frontiers | Frontiers in Education

TYPE Original Research
PUBLISHED 07 February 2025
DOI 10.3389/feduc.2025.1485600

Check for updates

OPEN ACCESS

EDITED BY
Hafiz Muhammad Wasif Rasheed,
Huazhong University of Science and Technology, China

REVIEWED BY
José Hernández-Ramos,
Metropolitan University of Educational Sciences, Chile
Dwi Wahyudiati,
Universitas Islam Negeri Mataram, Indonesia

*CORRESPONDENCE
Ahmad Alsaber
aalsaber@auk.edu.kw

RECEIVED 24 August 2024
ACCEPTED 24 January 2025
PUBLISHED 07 February 2025

CITATION
Alqallaf N, Almahmeed Z, Alsaber A, Alboloushi B, Alkandari A and Alhashem F (2025) Advancing education through e-learning innovation: the case of the Crocodile Chemistry program in higher education.
Front. Educ. 10:1485600.
doi: 10.3389/feduc.2025.1485600

Advancing education through e-learning innovation: the case of the Crocodile Chemistry program in higher education

Nawal Alqallaf[1], Zahra Almahmeed[2], Ahmad Alsaber[3]*, Bedour Alboloushi[4], Anwaar Alkandari[5] and Fatimah Alhashem[6]

[1]Department of General Sciences, College of Nursing, The Public Authority for Applied Education and Training, Kuwait City, Kuwait, [2]Department of Natural Sciences, College of Health Sciences, The Public Authority for Applied Education and Training, Kuwait City, Kuwait City, Kuwait, [3]Department of Business and Management, American University of Kuwait, Salmiya, Kuwait, [4]Department of Business and Management, Kuwait College of Science and Technology, Kuwait City, Kuwait, [5]Department of Business and Management, Kuwait Technical College, Kuwait City, Kuwait, [6]Independent Researcher, Kuwait City, Kuwait

Introduction: E-learning innovations have transformed higher education, particularly in STEM fields like chemistry. Traditional laboratory instruction faces limitations such as high costs, safety concerns, and accessibility issues. Virtual laboratories provide scalable alternatives to enhance student engagement and comprehension. This study evaluates the effectiveness of the Crocodile Chemistry program in improving students' understanding of chemical concepts, academic performance, and motivation at the Public Authority for Applied Education and Training (PAAET).

Methods: A quasi-experimental design compared an experimental group ($n = 102$) using Crocodile Chemistry with a control group ($n = 103$) following traditional laboratory instruction. Pre-test and post-test assessments were conducted using the Alternative Chemical Concepts Test. Paired t-tests measured performance changes, and correlation analysis assessed learning consistency. The Partial Credit Model (PCM) evaluated test reliability and instructional effectiveness.

Results: Paired t-tests revealed significant performance improvements for the experimental group ($p < 0.05$), whereas the control group showed minimal changes. PCM analysis demonstrated higher reliability for the experimental group (0.774) compared to the control (0.403), indicating better differentiation of student abilities. Correlation analysis showed a strong relationship between pre- and post-test scores ($r = -0.795$, $p < 0.001$), confirming the program's role in enhancing learning outcomes.

Discussion: The findings highlight the potential of virtual laboratories to modernize chemistry education by improving comprehension, engagement, and academic performance. This study supports the integration of digital tools in higher education to enhance learning outcomes and student motivation.

KEYWORDS

chemistry, e-learning, virtual laboratory, virtual simulation, Crocodile Chemistry program, chemical concepts

1 Introduction

The rapid advancement of digital technologies has transformed educational practices, particularly in higher education. E-learning tools, including virtual laboratories, have emerged as crucial strategies for enhancing the delivery of complex subjects like chemistry. Traditional methods of teaching chemistry rely heavily on physical laboratory experiences, which, while effective, are often constrained by safety risks, high costs, and limited accessibility. These challenges are particularly pronounced in regions like Kuwait where higher education institutions face significant obstacles in delivering effective laboratory-based education due to limited resource, growing student populations, and the pressing need to ensure safe learning environments. Modernizing laboratory practices is crucial to overcoming these obstacles, improving the quality of education, and equipping students with the skills required to meet contemporary scientific and industrial demands. This study is among the first to evaluate the effectiveness of the Crocodile Chemistry program in a higher education context in Kuwait, providing localized insights into its impact on student engagement, comprehension, and academic achievement. It investigates how virtual laboratories can bridge the gap by offering scalable and cost-effective solutions to enhance educational outcomes in higher education.

By addressing these challenges, the study seeks to demonstrate the potential of virtual laboratories as a significant advancement, offering dynamic and interactive approaches to learning complex scientific concepts. These platforms enable students to conduct a realistic simulations of chemical procedures in safe, controlled and three-dimensional virtual environments, helping them develop a deeper understanding of principles and concepts (Acenas et al., 2019).

By overcoming the limitations of traditional methods, virtual labs allow for repetitive experimentation, fostering improved learning outcomes, comprehension and retention of chemical principles and concepts. The COVID-19 pandemic has further underscored the importance of these invocations in ensuring the continuity of education despite physical constraints (Villanueva and Zimmermann, 2020; Alkandari et al., 2021; Al-Shamali et al., 2022). Chemistry education researchers have explored the effectiveness of virtual laboratory platforms in enhancing student engagement, conceptual understanding, and overall learning outcomes, despite growing global interest, virtual laboratories remain unexplored in Middle Eastern higher education, particularly in Kuwait, where challenges like resource limitations and infrastructure gaps may impact their effectiveness. One platform that has garnered attention is the Crocodile Chemistry program, which aims to provide a dynamic and interactive learning environment for chemistry students (Keith-Lucas, 2000). This study addresses this gap by evaluating the localized impact of the Crocodile Chemistry program on student engagement, comprehension, and academic achievement. Crocodile Chemistry is a virtual laboratory simulation software that enables students to perform a wide range of chemical experiments in a safe and interactive setting (Acenas et al., 2019). Virtual laboratories, such as the Crocodile Chemistry program, are transformative educational tools, enabling students to engage with chemical processes in a safe, controlled, and highly interactive environment. The primary aim of this innovation is to overcome the limitations of traditional educational methods by delivering realistic simulations of chemical procedures within an interactive, three-dimensional virtual environment. These platforms allow students to perform experiments that might otherwise be too dangerous, costly, or impractical in a traditional laboratory setting. Moreover, they offer the unique advantage of enabling repetitive experimentation, which fosters a deeper understanding of the underlying principles and concepts (Acenas et al., 2019). As educational institutions worldwide continue to adapt to the demands of the digital age, the role of virtual laboratories in enhancing student learning outcomes and engagement is increasingly critical.

The primary research question guiding this investigation is: To what extent does the Crocodile Chemistry program enhance the understanding and retention of chemical concepts among higher education students? Additionally, the study explores the program's influence on student motivation and engagement, evaluating its contribution to overall academic achievement in chemistry courses. By situating the research within specific institutional context and addressing the relationships between key variables (e.g., comprehension, motivation, and engagement), this study provides comprehensive understanding of how virtual laboratories can complement or replace traditional laboratory-based learning.

Furthermore, this study aims to contribute to the broader discourse on e-learning by providing empirical evidence on the effectiveness of virtual laboratories in higher education. It seeks to offer insights that can inform future educational strategies, particularly regarding the integration of digital tools into the curriculum. The findings of this study have the potential to benefit educators, policymakers, and students by highlighting best practices for implementing e-learning technologies in science education. As higher education institutions strive to prepare students for the challenges of the modern world, the adoption of e-learning innovations such as the Crocodile Chemistry program represents a crucial step forward. This study provides a comprehensive evaluation of the program's impact, thereby contributing to ongoing efforts to enhance the quality and accessibility of education through digital means.

1.1 The importance of research

This study evaluates the Crocodile Chemistry program's ability to improve chemistry understanding through interactive and repeated experimentation in a virtual environment and examines the wider implications of the integrating virtual laboratories into higher education, particularly in contexts where physical laboratories are scarce or unavailable. This study should help educators and policymakers create and execute e-learning initiatives that improve science education. The findings will contribute to the discourse on digital technologies in education and lay the groundwork for e-learning research.

2 Literature review

2.1 Overview of e-learning in higher education

The integration of technological advancement into the educational system represents a substantial stride forward in enhancing learning experiences. E-learning, a significant part of this technological advancement, has transformed higher education by bridging the gap between knowledge and application (Gupta and Gupta, 2020). This integration allows students to stay current with information and technological breakthroughs, enabling them to adapt to the demands of modern life. As a result, it is essential to focus on methods and approaches that keep pace with this influx of knowledge by providing a contemporary educational environment (Kirschner and Huisman, 1998; Alkandari et al., 2021). Instructors must employ a variety of teaching methods, such as collaborative and interactive teaching, to tailor content to students and support their learning. These methods involve expanding students' knowledge, altering their attitudes, and enhancing their performing abilities, all of which help individuals adjust their scientific conceptions. Essential skills include adopting and using diverse strategies and teaching approaches, such as cooperative education and active learning (Alkandari et al., 2021, 2024).

While there are many current teaching techniques, many still rely on conventional methods that emphasize the instructor as the primary source of information (Ibn Zaarour, 2003). These techniques focus on cognitive objectives for assessment purposes and predominantly use lectures and textbook questions to help students memorize information, facts, and concepts (Abdo, 1999). However, these conventional approaches often lead to misunderstandings by failing to help students fully grasp and comprehend surrounding phenomena (Omran, 2015). The challenges of traditional education—such as the vast explosion of knowledge, the diversification of educational fields, the shortage of qualified instructors, the dramatic increase in student enrollment, and the neglect of individual differences among students—are increasingly apparent in the face of these developments (Faraj, 2005). To address these issues, educators must implement effective teaching techniques and strategies that enhance students' understanding of chemical concepts (Bajpai, 2012; Omran, 2015).

Educational philosophies aim to improve the educational process by creating innovative techniques that support students in developing their personalities, solving challenging problems, and adopting positive self-attitudes. These philosophies emphasize that integrating technology into the classroom is essential for advancing and enhancing learning (Alkandari et al., 2024). Most reform movements and programs are based on constructivist philosophy, which encourages students to construct their own knowledge and positions them at the center of the educational process. Constructivism enhances learning by reshaping instructors' behaviors and redefining students' roles, fostering a more active and engaged learning environment.

Constructivist philosophy strongly emphasizes the use of technology in the classroom, including computers, networks, multimedia, electronic libraries, search engines, and internet portals. These tools facilitate the efficient and effective transfer of knowledge to students with minimal time and effort and maximum benefits (Chuaungo et al., 2022). E-learning, a significant technological advancement, enables students to study in various locations, such as their homes or classrooms. According to AlAwda (2012), e-learning transforms the perception of conventional education from a rigid and exclusive system into one that is adaptable and inclusive, providing learning opportunities to everyone, regardless of geography, ethnicity, gender, or special needs.

Scientific concepts, which are fundamental products of research, organize knowledge and serve as key objectives in education across various levels. For students to grasp scientific facts, overcome learning obstacles, and understand the connections between ideas, they must have a proper understanding of these concepts. E-learning and technological advancements play a crucial role in this process by making complex ideas more accessible and engaging, thereby enhancing students' enthusiasm for science. The four pillars of learning—"learning to know, learning to do, learning to live together, and learning to be"—as highlighted in the 1996 UNESCO report, should be central to achieving successful education (Palenti, 2023). Developing effective strategies to nurture future generations of critical thinkers is essential for raising intellectual standards. To achieve these goals, integrating technology into education is crucial. Applications such as virtual learning, virtual reality, smart electronic classes, virtual classrooms, computer simulations, and virtual labs have become integral to e-learning as technology has advanced (Dar Ibrahim, 2014). Virtual laboratories, in particular, have emerged as an important aspect of modern educational technology, allowing students to conduct experiments that might be too risky or expensive in a real lab (Martínez-Jimenez et al., 2003). This technology enables students to engage with a virtual world that closely mimics reality. Several studies have shown that virtual labs play a significant role in effectively conveying and demystifying scientific concepts to students (Reeves and Crippen, 2020). These laboratories allow students to actively participate in the learning process by helping them visualize complex ideas in a practical context (AlShehri, 2009).

In this context, this study aims to evaluate the effectiveness of the Crocodile Chemistry program in teaching chemical principles, enhancing student knowledge, and improving overall learning outcomes. The following sections explore the use of e-learning in chemistry education, focusing on how digital tools and virtual platforms are revolutionizing the teaching and understanding of chemical concepts.

2.2 The use of e-learning in chemistry education

In the field of chemistry, students are exposed to various abstract concepts that can be challenging to visualize, such as complex chemical processes and reactions. Teaching these core concepts requires not only a solid theoretical understanding but also a hands-on exploration of specific phenomena through laboratory experiments using specialized equipment. However, the number and type of chemical experiments conducted in laboratories are often limited due to safety concerns and insufficient

 10.3389/feduc.2025.1485600

infrastructure (Georgiou et al., 2007). To help students learn chemistry more effectively, instructors must integrate technology with active learning practices through e-learning.

E-learning refers to the integration of digital resources and computer-based tools to enhance the teaching and learning process (Seery and O'Connor, 2015). In chemistry, research underscores the importance of incorporating instructional computer systems, such as e-learning tools, to improve the effectiveness of chemistry education (Brindha et al., 2015; Wörner et al., 2022). A strong laboratory component is central to most chemistry courses, as practical experiments are essential for understanding chemical concepts. However, conducting these experiments can be costly, time-consuming, and sometimes hazardous (Georgiou et al., 2007). Given the significance of experiments in chemistry education, e-learning technologies offer an alternative by allowing students to engage in simulated chemical experiments. These simulations enable students to manipulate variables, observe reactions, and gain a deeper understanding of the underlying scientific principles (Jakkula et al., 2020).

A wide array of digital tools, including simulators and virtual laboratories, is available online to facilitate a deeper understanding of essential chemistry principles. The primary goal of these tools is to create a dynamic, progressive, and transforming learning process that enhances the study of chemistry (Urquizo et al., 2022).

2.3 Virtual laboratories as an innovative teaching tool

It is widely recognized that using virtual educational tools is crucial for teaching practical components across various academic levels (Darrah et al., 2014). In chemistry, virtual laboratories represent a significant technical advancement, offering an innovative approach to teaching that holds great promise for enhancing the learning process. A growing body of literature highlights the importance of virtual laboratories in chemistry education (Chan et al., 2021).

Virtual laboratories are described as experiential learning environments that closely mimic real-world experiences. They enable the development of laboratory practices through a user-friendly interface where various equipment and tools are accessible based on specific needs. Users can execute different instructions through the computer, facilitating an effective hands-on learning approach in a simulated setting (Urquizo et al., 2022). The integration of virtual laboratories has become a critical strategy to ensure the continuity of student learning, providing engaging and interactive experiences that can supplement or, in some cases, replace traditional laboratory activities (Villanueva and Zimmermann, 2020). Virtual laboratories have been shown to help students visualize abstract concepts, reinforce their understanding, and achieve better conceptual learning compared to traditional laboratory settings (Wörner et al., 2022). In particular, using virtual laboratories to teach chemistry helps decrease chemical waste and pollution while saving money, time, and resources (Potkonjak et al., 2016). This underscores the significance of virtual laboratories in chemistry education. Brinson (2015) compiled a literature review concerning empirical research related to the learning outcomes in virtual versus traditional laboratories (Brinson, 2015). According to his review, virtual laboratories provide equal or better achievement of learning outcomes in all categories.

Building on previous research, Chan et al. (2021) found that improved outcomes are observed when virtual laboratories are integrated with traditional teaching methods (Chan et al., 2021). Further studies support the use of virtual laboratories as a viable and effective approach in chemistry education, with research indicating that these simulated environments can enhance student understanding, engagement, and scientific skills (Chan et al., 2021; Link and Gallardo-Williams, 2022). For instance, Chans et al. (2022) examine the achievement of learning outcomes and students' perceptions of a virtual chemistry laboratory (Chans et al., 2022). The study found that at least 68% of the students reached a high level of competency and demonstrated a generally positive attitude toward the virtual learning experience. Similarly, Viitaharju et al. (2023) investigated the benefits and feasibility of virtual laboratories in chemistry through a practical case study. The researchers developed a 360-VR chemistry lab exercise and tested its effectiveness with over 150 students. The results showed a positive attitude toward virtual learning and reported several benefits, such as learning the correct procedures and tasks before performing real-life laboratory exercises. Researchers emphasized the importance of maintaining the use of virtual laboratories in the post-pandemic era. Recent studies have advocated integrating virtual laboratories as a supplementary tool to in-person courses, even when students can access physical laboratories (Link and Gallardo-Williams, 2022; Viitaharju et al., 2023).

Another study by Alhashem and Alfailakawi (2023) explores the effectiveness of technology-enhanced learning through virtual laboratories in chemistry education. The research focuses on the impact of virtual labs on pre-service teachers' understanding and engagement in organic chemistry lessons. The study compares an experimental group, which received additional virtual laboratory training before conducting hands-on lab work, with a control group that followed traditional teaching methods. Results indicate that virtual laboratories significantly enhance students' attitudes toward chemistry and engagement during lab sessions (Alhashem and Alfailakawi, 2023). However, the study found no significant differences between the groups in terms of technical understanding of the experiments, suggesting that virtual labs primarily benefit educational engagement rather than technical skill acquisition. The authors conclude that virtual laboratories are a valuable tool in modern science education, promoting the integration of technology to meet 21st-century learning outcomes.

Therefore, significant research has been devoted to leveraging the capabilities of virtual reality and digital technologies in chemistry education. Examples of these technological tools include Virtual ChemLab, Virtual Reality Undergraduate Projects Laboratory (VRUPL), and Lab 3D (Georgiou et al., 2007; Chan et al., 2021). These tools help instructors address challenges associated with traditional laboratories, such as hygiene, safety, and infrastructure concerns (Georgiou et al., 2007). In addition, these technologies enable students to engage in simulated environments to observe and interact with chemical phenomena within a fully interactive setting.

2.4 Crocodile Chemistry program

The literature indicates that modern teaching methods incorporating digital technologies and e-learning strategies are becoming more prevalent in chemistry education due to the expansion of digital technology. In particular, various types of virtual simulations for conducting chemical experiments online in virtual laboratories have emerged. One notable e-learning tool that has gained popularity in chemistry education is the Crocodile Chemistry program.

Crocodile Chemistry software is an advanced tool that replicates a chemistry laboratory environment, allowing students to design and conduct virtual experiments with ease. This software provides an interactive platform where students can engage in hands-on learning experiences, safely explore complex chemical reactions, and deepen their understanding of various concepts without the limitations of a physical laboratory (Keith-Lucas, 2000; Acenas et al., 2019).

The Crocodile Chemistry software allows students to understand the chemical and physical properties of elements in the periodic table. It addresses the challenge of visualizing molecular-level processes in chemical reactions by enabling students to model chemical processes and conduct various reactions safely. This software helps students develop essential skills such as research, creative thinking, and result analysis (Jurakulova, 2019). Its diverse capabilities make it particularly useful for virtual laboratory tasks, illustrating problem-solving techniques and visualizing chemical phenomena (Zendler and Greiner, 2020). Studies have shown that students using Crocodile Chemistry demonstrate an improved understanding of chemical concepts and increased engagement in the learning process (Rizman Herga et al., 2016). For example, Acenas et al. (2019) investigated the integration of ICT facilities, particularly Crocodile Chemistry software, into science education. They focused on secondary school teachers' experiences with simulated laboratory sessions to understand chemistry concepts. Their qualitative phenomenological study and thematic analysis revealed that the software enhances concept understanding, provides engaging learning experiences, introduces new laboratory practices, and aids in result extraction. The study concludes that incorporating Crocodile Chemistry into classroom instruction complements traditional lab methods and improves knowledge construction in chemistry education (Acenas et al., 2019).

Given the existing advantages of Crocodile Chemistry software, evaluating the effectiveness of the Crocodile Chemistry virtual laboratory program in higher education is essential. Researchers should consider various factors and use both quantitative and qualitative data to assess the program's impact on student learning and experience. Therefore, this research paper aims to investigate the role of Crocodile Chemistry virtual laboratories in enhancing chemistry education at the higher education level.

3 Materials and methods

The study involves a sample of 205 students from Public Authority for Applied Education and Training, divided into two groups: an experimental group (n = 102) and a control group (n = 103). The participants demographic details such as age, gender, and prior chemistry knowledge considered to ensure a representative sample. It was assumed that the students possessed relatively similar baseline knowledge of chemistry due to their enrollment in the same academic level and exposure to a standardized curriculum. While individual differences in prior chemistry experience may exist, this grouping helped neutralize potential variability. Furthermore, the same instructional approach was consistently applied by the researcher to both groups, ensuring uniformity in the teaching process.

All participants were enrolled in chemistry courses during the academic year 2023–2024. This approach allows for a thorough assessment of the Crocodile Chemistry programs impact on students understanding of chemical concepts while minimizing bias. Statistical analyses were performed using SPSS Version 28.0, including paired t-tests to identify variations in mean scores between pre- and post-tests for the experimental and control groups. Additionally, the item analysis using the partial credit model (PCM) was conducted to assess the impact of educational interventions in two chemistry courses. For both courses, the model's fit to the data was evaluated using the Akaike information criterion (AIC), Bayesian information criterion (BIC), the consistent Akaike information criterion (CAIC), and log-likelihood values.

3.1 Study tools

In line with the study methodology, the following instruments were used:

1. Alternative Chemical Concepts Test
2. Crocodile Chemistry Program 605

The Alternative Chemical Concepts Test is a computerized assessment comprising 30 multiple-choice questions, each with four possible answers. The test evaluates key concepts from the chemistry courses, focusing on areas where students may commonly have misconceptions. These concepts include atoms, protons, neutrons, electrons, charge, atomic number, mass number, electronic distribution, the periodic table, element symbols, molecules, homogeneous and heterogeneous solutions, metals, chemical reactions, oxides, acids, bases, salts, physical and chemical properties, reagents, combustion, negative and positive ions, standard solutions, states of matter, organic compounds, and chemical equations.

The Crocodile Chemistry Program 605 is an advanced virtual laboratory tool designed to enhance chemistry education by providing an interactive and safe environment for students to conduct experiments. This program simulates realistic chemical processes, allowing learners to engage with complex concepts such as molecular interactions and reaction mechanisms. By overcoming limitations of traditional laboratory settings, such as safety concerns, high costs, and restricted accessibility, the program offers a flexible and effective platform for teaching and learning. The program's interactive simulations enable students to visualize abstract chemical phenomena, fostering a deeper understanding and improving their ability to connect theoretical knowledge with practical applications. As a result, the Crocodile Chemistry

TABLE 1 Model information – PCM (chemistry I, sections I and II).

Section	AIC	BIC	CAIC	Log-likelihood	Parameters	Persons	Reliability
Chemistry I, section I	4,998	5,198	5,274	−2,423	76	103	0.403
Chemistry I, section II	4,998	5,198	5,274	−2,423	76	103	0.774

Program 605 plays a significant role in modernizing chemistry education, supporting academic progress, and enhancing student motivation in scientific learning.

3.2 Study procedures

The experimental group's instruction incorporated tasks designed using the Crocodile Chemistry software, evaluated through the Alternative Chemical Concepts Test, which aligned with the chemistry laboratory course manual. Students in this group utilized the Crocodile Chemistry program on college computers to complete assigned tasks. To ensure familiarity, the researcher demonstrated one activity before students independently completed the remaining assignments and drew their own conclusions.

In contrast, the control group performed the same activities in a traditional laboratory environment. This setup enabled a direct comparison between the control group's use of conventional methods (chemistry I) and the experimental group's use of the Crocodile Chemistry program (chemistry II). Both groups included participants with diverse levels of chemistry knowledge, and statistical analysis accounted for these variations to ensure unbiased results. To maintain consistency in training, the same researcher provided instructional guidance to both groups, ensuring standardized delivery of information.

3.3 Data collection

Data were collected using pre-test and post-test measurements of scores on multiple choice questions MCQ's, which measured subject knowledge and critical thinking. There were 30 MCQ's for each type C1 and C30, to meet the study's objectives and validate its hypothesis. The best rate was 70% and each multiple-choice question was worth one mark.

3.4 Software implementation and accessibility

The Crocodile Chemistry program was implemented using the official software version specifically designed for educational institutions. The software is compatible with both Windows and macOS operating systems and requires minimal system specifications, including 4 GB of RAM, a 2 GHz processor, and 500 MB of available storage space. Users can easily access the software through the official repository provided by the developers at Crocodile Chemistry Download.

The installation process is user-friendly, involving a simple download from the repository, running the installation file, and following on-screen instructions. No advanced configurations are required, making it accessible for educators and students alike. Additionally, a comprehensive user manual and troubleshooting guide are available on the official website to assist users with any technical issues, ensuring a seamless experience in integrating the software into educational practices.

4 Results

We conducted the item analysis using the partial credit model (PCM) to assess the impact of educational interventions and two chemistry courses. The Modell's fit was evaluated using AIC, and log-likelihood values (Table 1). Person separation and reliability was used to determine the test's ability to differentiate between levels of student abilities. Samples *t*-tests and correlation analysis were conducted to compare pre and post intervention scores assessing the intervention's effectiveness.

4.1 PCM model fit and reliability

Table 1 displays the model for statistics and reliability metrics for chemistry I (control) and chemistry II (experimental). Chemistry II demonstrated higher. Person separation reliability (0.774) compared to chemistry I (0.403), indicating improved discrimination of student abilities in the experimental group. These results suggest the Crocodile Chemistry program enhanced alignment between instructional methods and test items, contributing to better learning outcomes.

4.2 Pre- and post-test comparisons

The paired sample statistics presented in Table 2 compare pre- and post-intervention assessment results for chemistry I (control group) and chemistry II (experimental group). For chemistry I, most items show no significant difference between pre- and post-test mean scores, as indicated by higher p values ($p > 0.05$). This suggests that traditional laboratory methods had limited impact on improving students' comprehension and performance. Conversely, chemistry II demonstrates significant improvements in several items, with lower p values ($p < 0.05$). These results indicate that students who used the Crocodile Chemistry program exhibited enhanced comprehension and academic performance.

Notably, chemistry II showed greater gains in overall scores, with the pre-test mean increasing significantly in the post-test assessment. This highlights the effectiveness of the

TABLE 2 Paired sample statistics for pre- and post-intervention assessment in chemistry I and II, sections I and II.

	Chemistry I				Chemistry II			
Item	Pre *M* (SD)	Post *M* (SD)	*t*	*p*-Value	Pre *M* (SD)	Post *M* (SD)	*t*	*p*-Value
Q1	0.28 (0.452)	0.29 (0.457)	−0.13	0.897	0.25 (0.432)	0.49 (0.502)	−2.998	0.003
Q2	0.1 (0.298)	0.17 (0.382)	−1.521	0.131	0.18 (0.383)	0.45 (0.5)	−3.713	<0 .001
Q3	0.08 (0.269)	0.12 (0.322)	−0.894	0.374	0.15 (0.356)	0.31 (0.466)	−2.545	0.012
Q4	0.2 (0.405)	0.26 (0.442)	−0.865	0.389	0.27 (0.448)	0.5 (0.502)	−2.664	0.009
Q5	0.08 (0.269)	0.08 (0.269)	0	1	0.08 (0.27)	0.22 (0.413)	−2.629	0.01
Q6	0.04 (0.194)	0.05 (0.216)	−0.332	0.741	0.04 (0.795)	0.01 (0.099)	1.347	0.181
Q7	0.17 (0.382)	0.25 (0.437)	−1.209	0.23	0.25 (0.438)	0.5 (0.502)	−2.955	0.004
Q8	0.19 (0.397)	0.26 (0.422)	−1.021	0.31	0.2 (0.399)	0.49 (0.502)	−3.817	<0.001
Q9	0.18 (0.39)	0.24 (0.431)	−0.904	0.368	0.3 (0.462)	0.5 (0.502)	−2.252	0.026
Q10	0.17 (0.382)	0.26 (0.442)	−1.347	0.181	0.25 (0.438)	0.52 (0.502)	−3.17	0.002
Q11	0.12 (0.322)	0.17 (0.382)	−1.097	0.275	0.12 (0.324)	0.34 (0.477)	−3.539	<0.001
Q12	0.08 (0.269)	0.17 (0.382)	−1.989	0.049	0.19 (0.391)	0.44 (0.499)	−3.416	<0.001
Q13	0.18 (0.39)	0.21 (0.412)	−0.467	0.642	0.16 (0.365)	0.38 (0.488)	−3.243	0.002
Q14	0.08 (0.269)	0.17 (0.373)	−1.82	0.072	0.13 (0.335)	0.35 (0.48)	−3.458	<0.001
Q15	0.17 (0.373)	0.12 (0.322)	0.928	0.356	0.16 (0.365)	0.06 (0.236)	2.17	0.032
Q16	0.11 (0.31)	0.15 (0.354)	−0.783	0.435	0.18 (0.383)	0.37 (0.486)	−2.758	0.007
Q17	0.19 (0.397)	0.22 (0.418)	−0.456	0.65	0.17 (0.375)	0.4 (0.493)	−3.301	0.001
Q18	0.17 (0.373)	0.23 (0.425)	−1.094	0.276	0.11 (0.413)	0.43 (0.498)	−2.797	0.006
Q19	0.15 (0.354)	0.18 (0.39)	−0.684	0.495	0.21 (0.406)	0.33 (0.474)	−1.771	0.08
Q20	0.12 (0.322)	0.1 (0.298)	0.425	0.672	0.15 (0.356)	0.46 (0.501)	−4.417	<0.001
Q21	0.11 (0.31)	0.11 (0.31)	0	1	0.16 (0.365)	0.23 (0.42)	−1.122	0.264
Q22	0.1 (0.298)	0.04 (0.194)	1.616	0.109	0.09 (0.285)	0.19 (0.391)	−1.914	0.058
Q23	0.15 (0.354)	0.1 (0.298)	1	0.32	0.13 (0.335)	0.28 (0.453)	−2.534	0.013
Q24	0.14 (0.344)	0.15 (0.354)	−0.185	0.854	0.1 (0.299)	0.24 (0.426)	−2.46	0.016
Q25	0.08 (0.269)	0.12 (0.322)	−0.894	0.374	0.17 (0.375)	0.25 (0.438)	−1.379	0.171
Q26	0.17 (0.373)	0.24 (0.431)	−1.238	0.219	0.24 (0.426)	0.43 (0.498)	−2.486	0.015
Q27	0.16 (0.364)	0.17 (0.373)	−0.173	0.863	0.21 (0.406)	0.43 (0.498)	−2.959	0.004
Q28	0.19 (0.397)	0.15 (0.354)	0.844	0.401	0.19 (0.391)	0.37 (0.486)	−2.586	0.011
Q29	0.04 (0.194)	0.02 (0.139)	0.815	0.417	0.07 (0.254)	0.02 (0.139)	1.682	0.096
Q30	0.15 (0.354)	0.16 (0.364)	−0.179	0.858	0.11 (0.312)	0.07 (0.254)	0.942	0.348
Overall	4.12 (4.655)	4.95 (5.778)	−0.864	0.39	5.07 (6.437)	10.08 (10.083)	−3.224	0.002

Crocodile Chemistry program in fostering better alignment between instructional methods and assessment tasks, ultimately contributing to improved learning outcomes. The significant differences observed in the experimental group underscore the potential of virtual laboratory tools to enhance student engagement and understanding of chemical concepts compared to traditional methods.

Further, Figures 1, 2 compare the pre-test and post-test mean scores for chemistry I (control group) and chemistry II (experimental group), respectively. Figure 1 depicts the outcomes for the control group, where traditional laboratory methods were used, showing minimal changes in performance. This highlights the limitations of conventional approaches in enhancing student comprehension and retention of chemical concepts. In contrast, Figure 2 illustrates the results for the experimental group, where the Crocodile Chemistry program was implemented. The significant improvements in scores demonstrate the program's effectiveness in engaging students with more challenging concepts and enhancing their overall learning outcomes.

4.3 Correlation analysis

The correlation coefficients and significance levels presented in Tables 3, 4 provide insights into the relationship between pre- and post-test scores for chemistry I (control group) and

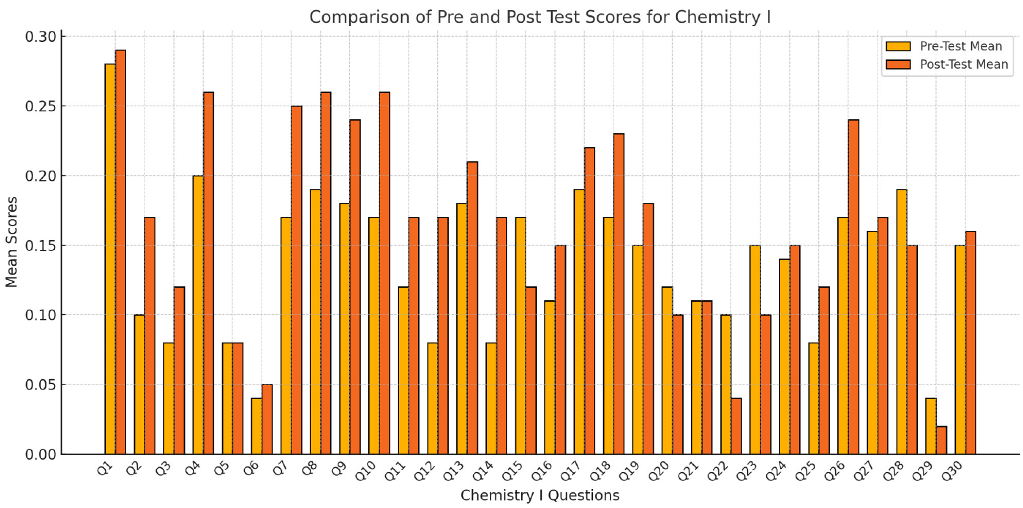

FIGURE 1
Comparison of pre-test and post-test mean scores for chemistry I.

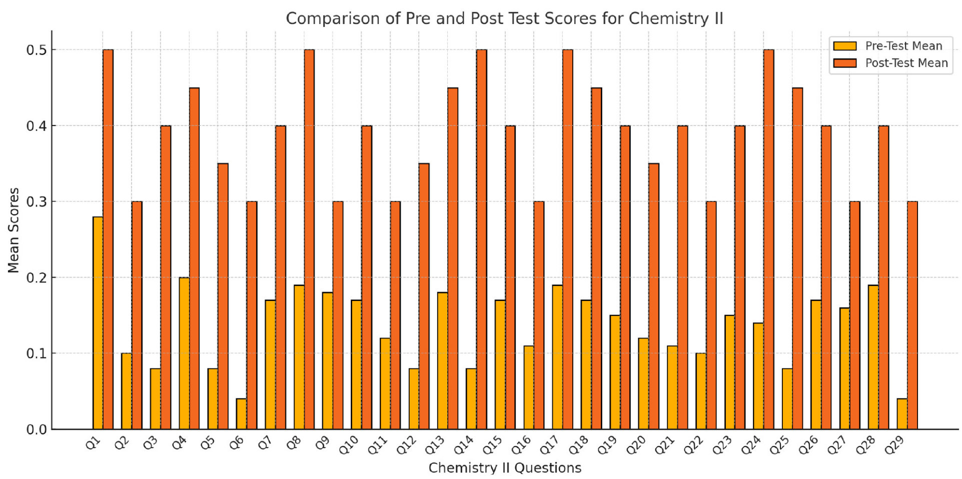

FIGURE 2
Comparison of pre-test and post-test mean scores for chemistry II.

chemistry II (experimental group). For chemistry I, the overall correlation between pre- and post-test scores is moderate and statistically significant ($r = -0.765$, $p < 0.001$). However, many item-specific correlations fail to reach statistical significance. For example, Q2 ($r = -0.151$, $p = 0.128$) and Q3 ($r = -0.105$, $p = 0.289$) show weak, non-significant correlations, indicating limited consistency in student performance across these items. Some significant correlations are observed, such as Q8 ($r = -0.293$, $p = 0.003$) and Q9 ($r = -0.269$, $p = 0.006$), but the overall pattern suggests that traditional laboratory methods in chemistry I resulted in inconsistent improvements in performance.

In contrast, chemistry II demonstrates stronger and more consistent correlations between pre- and post-test scores, reflecting the impact of the Crocodile Chemistry program. The overall correlation is robust and highly significant ($r = -0.795$, $p < 0.001$), suggesting substantial alignment between pre- and post-intervention performance. At the item level, many correlations are both significant and stronger compared to chemistry I. For example, Q1 ($r = -0.559$, $p < 0.001$), Q4 ($r = -0.615$, $p < 0.001$), and Q10 ($r = -0.608$, $p < 0.001$) highlight the consistency and effectiveness of the virtual laboratory program. Additionally, correlations for Q8 ($r = -0.484$, $p < 0.001$) and Q9 ($r = -0.661$, $p < 0.001$) reflect significant improvements in specific areas of chemical comprehension.

Overall, the comparison between chemistry I and II reveals that the Crocodile Chemistry program leads to stronger and more significant correlations between pre- and post-test scores. These results indicate that the program enhances student learning outcomes more effectively than traditional methods by fostering greater consistency and alignment between instructional approaches and assessments. The findings further emphasize the potential of virtual laboratory tools in modernizing chemistry education and improving student engagement and performance.

TABLE 3 Correlation coefficients and significance levels for pre-test and post-test scores across pairs in chemistry I.

		N	Correlation	Significance	
				One-sided *p*	Two-sided *p*
Pair 1	Pre and post	103	−1	<0.001	<0.001
Pair 2	Q1pre and Q1post	103	−0.401	<0.001	<0.001
Pair 3	Q2pre and Q2post	103	−0.151	0.064	0.128
Pair 4	Q3pre and Q3post	103	−0.105	0.145	0.289
Pair 5	Q4pre and Q4ppst	103	−0.302	<0.001	0.002
Pair 6	Q5pre and Q5post	103	−0.084	0.199	0.398
Pair 7	Q6pre and Q6post	103	−0.045	0.324	0.649
Pair 8	Q7pre and Q7post	103	−0.267	0.003	0.006
Pair 9	Q8pre and Q8post	103	−0.293	0.001	0.003
Pair 10	Q9pre and Q9post	103	−0.269	0.003	0.006
Pair 11	Q10pre and Q10post	103	−0.274	0.003	0.005
Pair 12	Q11pre and Q11post	103	−0.167	0.046	0.092
Pair 13	Q12pre and Q12post	103	−0.134	0.089	0.179
Pair 14	Q13pre and Q13post	103	−0.248	0.006	0.012
Pair 15	Q14pre and Q14post	103	−0.129	0.097	0.194
Pair 16	Q15pre and Q15post	103	−0.161	0.052	0.103
Pair 17	Q16pre and Q16post	103	−0.143	0.075	0.15
Pair 18	Q17pre and Q17post	103	−0.263	0.004	0.007
Pair 19	Q18pre and Q18post	103	−0.245	0.006	0.013
Pair 20	Q19pre and Q19post	103	−0.196	0.023	0.047
Pair 21	Q20pre and Q20post	103	−0.119	0.115	0.231
Pair 22	Q21pre and Q21post	103	−0.12	0.114	0.229
Pair 23	Q22pre and Q22post	103	−0.066	0.254	0.508
Pair 24	Q23pre and Q23post	103	−0.135	0.086	0.173
Pair 25	Q24pre and Q24post	103	−0.164	0.049	0.098
Pair 26	Q25pre and Q25post	103	−0.105	0.145	0.289
Pair 27	Q26pre and Q26post	103	−0.252	0.005	0.01
Pair 28	Q27pre and Q27post	103	−0.191	0.027	0.054
Pair 29	Q28pre and Q28post	103	−0.203	0.02	0.04
Pair 30	Q29pre and Q29post	103	−0.028	0.388	0.777
Pair 31	Q30pre and Q30post	103	−0.177	0.037	0.074
Pair 32	Overall_A and overallpost_A	103	−0.765	<0.001	<0.001
Pair 33	Overall and overallpost	103	−0.761	<0.001	<0.001

5 Discussion

The integration of innovative digital tools into education has transformed the teaching and learning landscape, especially in complex fields like chemistry. Virtual laboratories have emerged as a powerful solution to address challenges associated with traditional laboratory setups, including safety concerns, high costs, and limited accessibility. This discussion explores the role of the Crocodile Chemistry program in advancing chemistry education, focusing on its effectiveness in enhancing learning outcomes, fostering engagement and motivation, and addressing systemic limitations. Furthermore, the study examines the implications of adopting such technologies in higher education within Kuwait, providing a framework for future integration of virtual tools to modernize educational practices.

5.1 Effectiveness of virtual laboratories in chemistry education

The results of this study demonstrate the significant impact of the Crocodile Chemistry program on enhancing students' understanding of chemical concepts, academic performance, and engagement. These findings align with existing literature

TABLE 4 Correlation coefficients and significance levels for pre-test and post-test scores across pairs in chemistry II.

		N	Correlation	Significance	
				One-sided *p*	Two-sided *p*
Pair 1	Pre and post	102	−1	<0.001	<0.001
Pair 2	Q1pre and Q1post	102	−0.559	<0.001	<0.001
Pair 3	Q2pre and Q2post	102	−0.42	<0.001	<0.001
Pair 4	Q3pre and Q3post	102	−0.281	0.002	0.004
Pair 5	Q4pre and Q4ppst	102	−0.615	<0.001	<0.001
Pair 6	Q5pre and Q5post	102	−0.153	0.062	0.125
Pair 7	Q6pre and Q6post	102	−0.02	0.421	0.841
Pair 8	Q7pre and Q7post	102	−0.585	<0.001	<0.001
Pair 9	Q8pre and Q8post	102	−0.484	<0.001	<0.001
Pair 10	Q9pre and Q9post	102	−0.661	<0.001	<0.001
Pair 11	Q10pre and Q10post	102	−0.608	<0.001	<0.001
Pair 12	Q11pre and Q11post	102	−0.264	0.004	0.007
Pair 13	Q12pre and Q12post	102	−0.425	<0.001	<0.001
Pair 14	Q13pre and Q13post	102	−0.339	<.001	<0.001
Pair 15	Q14pre and Q14post	102	−0.282	0.002	0.004
Pair 16	Q15pre and Q15post	102	−0.108	0.14	0.281
Pair 17	Q16pre and Q16post	102	−0.357	<0.001	<0.001
Pair 18	Q17pre and Q17post	102	−0.367	<0.001	<0.001
Pair 19	Q18pre and Q18post	102	−0.457	<0.001	<0.001
Pair 20	Q19pre and Q19post	102	−0.36	<0.001	<0.001
Pair 21	Q20pre and Q20post	102	−0.384	<0.001	<0.001
Pair 22	Q21pre and Q21post	102	−0.233	0.009	0.019
Pair 23	Q22pre and Q22post	102	−0.149	0.068	0.135
Pair 24	Q23pre and Q23post	102	−0.241	0.007	0.015
Pair 25	Q24pre and Q24post	102	−0.183	0.033	0.066
Pair 26	Q25pre and Q25post	102	−0.262	0.004	0.008
Pair 27	Q26pre and Q26post	102	−0.483	<0.001	<0.001
Pair 28	Q27pre and Q27post	102	−0.443	<0.001	<0.001
Pair 29	Q28pre and Q28post	102	−0.369	<0.001	<0.001
Pair 30	Q29pre and Q29post	102	−0.038	0.351	0.702
Pair 31	Q30pre and Q30post	102	−0.094	0.173	0.345
Pair 32	Overall_A and overallpost_A	102	−0.795	<0.001	<0.001
Pair 33	Overall and overallpost	102	−0.791	<0.001	<0.001

emphasizing the advantages of virtual laboratories in providing interactive and safe learning environments. For instance, Brinson (2015) concluded that virtual laboratories achieve learning outcomes comparable to or surpassing traditional methods by fostering active engagement and providing opportunities for repetitive experimentation (Brinson, 2015). Compared to the control group, the experimental group using the Crocodile Chemistry program exhibited notable gains in post-test scores. This aligns with findings from Viitaharju et al. (2023), who highlighted that virtual laboratories improve comprehension and procedural learning by allowing students to practice and internalize experimental concepts in a simulated setting (Viitaharju et al., 2023). Furthermore, the statistically significant correlations observed in this study between pre- and post-test scores for chemistry II underscore the program's effectiveness in aligning instructional methods with assessment outcomes.

5.2 Enhanced engagement and motivation

The interactive nature of virtual laboratories like the Crocodile Chemistry program was found to substantially increase student engagement and motivation. Acenas et al. (2019) similarly reported that the gamified elements of virtual labs and their risk-free environment contribute to higher levels of student enthusiasm and retention of complex scientific concepts. Students' ability to repeatedly conduct experiments without constraints, as observed in this study, reinforces deeper conceptual understanding, consistent with the findings of Chan et al. (2021). Moreover, the significant improvements in chemistry II post-test scores, particularly in items requiring higher-order cognitive skills, highlight the transformative potential of virtual laboratories in stimulating critical thinking. This is supported by studies such as Zendler and Greiner (2020), which emphasize the role of virtual simulations in fostering analytical skills and problem-solving capabilities among learners.

5.3 Addressing limitations of traditional laboratories

The results highlight the Crocodile Chemistry program's ability to mitigate the limitations of traditional laboratory setups, including safety concerns, high costs, and accessibility barriers. Traditional approaches, as evidenced by the lack of significant improvement in chemistry I scores, often fail to provide students with adequate opportunities to engage in experimental learning. The findings of this study are consistent with Georgiou et al. (2007), who noted that virtual laboratories offer scalable and cost-effective alternatives to physical labs, enabling broader access to quality science education (Georgiou et al., 2007).

5.4 Contextual implications for higher education in Kuwait

This study provides critical insights into the application of virtual laboratories in Kuwaiti higher education institutions. The results underscore the necessity of integrating digital tools like the Crocodile Chemistry program to address infrastructure limitations and enhance learning outcomes. As Alkandari et al. (2021) observed, technological adoption in education is crucial for addressing challenges related to resource scarcity and increasing student populations. The findings suggest that virtual laboratories can play a pivotal role in modernizing educational practices in the region, thereby contributing to the broader discourse on digital transformation in education.

6 Conclusion

The integration of the Crocodile Chemistry program into higher education demonstrates its effectiveness in enhancing learning outcomes. The program improves the ability to accurately assess student understanding and aligns instructional methods with test items, fostering a cohesive and effective learning experience. By advancing comprehension, academic achievement, and motivation, the program provides a modern approach to chemistry education and supports the broader adoption of virtual laboratory tools to bridge the gap between theoretical concepts and practical applications.

The Crocodile Chemistry program stands out as a valuable resource for improving chemistry instruction through virtual laboratories. It enhances academic performance and deepens students' understanding of chemical principles by offering an engaging and adaptable learning environment. This study underscores the program's positive impact on student engagement and learning outcomes, offering actionable insights for future educational strategies and technological innovations. It highlights the importance of continuous innovation in teaching practices and contributes to the growing body of evidence supporting the integration of digital technologies and e-learning tools in higher education.

6.1 Limitation of the study

Even though the study produced favorable results, it also highlighted areas where the Crocodile Chemistry program could be improved. For instance, some pairings showed minimal progress, indicating that the virtual lab alone may not address all learning gaps. These results suggest the need for a blended learning approach that combines both online and in-person laboratory experiences to address a range of learning needs. Additionally, the study sample size, though sufficient for an initial analysis, may limit the generalizability of the findings. A larger sample size would provide more robust insights into programs effectiveness across diverse populations. Furthermore, heterogeneity among participants, including variations and prior. Chemistry knowledge and motivation levels may have influenced the results. Initial differences between experimental and control groups, such as familiarity with digital tools, could also contribute to variations in performance.

6.2 Future research

Future research should explore the long-term effects of virtual laboratories on students' academic performance. Further studies could focus on identifying specific chemical topics that benefit most from virtual simulations versus those that may still require traditional lab environments. Additionally, investigating how virtual laboratories integrate with other digital tools and active learning techniques could provide a more comprehensive understanding of their potential in science education.

Data availability statement

The original contributions presented in this study are included in this article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The studies involving humans were approved by the IRB – Kuwait Technical College. The studies were conducted in accordance with the local legislation and institutional requirements. The participants provided their written informed consent to participate in this study.

Author contributions

NA: Conceptualization, Data curation, Resources, Writing – original draft. ZA: Investigation, Resources, Writing – review & editing. AhA: Data curation, Formal analysis, Methodology, Software, Validation, Visualization, Writing – review & editing. BA: Investigation, Resources, Validation, Writing – review & editing. AnA: Investigation, Project administration, Resources, Supervision, Writing – original draft. FA: Investigation, Resources, Writing – original draft.

Funding

The author(s) declare that no financial support was received for the research, authorship, and/or publication of this article.

Acknowledgments

The authors acknowledge the American University of Kuwait (AUK) for their support and Kuwait Technical College for ethical oversight, both of which were vital to this research.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or funding relationships that could be construed as a potential conflict of interest.

Publisher's note

References

Abdo, S. M. (1999). *Fundamentals of Scientific Research in Educational and Social Sciences*, 1st Edn. Giza: Dar Al-Farouk for Culture and Publishing.

Acenas, R. C. B., Martin, R., and Bautista, R. G. (2019). Chemistry made easy: Unravelling the experiences of biological science majors in using a virtual laboratory. *Am. J. Educ. Res.* 7, 170–173. doi: 10.12691/EDUCATION-7-2-9

AlAwda, T. H. (2012). *Difficulties in Employing E-Learning in Palestinian Universities in Gaza as Seen by Professors and Students*. Gaza: Al-Azhar University.

Alhashem, F., and Alfailakawi, A. (2023). Technology-enhanced learning through virtual laboratories in chemistry education. *Contemp. Educ. Technol.* 15:e474. doi: 10.30935/cedtech/13739

Alkandari, A., Alseddiqi, A., and Alsaber, A. A. R. (2021). Measuring instructor's readiness on accepting the use of e-learning system during Covid-19 pandemic in higher education of Kuwait. *J. Acad. Bus. Econ.* 21, 29–40.

Alkandari, F., Alsaber, A., Al-Kandari, A., Alboloushi, B., and AlMutairi, S. (2024). Enhancing the effectiveness of digital transformation on teaching in higher education in Kuwait. *Front. Educ.* 9:1417062. doi: 10.3389/feduc.2024.1417062

Al-Shamali, S., Al-Shamali, A., Alsaber, A., Al-Kandari, A., AlMutairi, S., and Alaya, A. (2022). Impact of organizational culture on academics' readiness and behavioral intention to implement eLearning changes in Kuwaiti universities during COVID-19. *Sustainability* 14, 1–16. doi: 10.3390/su142315824

AlShehri, A. B. M. (2009). *The Effect of Using Virtual Laboratories on Acquiring Skills Laboratory Experiments in the Biology Course for Third-Year Secondary Students in Jeddah*. Saudi Arabia: College of Education, Umm Al-Qura University

Bajpai, M. (2012). Effectiveness of developing concepts in photoelectric effect through virtual lab experiment. *Int. J. Eng. Adv. Technol.* 1, 296–299.

Brindha, G., Krishnakumar, T., and Vijayalatha, S. (2015). Emerging trends in tele-medicine in rural healthcare. *Int. J. Pharmacy Technol.* 7, 8986–8991.

Brinson, J. R. (2015). Learning outcome achievement in non-traditional (virtual and remote) versus traditional (hands-on) laboratories: A review of the empirical research. *Comput. Educ.* 87, 218–237. doi: 10.1016/j.compedu.2015.07.003

Chan, P., Van Gerven, T., Dubois, J.-L., and Bernaerts, K. (2021). Virtual chemical laboratories: A systematic literature review of research, technologies and instructional design. *Comput. Educ. Open* 2:100053. doi: 10.1016/j.caeo.2021.100053

Chans, G. M., Bravo-Gutiérrez, M. E., Orona-Navar, A., and Sánchez-Rodríguez, E. P. (2022). Compilation of chemistry experiments for an online laboratory course: Student's perception and learning outcomes in the context of COVID-19. *Sustainability* 14:2539. doi: 10.3390/su14052539

Chuaungo, M., Nunhlimi, V. L. A., and Mishra, L. (2022). Integrating technology with constructivist pedagogy. *Int. J. Eng. Technol. Manag. Sci.* 5, 104–109. doi: 10.46647/ijetms.2022.v06i05.014

Dar Ibrahim, Y. S. (2014). *The Effect of Using the Virtual Laboratory for Science Experiments in Developing Science Processes and Acquiring Concepts Among Fifth-Grade Female Students in Palestine*. Palestine: An-Najah National University.

Darrah, M., Humbert, R., Finstein, J., Simon, M., and Hopkins, J. (2014). Are virtual labs as effective as hands-on labs for undergraduate physics? A comparative study at two major universities. *J. Sci. Educ. Technol.* 23, 803–814. doi: 10.1007/s10956-014-9513-9

Faraj, A. L. (2005). Stopping the Internet in education and its curricula. *Educ. J.* 74, 110–150.

Georgiou, J., Dimitropoulos, K., and Manitsaris, A. (2007). A virtual reality laboratory for distance education in chemistry. *World Acad. Sci. Eng. Technol. Int. J. Soc. Behav. Educ. Econ. Bus. Industrial Eng.* 1, 617–624.

Gupta, S. B., and Gupta, M. (2020). Technology and E-learning in higher education. *Technology* 29, 1320–1325.

Ibn Zaarour, R. H. D. (2003). *The Effect of using Computer-Assisted Instruction in the Visual Basic Language on Achievement in Mathematics and the Motivation of Immediate and Delayed Achievement for Class Students*. Palestine: An-Najah National University

Jakkula, S. K., Endla, P., Dugyala, P., and Kumaraswamy, T. (2020). Collaborative learning through virtual labs in engineering education. *IOP Conf. Ser. Mater. Sci. Eng.* 981:022095. doi: 10.1088/1757-899X/981/2/022095

Jurakulova, N. K. (2019). Opportunities of e-learning environment to improve the quality of education. *Eur. J. Res. Reflection Educ. Sci.* 7, 1176–1178.

Keith-Lucas, L. (2000). Crocodile chemistry (crocodile clips, ltd.). *J. Chem. Educ.* 77:1284. doi: 10.1021/ed077p1284

Kirschner, P., and Huisman, W. (1998). Dry laboratories in science education: Computer-based practical work. *Int. J. Sci. Educ.* 20, 665–682. doi: 10.1080/0950069980200605

Link, R. D., and Gallardo-Williams, M. (2022). We should keep developing digital laboratory resources in the postpandemic era. *J. Chem. Educ.* 99, 519–520. doi: 10.1021/acs.jchemed.1c01197

Martínez-Jimenez, P., Pontes-Pedrajas, A., Polo, J., and Climent-Bellido, M. S. (2003). Learning in chemistry with virtual laboratories. *J. Chem. Educ.* 80, 346–352. doi: 10.1021/ED080P346

Omran, M. K. (2015). *The Effect of Using the Addy and Shayer Model in Modifying Alternative Perceptions of Scientific Concepts Among Ninth Grade Students*. Gaza: University Islamic Gaza.

Palenti, C. (2023). Improving metacognitive ability through the reading questioning answering (rqa) model assisted with learning journals in nonformal educational study programs. *J. Ilmiah Visi.* 18, 80–86. doi: 10.21009/jiv.1802.2

Potkonjak, V., Gardner, M., Callaghan, V., Mattila, P., Gütl, C., Petrović, V., et al. (2016). Virtual laboratories for education in science, technology, and engineering: A review. *Comput. Educ.* 95, 309–327. doi: 10.1016/j.compedu.2016.02.002

Reeves, S. M., and Crippen, K. J. (2020). Virtual laboratories in undergraduate science and engineering courses: A systematic review, 2009–2019. *J. Sci. Educ. Technol.* 30, 16–30. doi: 10.1007/s10956-020-09866-0

Rizman Herga, N., Čagran, B., and Dinevski, D. (2016). Virtual laboratory in the role of dynamic visualisation for better understanding of chemistry in primary school. *Eurasia J. Math. Sci. Technol. Educ.* 12, 593–608. doi: 10.12973/eurasia.2016.1224a

Seery, M. K., and O'Connor, C. (2015). "E-learning and blended learning in chemistry education," in *Chemistry Education*, (Weinheim: Wiley-VCH Verlag GmbH & Co. KGaA), 651–670. doi: 10.1002/9783527679300.ch26

Urquizo, E., Sánchez, N. D. J., and Orrego, M. (2022). Experimental activities using virtual simulators to learn chemistry during Covid-19 pandemic. *Rev. Chakiñan Ciencias Soc. Humanidades* 17, 122–137.

Viitaharju, P., Nieminen, M., Linnera, J., Yliniemi, K., and Karttunen, A. J. (2023). Student experiences from virtual reality-based chemistry laboratory exercises. *Educ. Chem. Eng.* 44, 191–199. doi: 10.1016/j.ece.2023.06.004

Villanueva, O., and Zimmermann, K. (2020). Transitioning an upper-level, integrated laboratory course to remote and online instruction during the COVID-19 pandemic. *J. Chem. Educ.* 97, 3114–3120. doi: 10.1021/acs.jchemed.0c00740

Wörner, S., Kuhn, J., and Scheiter, K. (2022). The best of two worlds: A systematic review on combining real and virtual experiments in science education. *Rev. Educ. Res.* 92, 911–952. doi: 10.3102/00346543221079417

Zendler, A., and Greiner, H. (2020). The effect of two instructional methods on learning outcome in chemistry education: The experiment method and computer simulation. *Educ. Chem. Eng.* 30, 9–19. doi: 10.1016/j.ece.2019.09.001