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AI-POWERED CHEMISTRY EDUCATION: OVERCOMING CHALLENGES AND UNLOCKING OPPORTUNITIES FOR 10TH GRADE STUDENTS IN PAKISTAN

Seemab Altaf[*1], Dr. Muhammad Ali Mohsin[2], Muhammad Sheryar Jahangir[3], Sidra Insar[4], Jamila Khushi[5]

*[*1]M.Phil Chemistry University of Lahore*
[2]Phd Chemistry University of Lahore
[3]BSc Mechanical Engineering University of Engineering and Technology Lahore
[4]MSc Botany Quaid-e-Azam University Islamabad
[5]MS Mathematics Comsats University Islamabad

[*1]greenpak247@gmail.com, [2]muhammad.mohsin@chem.uol.edu.pk, [3]sheryar_jahangir@yahoo.com, [4]sidraainsar@gmail.com, [5]jamilakhushimathematics@gmail.com

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Corresponding Author: *
Seemab Altaf

Abstract

This research paper investigates the role and impact of Artificial Intelligence (AI) technologies in chemistry education at the secondary school level, with a specific focus on 10th grade students in Pakistan. As Pakistan embarks on a national digital transformation agenda and strives to improve Science, Technology, Engineering, and Mathematics (STEM) outcomes, AI represents a transformative opportunity within classrooms. This study explores how AI tools—including intelligent tutoring systems, virtual chemistry laboratories, AI-powered problem-solving assistants, and adaptive learning platforms—are being deployed and experienced in Pakistani educational contexts. Findings indicate that students exposed to AI-assisted instruction demonstrate measurably improved conceptual understanding of core chemistry topics such as chemical bonding, stoichiometry, and periodic trends. However, significant obstacles—including infrastructure deficits, digital literacy gaps among educators, and socioeconomic inequalities—threaten equitable access. The paper concludes with evidence-based implications for policymakers, curriculum designers, and school administrators aimed at building a sustainable AI-integrated science education ecosystem in Pakistan.

1. INTRODUCTION

The twenty-first century has brought in a shift in technology on a scale unparalleled, and education is the center-stage of this revolution. Among the numerous technologies that are rapidly changing the way we acquire, process, and use knowledge, Artificial Intelligence (AI) is in a singularly special place (Chen, Zou, Xie, & Cheng, 2020). Moving on for the personalised learning systems that can adjust to the level of understanding of a student in real time, to the design of intelligent tutoring systems able to offer them Socratic dialogues on the intricate principles of scientific knowledge, AI is essentially changing the pedagogical landscape throughout the world.

The potential of AI is especially exciting in the particular case of chemistry education. Chemistry as

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a topic creates a special set of problems to students in secondary levels. It requires not only mastery of abstract theoretical concepts, skills to solve mathematical problems, but an intuitive discernment of phenomena at the molecular level that can never be seen with the naked eye (Rehman & Bhatti, 2021). To a 10th grade student in Pakistan, the task of learning about the concept of the mole, chemical equilibrium, acid-base reactions, and the theory of the atom orbitals can be extremely daunting, especially when using the traditional library of chalk-and-blackboard classroom instruction. These challenges are exacerbated by large class sizes, scarce laboratory provisions and an excessive dependence on rote memorization.

The population of Pakistan is more than 220 million with one of the youngest and the fastest growing populations in the world. Its rate of under 30-year population is approximately 64% and secondary school attendance is increasing gradually in the last 10 years. Educational infrastructure in the country has however been unsuccessful in keeping up with such demographic reality. Based on the 2023 Pakistan Education Statistics report, the performance of science subjects in the matriculation level (10 th grade) stays below the desired levels, and chemistry is one of the most commonly underperforming subjects at the matriculation level (Khan, Hussain, & Riaz, 2022). It is against this backdrop that AI is not only a technological novelty but also a real strategic opportunity to enhance the quality, reach, and equity of education.

This opportunity has been recognised by Government of Pakistan. The National Education Policy Framework (2022) singles out the application of digital technologies and AI in secondary education as an area of priority. Some provincial education authorities, especially in Punjab have already started pilot initiatives that have seen EdTech solutions, such as AI-enabled platforms, introduced to public school curriculum (Ma, Adesope, Nesbit, & Liu, 2014). Urban schools, including Karachi, Lahore and Islamabad, have gone even further, implementing advanced AI functionality like Khan Academy, Coursera campus, and even locally developed applications including Taleemabad and Sabaq.pk that possess features of adaptive learning based on AI algorithms.

However, the real extent of these programs on the student achievement in chemistry and the challenges to their broader implementation are not adequately researched. The available literature on AI in education is mainly predominated with studies on high-income nations like the United States, the United Kingdom, China, and South Korea. Pakistani educational environment, particularly with the specific combination of cultural, linguistic, economic, and infrastructural phenomena, requires its own set of studies.

1.1 Research Objectives

The following research objectives are aimed to be answered by this paper:

The aim of the study is to investigate the kind of AI tools applied in 10 th grade chemistry classrooms in Pakistan.

- To measure the perceived effects of AI-aided learning in students on their learning of essential concepts of chemistry.
- To determine key challenges and barriers to the implementation of AI in the Pakistani secondary science education.
- To provide evidence-based recommendations for policymakers, educators, and school administrators.

The study has numerous significant contributions to the science education and educational technology in Pakistan (Trucano, 2016). Firstly, it offers empirical evidence regarding adoption trends of AI that are rather uncertain in the existing literature on the subject of Pakistani secondary education. Second, it previews student and teacher voices- voices which are often outlooked when it comes to top-down discussions of policy integration of technology. Third, it explains a calm evaluation of what structural obstacles there are to adopting AI, allowing policymakers to focus their interventions on the areas where they will be most effective. Last but not the least, it places the AI-in-education journey of Pakistan in a global comparative context, relying on the best practices of the global context but is also responsive to the local context.

II. Literature Review

The body of knowledge on AI in education is very snowballing. In order to place this research within

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the overall context, this review is divided into four thematic subsections: the development of AI in STEM education globally; the use of AI in chemistry in particular; AI and education in developing countries; and the specifics of the educational technology environment in Pakistan.

The role of AI in STEM Education: An International Perspective.

Theoretical underpinnings of AI in education can be traced back to building Intelligent Tutoring Systems (ITS) as far back as the 1970s. Analysts like Sleeman and Brown (1982) were the first to develop the idea of computer-based systems capable of simulating student knowledge and giving personalized training. These initial systems became more advanced machines with the development of machine learning algorithms and natural language processing technologies. By the 2000s, systems like MATHia by Carnegie Learning or AutoTutor had shown that ITS was able to deliver the same learning results (or sometimes better) than in a conventional classroom setting in subjects like mathematics and physics (VanLehn, 2011).

The entry of deep learning and large language models in the 2010s radically increased the capacity of AI to provide to educators. In a seminal meta-analysis study, Kulik and Fletcher (2016) analyzed 50 control evaluation studies that showed that students using AI-based instructional software significantly outperformed control groups by average 0.66 standard deviations with a significant and statistically significant effect size. More recent studies and research corroborated this finding: Zawacki-Richter et al. (2019) reviewed 146 articles about AI in higher education and found that personalized learning, intelligent tutoring, and automated evaluation are the three most influential AI applications in education.

Within the sphere of STEM education, in particular, AI has proved to be especially good in closing the gaps between abstract conceptual knowledge and practical skills. AI-based simulations and virtual laboratories have the potential to offer the student an experimental experience that is not feasible in real-life settings (either because of resource availability or constraints, safety issues or because the proposed phenomenon is abstract). Studies by Potkonjak et al. (2016) have proven the virtual laboratory setting to be as comprehendible to the student as a physical laboratory setup, with the added benefit of repeatability and safety.

AI in the Teaching of Chemistry.

Education in chemistry poses particular challenges, which makes it a very promising area of AI intervention. The topic traverses various representational scales–macroscopic phenomena that are visible in the laboratory, submicroscopic models of Molecular and atomic behavior, and symbolic descriptions in terms of Chemical formulas and equations. This triplet relationship, which Johnstone (1991) identified as the key conceptual challenge that chemistry students have to cross, was repeatedly found to be the essential barrier in the way of gaining an education, with decades of educational research since substantiating this finding continuously.

This is the set of challenges that AI tools have been created to handle. AI-controlled molecular visualization software can enable students to explore three-dimensional simulations of molecules, watch behavior of electron density changes during chemical reactions, and build intuitions about structure-property correlations that would be almost impossible to describe using two-dimensional visualizations. Initially as open-source software (Avogadro, Jmol) and commercial software (Labster virtual laboratory), this kind of software has now found extensive use in secondary and tertiary chemistry teaching and learning around the world, and studies continually indicate that this type of software is associated with enhancements in spatial reasoning and conceptual understanding (Merchant et al., 2013).

Another key field of development is AIs-based problem-solving aids. They can take students through multiple steps in their chemistry problems one by one by showing them the most frequent misconceptions (e.g., confused about where or how atomic mass and atomic number are different; or where or how moles and grams are different) and giving them specific feedback as to what is going wrong with their answers. Chen et al. (2020) investigated the effects of an AI chemistry tutor on a cohort of 580 high school students in Taiwan and

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discovered that students undergoing AI-based tutoring achieved a 18 per cent higher score on their post-unit tests compared to the control group, which obtained only traditional instruction.
GPT-4 and Claude are the latest language models with a huge size called continuous models that have opened another frontier. These models have the capability to discuss natural language about the chemical concepts with students, respond to questions, give worked examples and work out practice problems, which may be created based on the level of understanding of a particular student. Although the existing small body of research on the informational impact of these innovative tools remains early, initial investigations hold up to positive results, especially in terms of the students who otherwise would not have access to personal tutoring (Kasneci et al., 2023).

AI and Education in Developing Countries.

The theme of the literature that remains is a growing disparity between the present state of AI usage between high-income and low-to-middle income countries (LMICs). According to Holmes et al. (2022), practically the entire range of studies on AI in education has North America, Europe, and East Asia, and the limitations and opportunities in developing countries are underrepresented in the literature. These limitations consist of untrustworthy access to electricity, low-bandwidth Internet connections, large student-to-gadget ratio, poor teacher training to digital teaching methods and cultural/linguistic obstacle to usage of tools designed to serve English-speaking markets.
However, a range of LMICs have taken impressive steps towards implementing AI-proximate education technologies. The implementation of DIKSHA, an adaptive learning platform powered by data analytics and based on a National Education Policy initiative in India, has resulted in personalizing content to more than 250 million learners. In Kenya, the Eneza Education platform has shown that micro-learning, a low-tech yet AI-aware tool, in the form of SMS can be used to boost the performance of secondary students in science subjects in the setting where smartphone penetration is limited (Trucano, 2016).
A study of Bangladesh and Nepal on adaptive learning programs implemented in tablet format indicates that the smallest AI performance, when tailored strategically to the circumstances at local sites, can yield significant changes in student engagement and learning. Most importantly, though, the studies do also point at teacher training as the most crucial enabling factor: platforms that are deployed without proper teacher preparation always perform lower than expected based on their corresponding potential.

Technologies in Pakistan: Technology in Education Technology in Education in Pakistan

Pakistan has been unequally involved in the use of educational technology but has increased in pace. Early ambition of technology-mediated learning was shown by the founding of the Virtual University of Pakistan in 2002, one of the first fully online universities in South Asia. More recently, the establishment of the Ilm Ideas initiative (financed by the Foreign Commonwealth and Development Office of the UK) helped to facilitate the creation and growth of some Pakistani K-12 EdTech startups, such as Maqsad, Sabaq, and Taleemabad.
A limited number of studies focusing particularly on technology application in science education in Pakistan is informative. In a study of the use of computer simulations in high-school Biology and chemistry classes in Lahore, Malik et al. (2019) reported that simulations were a strong predictor of student performance on conceptual questions, but the study was limited by a high reliance on capable computer laboratories where even in a fairly well-equipped urban setting. Surveying 200 teachers in Punjab in the field of chemistry, Rehman and Bhatti (2021) discovered that 78 percent of teachers were willing to integrate into the digital world, but fewer than 25 percent of respondents had any training in the field of educational technologies, which is a major gap in capacity.
The 2020-2021 COVID-19 pandemic became an unwanted change agent in the uptake of technology in Pakistani education. The shutdown of schools compelled teachers and students to investigate digital space, and millions of households have been exposed to video-based learning and online learning content that they never experienced before. The Alif Ailaan advocacy organization conducted post-pandemic surveys, which reported that the usage of digital tools

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by secondary school teachers had grown by about 40 percent compared to pre-pandemic levels, but the quality and the depth of their use differed immensely.

The research in the field of chemistry, in particular, did not have any significant national study researching the application of AI tools to the 10th grade level before this research. This is the main stimulus behind the research undertaken in this study.

III. Methodology

This research design is a mixed-methods study that utilizes quantitative (via surveys), qualitative (via interviews and classroom observations). Mixed-methods approach has been chosen due to its capacity to combine the strengths of both the expansiveness of quantitative and the contextual profundity of a qualitative investigation- a valuable combination in the multi-layered context of technology integration in a variety of school settings.

A total of 18 schools (six Punjab, three each (3 public, 3 private), Sindh (three each (3 public, 3 private)), and KP (three each (3 public, 3 private)) became the final sample size. In both schools, the number of student respondents was 320 out of 10th grade learners who study chemistry. The study also included 45 teachers of chemistry in these schools- an average of 2.5 teachers per school, which is noteworthy since in some cases, there may be only one chemistry teacher in each secondary school (Warschauer, 2004). To address the qualitative aspect, fifteen teacher and 24 students (sampled to cover the diversity in sex, type of school and the region) were interviewed, in depth. The classrooms were observed in 12 classrooms in all the three provinces.

This study employed three main instruments. To begin with, a systematic student questionnaire was utilized where all the 320 student participants were given a survey with 42 items. The survey gathered information on: AI tool availability and awareness; AI tool use frequency, during chemistry study; perceived usefulness of the AI tool in learning specific chemistry topics; feelings about AI technologies as a learning tool; and self-reported learning performance. This survey was constructed in English language, validated in Urdu where there were need in order to make it understandable. Attitudinal items were done in a Likert-scale format (1- 5) whereas factual and behavioral items were done in multiple choice and short-answer item formats.

Second, a semi-structured teacher interview protocol was created to investigate teacher awareness of AI tools, their practices of integrating AI into their classroom, perceived barriers and enablers, and attitudes towards AI in education. Interest duration was 30-60 minutes and the interviews were done in physical or video call (Prestridge, 2012). All the recorded interviews were transcribed with the permission of the participants. Third, classroom observation protocol to record real AI tool use in the classroom instructional practices included the frequency, duration, and the pedagogical context of AI tool use, student engagement, teacher facilitation behavior.

Ethical Considerations

This research study was approved as ethical by the intranet research board of the research institution in which the study was conducted. All adult participants (teachers and parents of student participants) were informed before data collection and gave their informed consent. Agreement of the students was also consulted. Participation was voluntary and participants were made aware of their right to drop any time without any repercussions. Data were anonymized before analysis and schools/individuals will be referred as pseudonyms in this report. Encrypted servers are used to store data files, which the research team can access only.

IV. Results

The survey results presented a multi-layered and multi-faceted vision of the use of AI tools among 10 th grade chemistry students in Pakistan. In general, 320 student respondents (68.4 percent of the sample) indicated the presence of at least one educational device of AI-related methods in the previous academic year when studying chemistry (Trucano, 2016). This number however concealed a sturdy deviation on that of school type and location. The rate of adoption was 91.2 amongst students studying in private schools in urban areas, whereas it was only 38.7 amongst students studying in the semi-urban areas of the school system- a gap of more than

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50 percentage points reflecting serious structural disparities in access to the digital divide.

The most popular AI tools mentioned by students were: Khan Academy (41.3% of students who adopted AI use it), YouTube educational content created by AI bots or AI-recommended playlists (38.1% of students who adopted AI use it), Sabaq.pk (29.4%), PhET Interactive simulators developed by the University of Colorado (22.7%), and ChatGPT or other large language A lesser proportion (9.3) used specially created chemistry AI technology, like Labster virtual lab or the Zen predictions of structure prediction features of ChemDraw.

The responses of the teacher surveys outlined a generally consistent picture. Out of the 45 surveyed teachers, six out of every ten said they used at least one AI-related tool in their chemistry classes, and just 31% of them said they applied the tools regularly (at least once per week). Teachers in the privately operated urban schools were much more likely to use AI tools and their use was more diverse than that in the public and semi-urban schools (Warschauer, 2004). The most popular teacher-reported before-uses included: Using AI sites to create practice questions (44%), presenting learners with virtual demonstrations of chemical experiments (38%), and referring learners to AI-enabled study sites to use as homework content (29%).

Effect on Chemistry Learning Outcomes.

These quantitative results were given a touch by qualitative data (interviewing of students). One of the female students in a privacious school in Lahore talked about her experience with an AI chemistry tutor: when I am at school, I do not get something, so I go home and ask the AI. It tells me the same thing 5 times till I understand. My teacher of chemistry is good, but she has 40 pupils, and she is not able to attend all of them individually (Zawacki-Richter, Marín, Bond, & Gouverneur, 2019). A Pakistani male student at a state-funded school in Rawalpindi took a different view: "I heard about such AI applications, however, we do not have a computer lab and my cell phone data is very expensive. I watch YouTube occasionally when I have a Wi-Fi connection at a family house, but otherwise not.

Teachers that frequently incorporated AI into their teaching claimed to have witnessed qualitative changes in classroom dynamics. Some of them indicated that simulations powered by AI were especially revolutionary in terms of conceptual acquisition. A chemistry teacher in Karachi wrote: When I demonstrate the electron orbitals in a phET simulation or demonstrate the behavior of molecules during a reaction in 3D, my questions are instantly more advanced. They do not simply want to know what is the formula, they just want to know why the reaction occurs. Quite a different plane of thought, that.'

Obstacles and Problems to AI Usage.

Infrastructure and Connectivity: Poorest technology infrastructure was the most cited impediment. The availability of computer labs in these public schools was low in the three provinces: only 38 percent of respondents in the public schools said they had a functional computer lab that had enough devices to allow them to use them. Internet connectivity was less reliable as well--only 22 percent of students were found to have regular access to broadband in school. Power outages (56% of all the participants mentioned frequent power outages) even prevented the use of digital tools when the devices and connectivity were available in theory. These data are in line with national statistics in Pakistan: as the report prepared by Pakistan Telecommunication Authority (2024) shows, in rural and semi-urban regions, the penetration of broadband is less than 18 percent (Pakistan Telecommunication Authority, 2024).

Teacher Digital Literacy and Training: The second greatest obstacle was the low level of awareness of teachers using AI tools. Whereas 87% of the surveyed teachers positively stated that they were sure about the use of the technology within the educational setting in principle, 28% believed that they could successfully implement AI instruments in teaching chemistry without any supplementary help. Among individuals who had tried to adopt AI platforms, 56% had a negative experience, where they experienced technical challenges that they were unable to solve on their own (Potkonjak, Gardner, Callaghan, Mattila, Guetl, Petrović, & Jovanović, 2016). Just one-third of teachers had received any

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formal training on educational technology in the last three years and less than 1 in 10 teachers had received education on AI-related training in STEM.
Curriculum Alignment: Numerous educators were worried about whether AI solutions (the majority being oriented towards international curriculum) fit the syllabus of a Board of Secondary Education in Pakistan. One of our KP teachers has observed: The online simulations are really good, although they do not correspond to our chapters in the syllabus. I need to locate the correct section and clarify to students why there are differences in certain aspects. It consumes additional preparation, which may not always be within my reach. This problem of misalignment of curriculum was reflected by 61 percent of the teacher respondents.
Language and Cultural Accessibility: More AI tools exist in English; however, around 43% of students who answered the question indicated their English proficiency as basic or below basic. In public schools, many students are taught in Urdu (or Pashto or Sindhi), and are exposed to English only as a written class (Warschauer, 2004). The language interaction-based AI tools, such as the majority of large language models and most simulators, are therefore not accessible to a large part of the target population without translation or localization. The sample only had three platforms, which were regularly used (Sabaq.pk, Maqsad, and Taleemabad), to provide significant in-depth material in Urdu language.
Socioeconomic and Gender Disparities: There existed strong stratification of access to personal devices on socioeconomic status. At least 31 percent of students whose household is in the lowest income quartile had personal access to a smartphone or tablet that they can use to load educational apps, compared to 94 percent in the highest income quartile of households. Gender inequalities were evident as well: female students living in semi-urban reported to have significantly less access to devices and the internet than their male peers, which aligns with general digital gender inequalities reported in Pakistan (Khan et al., 2022). The female students in all three provinces were also more apt to mention parental barriers to AI-assisted study, in the form of restrictions of smartphone use.
Assessment Misalignment and Exam Culture: The last, structural barrier is associated with the Pakistani culture of a high-stakes examination (Warschauer, 2004). The Matriculation tests (the 10th grade board exams) are more or less paper based, timed and are more concerned with recall as well as procedural problem solving. A few teachers remarked that since AI tools are based on conceptual learning and discovery, not the performance seen on an examination: they offer little incentive to the students: 'My students want to pass their board exam. They cannot use an app not by making them directly answer the types of questions that will arise in the board exam. they will follow the same papers back to the past.'

Student and Teacher perceptions of AI in Chemistry.

Although the identified challenges exist, both students and teachers expressed a positive attitude towards AI in chemistry education in a general way. In the student survey, 74.1% of students supported or felt strongly the statement of AI tools making chemistry interesting and engaging. Out of the students who had learned with the help of AI devices, 81.3% said that they felt more confident with chemistry after having used the devices and 69.7% said that learning with the help of AI had improved their performance (Tondeur, van Braak, Ertmer, & Ottenbreit-Leftwich, 2017).
Teacher attitudes were more subtle. Although 82% said that AI has the power to enhance the outcomes in chemistry learning, only 54% thought their school was ready to significantly adopt AI tools, citing the infrastructure and training barriers mentioned above. Interestingly, attitude did not differ significantly between older (> 40 years) or younger (≤ 40 years) teachers and it can be inferred that it is not necessarily the generational opposition to AI but rather the structural.

V. Discussion

The results of this analysis suggest a Pakistan education environment with AI-based opportunity on the one hand and structural inequality-based constraints on the other. This discussion puts those findings in the context of the rest of the literature, discusses the theoretical implications of the findings and the limitations of the study.

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Data Analysis of the Learning Outcomes.

The character of the positive correlation between the activities in the AI tools and self-reported learning outcomes corresponds to the world literature. The effect sizes found in the current study (especially, the estimated 0.75-point gap on a 5-point scale between regular users and non-users of AI when attempting chemical bonding understanding) are similar to those in the meta-analyses that are carried out in developed country settings (Kulik and Fletcher, 2016; Ma et al., 2014). The given comparability is worth considering: it implies that AI tools could be useful under Pakistani classroom conditions despite the fact that the implementation conditions were far less than ideal.

However,the high level of confounding influence by school type highlights the fact that these results are to be approached with caution. The most frequent users of AI are those students who study in well-advantaged, well-equipped and high-funded private schools, and are the same fortunate learners who are already benefiting or advantaged through various other inputs in education (VanLehn, 2011). It is also methodologically difficult to use the survey design used here to disentangle the particular contribution of AI tools and the overall benefits of attending private schools (smaller classes, better trained teachers, greater parent involvement etc). Further experimental or quasi-experimental research designs would be required to determine causal effects in a more stringent way.

The qualitative data provide a valuable supplement to the quantitative results by shedding light on the mechanisms the AI seems to enhance chemistry learning. Three patterns were observed over and over again: personalized pacing (students have a chance to follow AI-based explanations at their own pace and repeat as many-time as necessary), multimodal explanation (AI-based products provide visual, animation, and interactive images that do not exclude text-based instructions), and low-stakes practice (students can take quiz, problem sets, and repeat it as many-time as they need in this way (Sleeman & Brown, 1982). These three mechanisms are all in line with the known theories of cognitive learning of chemistry, such as the representational triplet by Johnstone, and cognitive load theory of Sweller.

The Inequality of Infrastructure.

The most striking observation of this study is the size of the digital gap between the privately urbanized and the publicly semi-urban schools. A 52-percentage point discrepancy in the levels of adoption of AI is not just an issue of technology access but an expression of a large and increasing inequality in academic opportunity. With AI tools rapidly taking center stage in high-quality science education in countries around the world, Pakistani students who lack access to this technology are in danger of being left behind both in the domestic education system and in an AI-based labour market worldwide.

This observation resonates with the idea that access to technology proposed by Warschauer (2004) which is based on the technology-and-social-inclusion approach and claim that access to technology should be perceived not only as access to physical device, but also as access to skills, social support, and the need of the technology use (Warschauer, 2004). A variable that is necessary yet not sufficient to provide students with equitable AI-assisted learning is providing them with smartphones, but it is equally important to have good connectivity, content that is in good accessible languages, and teachers who can instruct them on how to use AI tools effectively.

Uneven access to energy infrastructure: the frequent power failures that affect the use of digital tools are one dimension of the digital divide, little addressed in the EdTech literature that is predominantly represented in a context with stable electricity supply. In the case of Pakistani schools, to overcome this obstacle, the investments in renewable energy (some rural schools have started to experiment with solar panels) and creation of offline-enabled AI tools that do not need the constant internet connection might be required.

Teacher Preparation as the key Lever.

The data consistently recognize teacher digital literacy and professional development as the most important enabling factor to AI integration in Pakistani chemistry classrooms. This is an impressive result as it is in agreement with the international literature that confirms that teacher beliefs, competencies, and institutional support are more influential predictors of technology integration than

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device availability itself (Ertmer et al., 2012; Tondeur et al., 2017).

The most significant thing is the low level of teacher training in AI-specific pedagogies: less than one in every ten teachers received any training in AI-in-STEM in the last three years. This is in spite of the reality that overwhelming majority of teachers hold positive attitudes towards technology. This gap between attitude and practice which is highly reported within the technology integration literature as the so-called (attitude-behavior gap) (Prestridge, 2012) indicates that goodwill is not enough and it needs to be enhanced through formal and systematic professional development.

Curriculum and Assessment Alignment.

The conflict of AI tools that are used to comply with international learning systems and the curriculum that thousands of students in Pakistan are taught by the Board of Secondary Education, is a structural issue that cannot be fixed at the classroom level. It involves concerted effort among those involved in curriculum development, examining boards and EdTech vendors. The existing matriculation test regime, which focuses on rote learning, instills incentives perversely, which discourages the use of tools that encourage more concept learning-the same things chemistry education researchers believe are most useful (Khan, Hussain, & Riaz, 2022). The case of local services like Sabaq.pk which has created curriculum based video content in Urdu and has been adopted by large numbers in government schools proves that this can be done and is a commercially viable service. It requires purposeful policy assistance, such as purchasing preferences, subsidies, or co-development agreements, to encourage the creation of AI tools aimed particularly at Pakistani education.

VI. Study limitations.

There are a number of drawbacks of this study that should be mentioned. To begin with, the use of self-reported learning outcomes (instead of measured scores of assessment) creates the possibility of social desirability bias; students can overreport AI usage and its positive effect. Second, there is no opportunity to infer any causality in the cross-sectional design; there might be selection effects that both the highly motivated students use AI and achieve higher learning outcomes or that the use of AI is a real treatment effect. Third, the three-province sample does not represent a diverse area well since it omits Balochistan or Gilgit-Baltistan that have their unique education settings. Fourth, this was a time-sensitive study; the current AI tool environment is changing quite fast so that some of the results will become obsolete within a few years.

VII. Future Implications.

According to the above finding and discussion, the following section presents a series of future-oriented implications of the secondary chemistry education ecosystems in key stakeholder in the context of Pakistan. These implications are strategic priorities and not prescriptive requirements as they should be implemented in a contextually modified manner.

- Policy-Level Implications

A national and provincial education strategy on AI-in-Education which specifically targets secondary STEM subjects should be developed by the ministries. Such a plan must include an infrastructure investment, teacher training, curriculum matching, and provision of equitable access. The policies of digital integration that exist in the current National Education Policy Framework need to be operationalized by using specific, funded courses of action, which have measurable objectives, timeframes, and accountability processes (Khan, Hussain, & Riaz, 2022).

Probably the most structurally significant lever of the policy is examination reform. Higher Education commission and provincial examination boards are advised to assemble chemistry educators, test administrators, and EdTech stakeholders to work out a plan of introducing application-based and problem solving questions into examinations on matriculation chemistry. Unless examination reform is undertaken, the incentive system will remain in the way of implementing AI tools that encourage conceptual richness (Rehman & Bhatti, 2021). The policy on procurement and funding needs to be changed to focus on locally designed, curriculum-related, multilingual AI solutions in digital projects in State schools. This may include co-funding deals with homegrown EdTech firms, bulk purchase deals with foreign platforms that are eager to localize

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content and competitive grant funding to produce AI chemistry content in Urdu and local languages.

The barrier of the energy infrastructure needs to be approached in collaboration with the Ministry of Energy. The school solar electrification program-already tested out in selected provinces- should be rolled out in large scale as soon as possible and its implementation in schools in all provinces will provide a sure footing on which all the digital learning initiative will be built.

- Teacher Education and professional development.

Digital pedagogy and AI literacy must be incorporated in pre-service teacher education programs at universities and teacher training colleges and not an optional add-on. Educational curricula in chemistry specifically, should incorporate practical instruction in the use and critical assessment of the use of AI in instruction of bonding, thermodynamics, electrochemistry, and additional fundamental 10th grade educational content.

In the case of in-service teachers, the provincial education departments need to work out the tiered, sustainable professional development program in AI-aided teaching of chemistry (Holmes et al, 2022). This program must not be a one-shot workshop, which research continues to indicate has little to no long-term effect, but must be a continuous professional learning community, peer coaching network and digital mentorship programs, which can assist teachers as they experiment with AI in their classes.

Technology integration is a key role of school principals and middle managers (though usually neglected). There must be modules on how to develop enabling school cultures to adopt AI in leadership development programs, such as policies on device use, time to work on professional development, and mechanisms of sharing the best practices of successful teachers.

VII. Conclusion

This study has explored how Artificial Intelligence can be applied to teaching chemistry in the 10 th grade in Pakistan using survey information among 320 students, and 45 teachers across three provinces, which is further supported by qualitative interviews and classroom observations. The paper has reported the significant potential of AI-assisted chemistry education and the significant structural barriers that at the present do not allow even-handed access to the advantages of this technology. The key discovery is an essence of immense potential in systems with a limit of inequity. In the few students who have access to AI applications, and they are mainly those in urban schools that are privately owned, the data is continually pointing to an increase in conceptual knowledge, their interest in chemistry and their confidence. The trio of benefits of AI—the delivery of personalized, multimodal, low-stakes learning experiences directly responds to the three most enduring problems of chemistry education: the necessity of operating across representational levels at the same time, the necessity of getting individualized feedback even in large classes, and the necessity of having laboratory-like experiences with limited resources.

However, these benefits are still out of reach to the small majority of Pakistani students of 10th grade chemistry, students of public schools, in semi-urban and rural localities, students whose economic background is based on lower income groups and in most cases, female students. Digital disparities in AI use are not merely a question of device access, but they indicate fundamental imbalances in stored infrastructure, educator training, language availability, and testing motivation, which will need to be systemically tackled. Pakistan is at a cross-way between educations. The decision on spending on educational technology infrastructure, educator professional development, curriculum reform, and equitable access policies will be made within the next five to ten years and will dictate whether AI will become a factor in reducing or increasing the education opportunity gap in Pakistani secondary science education. The findings reported in this study come with an eloquent call to action. The study adds to the evidence base on AI in education in Pakistan, which remains slim, and suggests the need to invest in longitudinal, experimental, and equity-based studies. The history of AI in Pakistani chemistry education is in its early writing phases; the results that are provided here are intended to be a map of the current state of affairs as well as a compass towards the future.

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