adoption and effectiveness of Machine Learning-based ITS. These systems often rely on stable and high-speed internet connections to function effectively, especially for cloud-based learning platforms, real-time data processing, and continuous system updates. However, in many regions, inconsistent or limited internet access disrupts learning activities and reduces system efficiency. According to Ibrahim and Musa (2023), poor internet connectivity is a major constraint to the successful implementation of digital learning systems in schools, particularly in rural and underserved areas. This challenge directly affects the consistency and reliability of ITS-supported instruction.

Finally, data privacy and security concerns represent a critical challenge in the adoption of Intelligent Tutoring Systems. Since ITS collect and analyze large amounts of student data, including learning behaviour, academic performance, and personal information, there is an increased risk of data misuse, unauthorized access, and privacy violations. According to Zhang and Kumar (2024), concerns about data protection and ethical use of students' information remain a major issue in artificial intelligence-based educational systems. Similarly, Oke and Balogun (2023) emphasized the need for strong cybersecurity frameworks to protect learner data and ensure ethical compliance in digital education platforms. Without adequate safeguards, stakeholders may be reluctant to fully adopt ITS in educational settings. Hence, although Machine Learning-based Intelligent Tutoring Systems offer significant benefits for improving chemistry curriculum implementation, their adoption is constrained by infrastructural limitations, financial constraints, limited teacher competence, resistance to change, connectivity issues, and data security concerns. Addressing these challenges is essential for ensuring effective integration and maximizing the educational benefits of intelligent tutoring technologies in chemistry education.

Strategies for Effective Adoption of ITS

The successful adoption of Machine Learning-based Intelligent Tutoring Systems (ITS) in chemistry education requires well-structured strategies that address infrastructural, human capacity, financial, and policy-related challenges. These strategies are essential for ensuring that intelligent technologies are effectively integrated into classroom instruction and that their benefits are fully realized in the implementation of the chemistry curriculum. A coordinated effort among government agencies, educational institutions, teachers, and private stakeholders is therefore necessary to achieve sustainable adoption of ITS in educational systems. One key strategy is government support and policy formulation. Government plays a central role in creating an enabling environment for the integration of educational technologies through the development of policies that promote digital learning and artificial intelligence in education. Such policies can provide guidelines for the use of ITS, set standards for implementation, and ensure quality assurance in digital instruction. According to Okeke and Nwafor (2023), effective policy frameworks significantly enhance the integration of ICT-based instructional systems in schools by providing clear direction and institutional support. Similarly, Yusuf and Ibrahim (2024) emphasized that government commitment is essential for scaling up educational technology innovations and ensuring their sustainability in public education systems.

Provision of digital infrastructure is another critical strategy for effective ITS adoption. Intelligent Tutoring Systems require reliable access to computers, internet connectivity, electricity, and updated software systems. Schools must therefore be equipped with adequate ICT facilities that support seamless integration of intelligent learning platforms. According to Akinola and Eze (2023), the availability of functional ICT infrastructure is a major determinant of successful technology-enhanced learning in science education. Without adequate infrastructure, the implementation of ITS becomes ineffective and unsustainable, particularly in resource-limited environments. Continuous teacher training and retraining is also essential for effective adoption of ITS. Teachers must possess the necessary digital skills and pedagogical competence to operate intelligent systems and integrate them into classroom instruction. Regular professional development programmes can help educators become familiar with Machine Learning tools, interpret learning analytics, and apply ITS outputs to instructional decision-making. According to Adeyemi and Ogunleye (2024), continuous teacher training significantly improves ICT integration and enhances instructional effectiveness in science subjects. Similarly, Oladipo and Hassan (2022) noted that teacher capacity building is a key factor in the successful implementation of educational innovations.

Integration of ITS into teacher education programmes is another important strategy. Teacher preparation institutions should incorporate digital pedagogy, artificial intelligence, and intelligent tutoring systems into their curricula to prepare future educators for technology-driven classrooms. This ensures that newly trained teachers enter the profession with adequate knowledge and skills in using intelligent instructional tools. According to Uzochukwu and Eze (2023), embedding ICT and AI-based training in teacher education programmes enhances teachers' readiness for modern classroom demands and improves instructional quality. Public-private partnerships in educational technology also play a significant role in promoting ITS adoption. Collaboration between government, educational institutions, and private technology companies can facilitate funding, development, deployment, and maintenance of intelligent tutoring systems. Private sector involvement can also support innovation, provide technical expertise, and reduce the financial burden on government. According to World Bank (2023), public-private partnerships are effective in accelerating digital transformation in education systems, particularly in developing countries.

Finally, phased and context-sensitive implementation is necessary for sustainable adoption of ITS. This strategy involves gradual integration of intelligent systems into the education system based on available resources, institutional readiness, and contextual realities. A phased approach allows stakeholders to evaluate effectiveness, address emerging challenges, and make necessary adjustments before full-scale implementation. According to UNESCO (2022), context-sensitive implementation ensures that educational technologies are adapted to local needs, thereby improving acceptance and effectiveness. This approach is particularly important in environments with infrastructural and financial constraints. Consequently, the effective adoption of Machine Learning-based Intelligent Tutoring Systems in chemistry education depends on strong government support, adequate infrastructure, teacher capacity development, integration into teacher education, collaboration with private sector stakeholders, and gradual implementation strategies. These measures collectively ensure successful integration of ITS into the chemistry curriculum and enhance teaching and learning outcomes.

Conclusion

This paper examined the adoption of Machine Learning-based Intelligent Tutoring Systems (ITS) for effective chemistry curriculum implementation. The discussion highlighted the concept of Machine Learning and Intelligent Tutoring Systems as interrelated technological innovations that support adaptive, data-driven, and learner-centered instruction. It further explored the key characteristics of ITS, including adaptive learning, real-time feedback, predictive analytics, automated assessment, and personalized instruction, all of which contribute significantly to improving teaching and learning processes in chemistry education. The paper also discussed the relevance of ITS in enhancing personalized learning experiences, improving understanding of abstract chemistry concepts, increasing student engagement, supporting teachers through data-driven instruction, and boosting students' academic achievement. In addition, the challenges affecting ITS adoption such as inadequate ICT infrastructure, high cost of implementation, limited digital competence among teachers, resistance to technological change, poor internet connectivity, and data privacy concerns were critically examined. Finally, strategies for effective adoption were presented, emphasizing the importance of government support, provision of digital infrastructure, teacher training, integration into teacher education programmes, public-private partnerships, and phased implementation approaches.

The importance of Machine Learning-based Intelligent Tutoring Systems in improving chemistry curriculum delivery cannot be overstated. ITS provide innovative instructional support that transforms traditional teacher-centered methods into more interactive, adaptive, and individualized learning experiences. Through continuous monitoring of learners' progress and real-time instructional adjustments, ITS help to bridge learning gaps, simplify abstract chemistry concepts, and promote meaningful understanding among students. The use of intelligent systems in chemistry education also enhances assessment practices by ensuring timely feedback and objective evaluation of learners' performance. Consequently, ITS represented a transformative approach to improving curriculum implementation and achieving better learning outcomes in chemistry education. However, the successful adoption and sustainability of Machine Learning-based Intelligent Tutoring Systems require strong collaborative efforts among key stakeholders in education. Government agencies must provide supportive policies, adequate funding, and necessary ICT infrastructure to facilitate effective implementation. School administrators and educators must also embrace continuous professional development to enhance their digital competencies and instructional effectiveness. In addition, collaboration with private technology developers is essential in providing technical expertise, system maintenance, and innovation support. Parents and the wider society also have roles to play in supporting the acceptance and ethical use of educational technologies. When these stakeholders work together in a coordinated manner, the integration of ITS into chemistry education will be more effective, sustainable, and impactful in improving curriculum delivery and overall educational outcomes.

Recommendations

Based on the literature review and discussion of this paper on Machine Learning-based Intelligent Tutoring Systems (ITS) for chemistry curriculum implementation, the following recommendations are made to enhance effective adoption and utilization in schools:

1. Schools should integrate Intelligent Tutoring Systems into chemistry instruction as a complementary tool to traditional teaching methods in order to promote personalized learning and improve students' understanding of abstract chemistry concepts.
2. Government should provide adequate ICT facilities, stable internet access, and reliable electricity supply in schools to ensure the effective implementation and sustainability of Intelligent Tutoring Systems in chemistry education.
3. Teachers should be trained and retrained in digital literacy and AI-based instructional practices to enable them effectively use Intelligent Tutoring Systems for improved classroom instruction and learner support.
4. Educational stakeholders, including school administrators, policymakers, and private sector partners, should ensure equitable access to intelligent learning technologies across all regions to reduce digital inequality in chemistry education.
5. Policies should be developed and enforced to guide the ethical use, data protection, and security of students' information in the deployment and use of Intelligent Tutoring Systems in educational settings.

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