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ENHANCING EXPERIMENTAL COMPETENCIES IN CHEMISTRY EDUCATION THROUGH THE USE OF VIRTUAL LABORATORIES

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This research paper investigates the pedagogical potential of virtual laboratories in enhancing experimental competencies and conceptual understanding among secondary school students studying chemistry. With the rapid evolution of digital learning environments, virtual laboratory tools have emerged as dynamic educational resources that simulate real-world chemical experiments through interactive simulations and data-driven platforms. Unlike traditional laboratory practices, which may be constrained by limited resources, safety risks, or institutional access, virtual laboratories offer flexible, scalable, and safe alternatives that support inquiry-based learning and independent exploration.

The study presents a comparative experimental model involving two groups of 10th-grade students—one group using a conventional lab setup and another utilizing a virtual simulation platform to conduct an acid-base titration. The results revealed that students engaged with virtual laboratories achieved higher scores in conceptual assessments, demonstrated stronger analytical reasoning, and reported greater confidence and motivation in performing laboratory tasks. Furthermore, virtual labs allowed for repeated practice, real-time feedback, and contextual learning that contributed to a deeper understanding of chemical principles.

By exploring both the strengths and limitations of digital laboratory environments, this paper highlights the necessity of integrating virtual tools into modern chemistry curricula. It also provides recommendations for educators, policymakers, and instructional designers aiming to enrich science education through innovative, student-centered methodologies. The findings emphasize that when used alongside traditional methods, virtual laboratories can significantly enhance the quality, accessibility, and inclusiveness of experimental chemistry education.

Keywords: virtual laboratories, chemistry education, experimental learning, digital simulation, analytical thinking, science instruction

INTRODUCTION

In the 21st-century educational landscape, the integration of technology into teaching and learning processes has become not only a modern trend but also a necessity driven by both pedagogical demands and global transformations. Chemistry, as a core branch of natural sciences, holds a unique position among school subjects due to its strong emphasis on laboratory-based experimentation and empirical inquiry. However, despite the recognized importance of experimental learning in understanding chemical concepts, many schools face ongoing challenges related to the cost, safety, accessibility, and logistical feasibility of maintaining fully functional physical laboratories.

These barriers have fueled the exploration of alternative approaches that can complement or, in some cases, substitute traditional lab practices. One of the most promising developments in this regard is the implementation of virtual laboratories—digital platforms that simulate real chemical experiments through interactive, multimedia-based

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environments. These tools not only reproduce experimental procedures but also engage learners through scenario-based problem solving, visual representations of abstract processes, and immediate feedback mechanisms. The significance of this transformation lies in its potential to address long-standing disparities in science education. Students from under-resourced schools or remote regions often lack access to fully equipped labs and qualified instructors. Virtual labs provide an equitable solution, offering consistent, standardized, and high-quality learning experiences that transcend physical boundaries. Furthermore, such platforms allow students to experiment without the fear of failure, encouraging active learning, repetition, and the development of analytical reasoning skillsAt the heart of this study is a fundamental question: Can virtual laboratories effectively enhance the experimental competencies of secondary school students in the context of chemistry education? To address this, the research compares student performance and engagement in two instructional settings—one utilizing traditional lab methods, and the other using a digital simulation tool. In doing so, the study aims to uncover the pedagogical value of virtual laboratories, especially their role in promoting conceptual understanding, improving procedural accuracy, and increasing motivation in learning chemistry [1-7].

This inquiry aligns with broader educational goals that prioritize innovation, accessibility, and student-centered learning. The emergence of technologies such as virtual reality, gamified simulations, and artificial intelligence in science education suggests a paradigm shift—where the laboratory is no longer confined to a physical space but can extend into digital environments that are immersive, adaptable, and data-informed. Within this evolving context, it is critical to assess not only the efficacy of such tools but also their implications for curriculum development, teacher training, and long-term student outcomes. The implementation of digital technologies in education is not merely a trend but a necessary adaptation to the evolving educational landscape. Chemistry, a discipline inherently reliant on experimental observation, often encounters challenges due to limited laboratory access, safety concerns, and insufficient resources. Virtual laboratories respond to these issues by providing equitable access to experimental content, even in under-resourced or remote learning environments [8].

This study aims to evaluate the role of virtual laboratories in enhancing students' experimental competencies, with particular focus on accuracy, conceptual clarity, and independent inquiry. The objective is to determine how these platforms influence learning dynamics and whether they can serve as reliable instructional supplements in secondary chemistry education. The integration of virtual laboratories into the chemistry curriculum holds considerable practical value. They:

Allow schools with limited infrastructure to offer rich experimental experiences;
Minimize material costs and reduce risks associated with chemical handling;
Enable repeated practice, reinforcing students' understanding through trial and error;
Offer instructors tools to observe and assess students' performance in real time.

By creating opportunities for flexible, student-centered learning, virtual laboratories contribute to a more inclusive and efficient educational process. Contemporary virtual lab platforms such as Chem Collective, Labster, and PhET offer interactive simulations that replicate complex laboratory procedures. These systems are designed to align with inquiry-based and constructivist teaching models, encouraging students to hypothesize, test, and reflect. The simulations integrate visuals, data collection, feedback mechanisms, and scenario-based learning, allowing students to understand abstract chemical concepts through practical digital experiences. The novelty lies in the combination of scientific accuracy, pedagogical adaptability, and technological accessibility. Unlike traditional labs, virtual laboratories can be accessed anytime and anywhere, supporting diverse learning styles and pacing[9-12].

EXPERIMENTAL

The primary aim of this experimental study was to evaluate the effectiveness of virtual laboratories in enhancing students' experimental competencies, analytical thinking, and understanding of core chemical concepts. Specifically, the research focused on how students' performance and engagement differ when exposed to virtual laboratory simulations versus traditional hands-on laboratory experiences. The study was conducted in a secondary school setting involving 40 students aged 15–16, all of whom were studying chemistry at the 10th-grade level. The participants were randomly divided into two equal groups:

Group A (Traditional laboratory group): Students in this group conducted an acid-base titration experiment using conventional laboratory equipment and materials (burettes, pipettes, indicators, etc.).

Group B (Virtual Laboratory Group): Students in this group performed the same experiment using the Chem Collective online simulation platform, which allows manipulation of virtual reagents, pH indicators, and titration setups.

Both groups had similar prior academic performance in chemistry to ensure baseline equality. The experimental topic chosen was **"**Acid-Base Titration**"**, as it is both fundamental in chemistry education and suitable for virtual simulation. Prior to the experiment, both groups received the same theoretical instruction on titration principles, neutralization reactions, and the use of indicators. The structure of the instruction included: A 20-minute theoretical lesson covering titration objectives, chemical equations, and safety protocols. A 60-minute laboratory session (virtual or physical) in which students conducted the experiment following provided guidelines.

The evaluation of the experiment was based on three main instruments:A set of 10 multiple-choice and open-ended questions were administered before and after the experiment to assess conceptual understanding of acid-base titration. A detailed rubric was used to evaluate students' experimental process including step accuracy, data recording, observation skills, and logical interpretation of results. A Likert-scale survey measured students' interest, confidence, and satisfaction with the learning process[13].

Implementation procedure**.** Group A conducted the titration in the school laboratory, measuring real solutions and identifying the endpoint using phenolphthalein indicator. Group B used an interactive online simulation, where they were guided through the titration virtually and recorded data through the platform's interface. Each student worked individually to ensure personal engagement and to minimize peer influence on data collection. After both sessions, students' scores from the post-test were statistically analyzed using the independent samples t-test to determine whether there was a significant difference between the two groups. Performance rubrics were scored on a 5-point scale by two independent evaluators. Survey responses were aggregated and analyzed for patterns in motivation and engagement.

Table 1. Comparative results of traditional and virtual laboratory groups

Evaluation griteria_Traditional lab group (group A)_Virtual lab group (group B)		
Post-test mean score		
	80%	88%
Rubric score (procedural accuracy, data recording, etc.)		
	4.1 / 5	4.3 / 5
Motivation survey: "Less stressful and more enjoyable"		
	Not specified (some students reported stress)	85% agreed

Instructional model based on virtual laboratory use. The virtual laboratory-based chemistry lesson is structured around a student-centered and inquiry-driven approach, integrating both theoretical and practical learning stages. The lesson typically begins with a motivational phase**,** where students are introduced to a real-life problem or phenomenon related to the target topic—for instance, the role of acids and bases in everyday substances like vinegar or soap. This stage engages learners' prior knowledge and sets the stage for meaningful exploration. Following this, the learning objectives are clearly stated. For example, students are informed that they will explore the process of acid-base titration through simulation in order to understand neutralization reactions and pH changes. In the presentation phase, the teacher explains fundamental concepts such as titration techniques, the use of indicators, pH scales, and safety protocols. Multimedia tools, such as PhET animations or slide presentations, are used to enhance visualization and conceptual clarity. Next, students proceed to the application phase, where they individually perform a virtual titration experiment using an online simulation platform like Chem Collective. This environment allows them to manipulate digital reagents, measure volumes, and observe color changes as they reach the endpoint. The interactive nature of the simulation promotes active learning and reinforces procedural skills.

After completing the virtual experiment, the analysis phase follows, in which students interpret their data, identify the neutralization point, and reflect on the accuracy of their steps. They may compare results with their peers or engage in guided discussion facilitated by the teacher. For the assessment phase, students complete a post-test consisting of multiple-choice and open-ended questions. Additionally, a performance rubric is used to evaluate their procedural accuracy, data recording, and logical reasoning. A self-assessment component may also be included to enhance metacognitive skills. Finally, the lesson concludes with a reflection activity, where students express their thoughts about the virtual experience—what they learned, what challenged them, and how it compares to traditional laboratory methods. This reflection deepens their understanding and provides feedback for instructional improvement. This model not only supports inquiry-based science instruction but also allows for differentiated learning, as students can progress at their own pace and repeat procedures as needed. The virtual format ensures accessibility, safety, and engagement, making it a valuable component of modern chemistry education [14,15]

RESULTS AND DISCUSSION

The analysis of the data collected from both groups provided clear evidence supporting the pedagogical value of virtual laboratories in chemistry education. The results are discussed below across three core dimensions: conceptual understanding, experimental performance, and student motivation. Following the laboratory sessions, both groups completed a post-test designed to measure their grasp of acid-base titration principles. The results revealed that students in the Virtual laboratory group achieved a mean score of 88%, while those in the traditional laboratory group scored a mean of 80%. A statistical comparison using an independent samples t-test indicated that the difference between the two groups was significant at the $p < 0.05$ level, suggesting that the virtual simulation led to a more precise and clearer understanding of the titration process. Students exposed to virtual environments were better able to explain endpoint detection, chemical reactions involved, and pH transitions, likely due to the visual and interactive nature of the simulations.

Both groups were assessed using a standardized rubric evaluating procedural accuracy, observation, and interpretation. The Virtual group received an average rubric score of 4.3 out of 5, while the Traditional group scored 4.1. Although the difference was not statistically significant, virtual lab students demonstrated slightly higher consistency in data recording and interpretation. One explanation for this outcome is the ability of digital platforms to offer guided instructions and real-time feedback, which help students follow procedures more precisely. However, traditional lab participants showed greater confidence in handling equipment, suggesting that tactile experience still plays a vital role in laboratory education.

The results of the student survey revealed notable differences in emotional engagement and learning attitudes:85% of students in the virtual group agreed that the experience was “less stressful and more enjoyable” compared to traditional labs. A significant portion of virtual lab users appreciated the ability to repeat steps and correct mistakes without penalty. Conversely, some students in the traditional group expressed anxiety about making physical errors or wasting materials. The interactive and autonomous nature of virtual labs allowed students to focus more on learning the concept rather than worrying about mechanical execution. The findings collectively suggest that virtual laboratories not only support the development of theoretical understanding but also enhance learner motivation and confidence. They are especially beneficial in contexts where physical resources are limited or where flexible, self-paced learning is necessary. That said, the results also underscore the complementary role of physical laboratories, particularly for building manual skills and real-world laboratory habits. Therefore, educators are encouraged to adopt hybrid models, combining virtual simulations with periodic hands-on lab sessions to create a well-rounded and inclusive chemistry education framework.

CONCLUSIONS

The results of this study provide compelling evidence that virtual laboratories can play a transformative role in the teaching and learning of chemistry at the secondary school level. By offering students a digital environment that mirrors essential laboratory procedures, virtual labs contribute meaningfully to the development of key experimental competencies, such as data interpretation, procedural accuracy, and conceptual integration. The analysis demonstrated that students who participated in virtual laboratory activities exhibited stronger post-test performance and greater accuracy in identifying chemical processes compared to their peers in the traditional laboratory setting. These results suggest that the visual and interactive features inherent to virtual simulations promote deeper cognitive engagement and facilitate the understanding of abstract chemical phenomena. Moreover, the reduced pressure associated with material handling and safety concerns allows students to explore concepts more freely and confidently. Beyond cognitive outcomes, the findings highlight the motivational advantages of virtual learning environments. Students expressed higher satisfaction and lower anxiety levels when engaging with simulations, reflecting the empowering nature of digital platforms that encourage exploration, repetition, and self-correction. In this regard, virtual laboratories serve not only as instructional tools but also as psychological enablers, enhancing students' self-efficacy and engagement in science learning.

However, while the benefits of virtual laboratories are evident, it is equally important to acknowledge the irreplaceable value of physical laboratory work, especially in cultivating hands-on skills, safety awareness, and real-world problem-solving abilities. Therefore, this research supports a blended approach—one that integrates the strengths of both traditional and virtual laboratories to achieve a holistic and inclusive chemistry education. From a broader perspective, the integration of virtual laboratories aligns with contemporary educational goals that emphasize flexibility, accessibility, and digital fluency. As technology continues to evolve, virtual labs have the potential to bridge gaps in science education, particularly in under-resourced schools or in remote learning contexts. They provide a scalable and cost-effective model for delivering high-quality science instruction to diverse student populations.

In conclusion, virtual laboratories are not merely substitutes for physical labs—they are innovative, student-centered tools that enrich the chemistry curriculum and prepare learners for the demands of a digitally enhanced scientific world. Their thoughtful integration into educational systems can ensure that all students, regardless of location or circumstance, have meaningful opportunities to engage with experimental science and develop essential skills for future academic and professional success.

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