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Technology-Enhanced Learning Approaches for Teaching Abstract Chemical Concepts in Resource-Limited Settings

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Abstract

This review evaluates technology-enhanced learning resources that include virtual laboratories, simulations and mobile applications to teach abstract concepts of chemistry in resource-limited learning environments. Findings have indicated that digital learning materials are significant in enhancing the understanding of abstract chemistry concepts among students, improve academic success, motivation and involvement of learners through interactive and multimedia-based learning. However, the effective implementation is limited by critical factors including infrastructural limitations, device access, internet connectivity, teacher preparation and pedagogical approaches of integrating with other approaches. Virtual laboratories and the augmented reality (AR) applications helped in the visualisation of the molecular structure and reactions that may be difficult to achieve in resource-limited setting of developing countries. Despite the established benefit, the current obstacles of the high cost of implementation, technical problems, digital literacy, the reluctance to alter the ongoing pedagogical practices restrain its usage. Meanwhile, best practices revolve around blended learning systems that combine traditional and online systems, intensive and comprehensive teacher training programs, curriculum alignment, and solutions sensitive and adaptable to offline functionality and low bandwidth environments. This review is appropriate in the discussion of educational policy as it identifies evidence-based methods of quality chemistry education through the combination of the appropriate technology in resource constrained facilities and the necessity of making a systemic investment in digital infrastructure and capacity building in order to ensure equitable educational achievement.

Keywords: Virtual laboratories, Chemistry education, Resource-limited settings, Educational technology, Mobile learning applications, Digital simulations

INTRODUCTION

The use of technology-enhanced learning tools, including virtual laboratories, simulations, and mobile applications to teach abstract chemical concepts under the constraint of resources has become a highly important field of study because of its capacity to resolve long-standing problems in education. The selection of digital tools in chemistry education over the past years has followed the trend of growing interactivity and accessibility, starting with the use of basic computer simulations to the use of more advanced augmented reality and mobile learning applications (Guzmán et al., 2025; Sobowale et al., 2024; Yuri, 2025). They are also relevant in terms of enhancing student interaction and conceptual knowledge, especially in situations when the traditional laboratory facilities are limited or poorly developed (Le et al., 2022; Manyilizu, 2023). As an example, virtual laboratories have shown the ability to complement or even substitute physical labs and provide flexible, inexpensive alternatives that can improve the provision of useful science education (George & Kolobe, 2014; Ndebvu et al., 2024). Since chemistry is a fundamental STEM subject with abstract and complex concepts, improving the teaching of

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chemistry with the help of technology is critical to promote scientific literacy and STEM career options (DeWallace-Marenholz, 2025; Murphy et al., 2022).

In spite of these innovations, there are still problems with efficient application of technology-based learning in resource-limited conditions. Access to physical laboratories, lack of teaching materials, and infrastructural issues associated with restricted hands-on experimentation complicate the issue (Barraza Rodríguez, 2024; Manyilizu, 2023; Samson et al., 2024). Although virtual labs and simulations are already promising in terms of helping students achieve a higher academic level and increase their motivation, there is a knowledge gap in terms of their comparative effectiveness, contextual flexibility, and optimal ways of implementation in different educational environments (Bazie et al., 2024; Hanine et al., 2025; Iwag, 2025). Additionally, there are still discussions regarding the degree to which virtual experiences can replace real lab work, and some of the studies indicate that instead of replacing, they complement each other (Davenport et al., 2012; Mphafudi & Ramaila, 2021). The outcomes of such a gap encompass poor performance of students in chemistry and inability to scale up technology-based interventions in underserved areas (Hanson et al., 2017; Ogunde et al., 2013).

This review is aimed at analysing some existing evidence about the application of virtual labs, simulations and mobile apps in teaching abstract chemical concepts in resource-limited environments. Its purpose is to determine the efficacy of such approaches and generalise the best practices to be applied in them, thus, filling the knowledge gaps on empirical data and contextual knowledge. This review will be helpful to the literature on the use of technology in improving chemistry education by consolidating various studies under geographic and technological settings and providing insights to educators, policymakers, and developers with an interest in optimising chemistry

METHODOLOGY

Search terms such as virtual labs, augmented reality solution, mobile learning solutions, immersive technologies, and pedagogical implementation strategies in developing country were used to make a search on Google Scholar. This gave over 1,000 search results, which were screened using a set of pre-defined inclusion and exclusion criteria. Studies were included if they were published between 2012 and 2026, were peer-reviewed journal articles, conference proceedings, or theses reporting empirical, quasi-experimental, mixed-method, or case-study findings on the use of virtual laboratories, simulations, augmented/virtual reality, or mobile applications in teaching chemistry concepts, and were conducted in or relevant to resource-limited educational settings. Studies were excluded if they were purely theoretical or opinion-based with no reported outcome data, were not available in full text, or addressed technology-enhanced learning in subjects other than chemistry or general science without chemistry-specific findings. Titles and abstracts of the retrieved records were first screened for relevance, followed by full-text screening of shortlisted articles, after which 20 papers met all inclusion criteria and were selected for this study. The studies were thematically analysed to find recurring trends. Coding and analysis of themes was used to determine frequency and recurrent themes which was interpreted for quantitative comparisons (based on effectiveness and impact scores) and qualitative information obtained from quasi-experimental, mixed-method, qualitative case study and intervention-based studies from various nations in this study such as Nigeria, Tanzania, Indonesia, Ethiopia and Malawi.

The effectiveness and impact scores reported in this review (e.g., Figures 1–3) were derived through a structured data extraction process. For each of the 20 included studies, outcome data reported by the original authors; such as percentage gains in academic performance, conceptual understanding, engagement, or skill acquisition; were extracted using a standardised extraction form capturing the technology type, sample characteristics, outcome measure, and reported quantitative result. Where studies reported outcomes on different scales (e.g., raw test scores, Likert-scale ratings, or qualitative engagement ratings), these were converted to a common percentage-effectiveness scale using a simple scoring rubric in which the reported outcome was expressed as a proportion of the maximum possible score or, where applicable, as the percentage improvement relative to a traditional/control comparison group. Scores for each technology category (e.g., simulations, virtual laboratories, augmented/virtual reality, mobile applications, game-based learning) were then averaged across the studies reporting on that category to produce the aggregated effectiveness scores presented in Figure 1, while the barrier and implementation-impact percentages in Figures 2 and 3 were obtained by calculating the relative frequency with which each barrier or implementation factor was reported across the thematically coded studies. No inferential statistical testing was performed; the percentages therefore represent descriptive, frequency- and outcome-based aggregation rather than results of formal hypothesis testing.

RESULTS AND DISCUSSION

Results

Distribution of research themes

The barriers to adoption were the most common theme among the reviewed literature, these studies explored infrastructural, pedagogical, technical, and economic barriers (Guzmán *et al.*, 2025; Hanine *et al.*, 2025; Shambare & Simuja, 2024). The second most intense theme was conceptual understanding, in which the virtual laboratories and simulations improved students' understanding of abstract concepts in chemistry or chemistry related subject (Bazie *et al.*, 2024; Mphafudi & Ramaila, 2021). Studies that investigated student engagement, noted overall increased motivation and active participation during the application of technology-enhanced tools (Assaf, 2025; Sailema-Castro *et al.*, 2025; Samson *et al.*, 2024). The aspect of accessibility and the usability was considered in many studies, and heterogeneous effectiveness was observed depending on internet access, availability of devices, and infrastructure (Ndebvu *et al.*, 2024; Yuri, 2025). Implementation strategies were given, and was pointed out in these studies that pedagogical frameworks, teacher training, and curriculum alignment are critical success factors in chemistry teaching (Sobowale *et al.*, 2024).

Comparative effectiveness scores for different technology-enhanced learning tools

Figure 1 compares scores of comparative effectiveness of the various technology enhanced tools of learning in terms of aggregated student performance and engagement scores. Simulations showed the best results with the highest effectiveness of 88 percent, especially in visualisation of dynamic chemical reactions and equilibrium reactions (Davenport *et al.*, 2012; Rogers *et al.*, 2000).

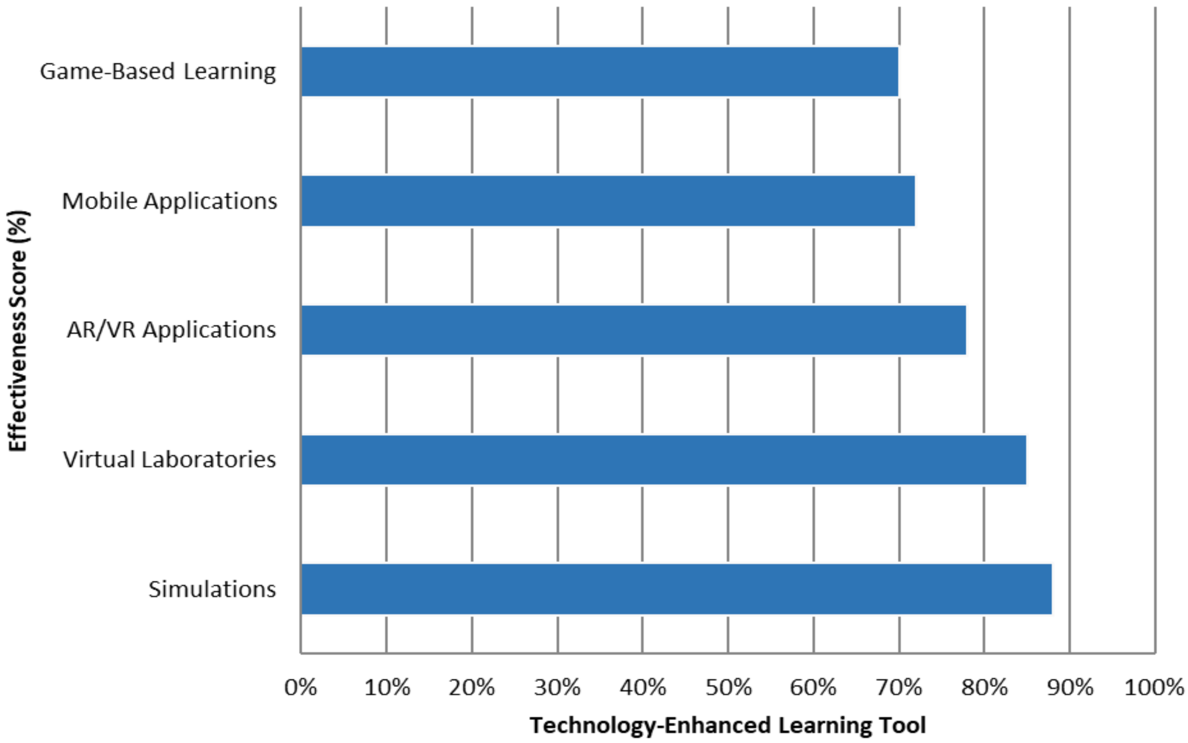

Figure 1. Comparative effectiveness scores for different technology-enhanced learning tools.

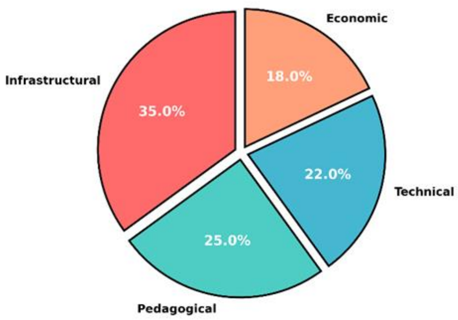

Figure 2. Barriers to technological adoption.

The ratio of virtual laboratories was 85 percent and was found particularly useful in a setting that did not provide physical laboratory infrastructure (George & Kolobe, 2014; Manyilizu, 2023; Ndebvu *et al.*, 2024). Applications of augmented and virtual reality had 78% effectiveness in the studies, and their ability to produce immersion in the process of molecular visualisation and 3D visualisation of chemical structures was mentioned (Nagpal *et al.*, 2024; Samson *et al.*, 2024; Yuri, 2025). Mobile apps scored 72% efficiency, which was also positively affected by the ability to go offline and use low-end devices when bandwidth was limited (Ndebvu *et al.*, 2024; Sobowale *et al.*, 2024). One of the methods of game-based learning proved to be 70% effective, inducing self-directed learning and student agency based on the interactive gameplay (Benzon *et al.*, 2025).

Dual analysis of barriers to adoption

The reasons why people are reluctant to adopt and (as shown in Figure 2) suggest that there are barriers to adoption, each broken down into infrastructural (35%), pedagogical (25%), technical (22%), and economic (18%) issues. Limited infrastructure was also the most commonly identified specific barrier reported, which included inadequate electricity supply, insufficient access to internet, and the lack of computer laboratories (Guzmán et al., 2025; Hanine et al., 2025; Manyilizu, 2023). Connection was an impediment to implementation, especially in rural and remote learning institutions (Barraza Rodríguez, 2024; Shambare & Simuja, 2024). This issue has been identified as a serious problem that needs the extensive use of professional development initiatives (Kurniawan et al., 2025; Sailema-Castro et al., 2025; Toma et al., 2025). Studies also noted that high implementation cost, including the cost of software license, hardware acquisition, and software maintenance have been contributory to these barriers (Hanine et al., 2025; Ogunde et al., 2013). The problem of availability of devices and resistance to pedagogical change were reported to be as a result of institutional and personal reluctance to transition to the use of technology-enhanced educational instruction (Sailema-Castro et al., 2025; Shambare & Simuja, 2024).

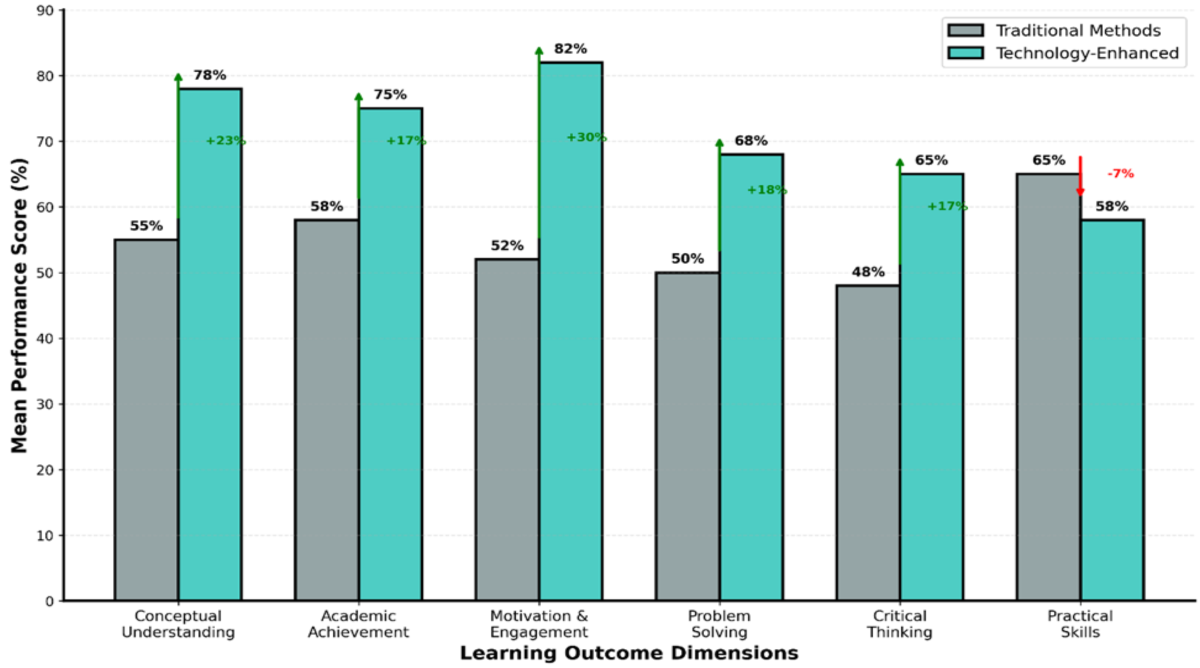

Figure 3. Comparison of mean performance scores between traditional and technology-enhanced instructional approaches across six learning outcome dimensions.

Traditional and technology-enhanced instructional approaches

Figure 3 draws a comparison of learning results of traditional and technology-enhanced instruction methods in the six dimensions. The most significant difference was found in motivation and engagement with technology-enhanced methodologies achieving 82% improvement in students' performance compared to 52% achievement with the use of traditional methods (Assaf, 2025; Benzon et al., 2025; Sailema-Castro et al., 2025). The positive results were as demonstrated by a 23-point increase in the conceptual understanding that went as high as 78, showing good performance in the use of virtual laboratories and use of simulations in understanding abstract concepts in chemistry (Bazie et al., 2024; Guzmán et al., 2025; Mphafudi & Ramaila, 2021). The problem-solving skills improved by 18 (from 50% to 68%) with the help of the interactive simulation environments which facilitated exploratory learning (Davenport et al., 2012; Situmorang et al., 2026). The academic performance increased by 17 points from 58% to 75% confirmed using controlled quasi-experimental studies (Bazie et al., 2024; Iwag, 2025). The digital learning activities were based on inquiry and gained 17 points increase (from 48% to 65%) in critical thinking skills (Benzon et al., 2025; Mphafudi & Ramaila, 2021). Interestingly, practical capabilities showed a negative change of 7 points (65% to 58%), which means that virtual sessions, even though useful, cannot possibly substitute the manual work-related competencies, such as manipulative techniques and safety measures in case of the necessity of hands-on laboratory tasks (Hanine et al., 2025; Mphafudi & Ramaila, 2021; Shambare & Simuja, 2024).

Implementation Frequency vs impact on Learning Outcome

Teacher training and professional development became the most necessary implemented practice as well as the highest impact score of 88, which made it a critical success factor (Kurniawan *et al.*, 2025; Mahbub *et al.*, 2024; Sailema-Castro *et al.*, 2025; Toma *et al.*, 2025). The alignment of the curriculum was used in studies with 82% impact score and focusing on the need to combine the use of technological tools with existing education systems (Murphy *et al.*, 2022; Sobowale *et al.*, 2024). Contextual adaptation has the score of impact equal to 84 percent, thus emphasising the significance of adapting solutions to local infrastructural and cultural conditions (Shambare & Simuja, 2024; Yuri, 2025). An integrated method of delivering teaching using both traditional and digital means of delivery has an impact score of 85% (Hsiung, 2018; Kurniawan *et al.*, 2025). The need to support technical developent and develop suitable infrastructure has 75% impact rating, reflecting the current issues of the resource-constrained environment (Hanine *et al.*, 2025; Manyilizu, 2023). The factors of offline and mobile compatibility (with 78% impact score), also include the limitation of connectivity, downloadable content and mobile-optimised software (Ndebvu *et al.*, 2024; Samson *et al.*, 2024). Also, student-centered design principles were applied with an impact score of 76%, pedagogical models like Technological Pedagogical Content Knowledge, TPACK and ADDIE were also used with an impact score of 80% (Shambare & Simuja, 2024; Sobowale *et al.*, 2024).

Discussion

The results shed some light on important aspects of technology-based chemistry teaching where resources are scarce, and some of the most encouraging factors and the challenges that still persist are identified as an issue that should be given due attention.

Most studies focus more on the barriers to adoption due to the high barriers facing technology adaptation in under-resource contexts (Guzmán *et al.*, 2025; Hanine *et al.*, 2025). This focus helps to highlight that no solutions based on the use of technology are sufficient without considering systemic infrastructural issues, such as unstable electricity, low connectivity, and insufficient access to devices (Manyilizu, 2023; Shambare & Simuja, 2024). The high consideration of student engagement may be connected to the fact that motivation is a very important mediator of learning results, and the technologies used should create interactive and immersive experiences that promote active engagement (Benzon *et al.*, 2025; Sailema-Castro *et al.*, 2025).

The difference in the effectiveness scores of the different forms of technology indicate significant details to decisions on implementation. The high-level impact of interactive simulation is in line with constructivist theory of learning where the student is able to manipulate variables and see the effects in real time thus enhancing conceptual learning (Davenport *et al.*, 2012; Rogers *et al.*, 2000). A high performance of virtual laboratories signifies that this tool is an effective alternative when real-life infrastructure is not present, albeit not the replacement of practical experiences (George & Kolobe, 2014; Manyilizu, 2023; Ndebvu *et al.*, 2024). The relative lack of effectiveness of mobile applications in the cases of its accessibility benefits implies that the quality of pedagogical design is as important as technological reach (Sobowale *et al.*, 2024). This observation lends credence to the notion that contextually tailored solutions that have been well designed should be given priority as opposed to the increase in access to technology.

Infrastructure limitations represent the most common barrier based on the barrier analysis, which supports the idea that technological potential will continue to be unfulfilled unless the key resources are purchased (Hanine *et al.*, 2025; Manyilizu, 2023). Nevertheless, the fact that the signs of the pedagogical barrier are quite large suggests that although technology can be available, inefficient use of technologies is caused by the lack of preparation of teachers (Sailema-Castro *et al.*, 2025; Toma *et al.*, 2025). This observation disputes the technology-based approaches, indicating that capacity building should also be a very important intervention target. The reported resistance to change is more indicative of an underlying institutional and cultural issue that needs the application of change management measures instead of technical training (Shambare & Simuja, 2024).

Technology-enhanced strategies present strong arguments as the learning outcomes comparison demonstrates and become apparent in the situations where there are major weaknesses. The 30-percentage point difference in motivation and engagement may indicate that these tools cover the affective areas that remain unexplored during the conventional teaching process, which can lead to a rise in perseverance in the new difficult STEM areas (Assaf, 2025; Benzon *et al.*, 2025). The 23-point increase in conceptual knowledge confirms the ability of technology to bring abstract concepts close to reality by communicating and visualising them (Guzmán *et al.*, 2025; Mphafudi & Ramaila, 2021). Nevertheless, the 7-point drop in the number of practical skills is a serious warning sign, which may indicate that virtual experiences are not capable of completely replacing hands-on laboratory efforts to build manipulative competencies and share the safety awareness (Mphafudi & Ramaila, 2021). This finding encourages the combination of both virtual and real experiences where possible or additional virtual learning with specific practical lessons when resources are available (Hsiung, 2018; Kurniawan *et al.*, 2025). Meanwhile, teacher training has been identified as a key prerequisite to successful implementation of technological pedagogical innovations (Mahbub *et al.*, 2024; Sailema-Castro *et al.*, 2025; Toma *et al.*, 2025). The results of this research raise questions to existing resource allocation models that are heavily skewed towards hardware acquisition with limited human capacity building. Instead of promoting a wholesale substitution of conventional teaching techniques, pedagogical integration advocates the practice of blended learning techniques, which have shown high levels of effectiveness continuously, with an impact score of 85% (Kurniawan *et al.*, 2025). Likewise, the contextual adaptation with high impact rating (84%) implies the ineffectiveness of standardised, one-size-fits-all solutions in variety of resource-constrained contexts, concurring that, instead, locally responsive and contextual-specific designs are necessary with the implementation of technology-enhanced learning resources (Shambare & Simuja, 2024; Yuri, 2025).

CONCLUSION

This review indicated that technology-enhanced learning tools are important in improving curriculum achievement in limited resources environments, especially through improvement of conceptual knowledge, student motivation, and academic success. The virtual laboratories, interactive simulations, and mobile applications prove beneficial to overcome the challenges encountered in teaching abstract concepts of chemistry in areas with limited laboratory resources. However, successful implementation is heavily reliant on the response to multifaceted barriers that include infrastructural issue, teacher readiness, and adjustment to the context instead of just using technology. Although the benefits of using technology-enhanced tools in cognitive and effective learning outcomes are evident, the fact that learning practical skills development is significantly reduced proves that they are not entirely applicable in substituting working laboratory experiences. Hybrid solutions with virtual and physical learning that can be offered and strategic supplementation in case of limited resources are the key to optimal results. The effects of retention in the long run, rigorous cost-effectiveness analysis, and scalable strategies of implementation should be researched in the future. The policy makers and educators need to understand that, democratising quality teaching of chemistry with the help of technology needs systemic investment in both digital infrastructure and human capacity development; and that success is dependent on context sensitive integration of pedagogy and not the use of technology in isolation.

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