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A Systematic Review of 21st-Century Chemistry Laboratory Experiments and Classroom Instructions Facilitated/Aided With Digital Technologies and E-Resources

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Abstract

The study is a systematic review that looked at several technological tools used by academics to support 21st-century chemistry classroom instruction and lab experiments. Different databases, search engines, journals, and libraries were searched to obtain the most recent and relevant studies conducted from 2012 to 2022. The result reveals that the VR2E2C system, Authentic Intelligent Robotics for Chemistry (AIR-Chem), and LEGO-based automation device were the robotics tools used by researchers to facilitate classroom instruction of chemical concepts, including inorganic and general chemistry. It also reveals that the type of web resource that is integrated with an LMS, such as Google Classroom, Edmodo, Mooc, Moodle, and others, is the one that is utilized most frequently. Furthermore, the findings reveal that the virtual laboratories used for facilitating chemistry instruction include the Virtual Reality Multisensory Classroom (VRMC), Blackboard Learning System (BLS), PhET interactive simulation, ChemVLab+, and Interactive Molecular Dynamics in Virtual Reality (iMD-VR). Other findings reveal that computer and mobile device software applications used by researchers include Elements 4D, MoleculAR, iMolview Lite, MATLAB, Courseware, and CHEMTrans. The study concluded that technological advancement in the twenty-first century revolutionized chemistry instruction, making it more realistic than abstract.

Keywords: Chemistry, Instruction, Technology, 21st century, Experiment, Classroom.

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Introduction

As computers, tablets, smartphones, and other forms of technology are used more frequently in classrooms, researchers are interested in investigating and researching digital technologies' effectiveness in education and formative assessment. Interactive computer simulations are becoming increasingly influential teaching aids for chemistry nowadays. Students are learning through exploration in the simulations' animated, interactive, and game-like worlds. The simulations are easily accessed online and are made to be versatile tools to suit a variety of implementation techniques and instructional situations.

Many developing technologies have found widespread uses in the field of chemical education, including robotics, learning analytics, virtual reality (VR), and augmented reality (AR) (Chiu, 2021). For example, modern chemistry education places much emphasis on hands-on activities in the classroom, visualizing and interacting with chemical structures, and using virtual chemistry labs. While engaging and enjoyable for students and teachers, technology offers flexible access to several representations, makes the unseen visible, stimulates inquiry, and enables safe and quick access to numerous trials.

Psychologically, an experiment is an investigation in which a hypothesis is scientifically tested by manipulating an independent variable (the cause) while the dependent variable (the effect) is measured. Thus, experimentation is the manipulation of variables to establish cause-and-effect relationships. This experiment is mainly conducted in laboratories, hence the name laboratory experiment. Generally, laboratory experiments are a research method by which researchers create controllable environments to test hypotheses. A chemistry laboratory experiment is conducted under highly controlled conditions where accurate measurements, observations, and extractions are possible. Chemistry laboratory experiments are easy to replicate because standardized procedures are mostly utilized (Aliyu, 2022). Thus, a chemistry laboratory experiment is an experiment that uses a carefully controlled setting and standardized procedure to accurately measure how a change in the independent variable (the variable that changes) affects the dependent variable (the variable measured).

According to An et al. (2020), many educators have argued that, given their significance, laboratory experiences must be an essential component of science instruction. They listed the objectives of laboratory experiments as including (i) piquing and maintaining students' interest in science; (ii) encouraging original thought and conceptual understanding of the subject; (iii) advancing the science process and practical skills; and (iv) developing the study's inquiry skills. Interestingly, most chemical concepts are learned through laboratory experimentation and modeling. Thus, learning chemistry, whether in the classroom or the laboratory, requires effectively planned instruction. Instruction means the efforts of somebody superior in knowledge, skills, and attitude to plan, design, implement, and evaluate the teaching-learning process to benefit the recipients (learners). A classroom is a room in a school or college where instruction occurs. Classroom instruction means training in a setting where individuals receiving training are assembled and learn through organized formal education techniques (Muchtar et al., 2021). Traditionally, schools delivered classroom instruction with chalk and board. However, the demand for 21st-century skills and knowledge and the challenges brought by the COVID-19 pandemic force teachers to use technology to facilitate classroom instruction. Today, teachers systematically plan, design, implement, and evaluate the total process of teaching and learning based on specific instructional objectives, using available human and non-human elements (such as digital technology) to improve the quality of instruction. Today, web-based applications, virtual laboratory tools, and other digital technologies are predominantly used by chemistry educators to facilitate classroom instructions and laboratory experiments in the teaching and learning of chemistry at both secondary and tertiary education levels.

Learning of Chemistry Concepts in the 21st Century

Chemistry demands students to understand chemistry at the macroscopic, microscopic, and symbolic levels. To complete this task, students must employ both highly abstract verbal and nonverbal thinking capabilities and subject-specific thinking abilities. As a result, in a "normal" classroom setting, teachers attempt to convert abstract chemical information into a teachable form, primarily through vocal explanations supplemented by parallel symbolic representations of information on the board. Students must focus on both the verbal cues and the visual input simultaneously to integrate them and make sense of them (Marchak et al., 2021). This demonstrates that the metacognitive processes necessary to comprehend and use an idea in any problem-solving are fundamentally based in chemistry.

Visual comprehension is a conceptual competency that relies on verbally mediated sense-making processes because it impacts how the subject's theoretical and experimental notions are learned and taught. It is impossible to ignore the importance of these representational skills in creating accurate mental models and giving the correct meaning to abstract chemical material through visualization. The fundamental premise behind traditional teaching methods is that the information humankind has amassed in the past must be transmitted to students in its current state. Therefore, lecturing has long been the primary method of achieving this goal, and as a result, learners have developed a passive attitude, both physically and cognitively.

Problem Statement

Researchers (Binti Ibrahim & Hj. Iksan, 2018 and Zoller, 2012) have found that learning chemistry can be challenging for various reasons, including complex concepts and misconceptions. According to certain studies (Luxford & Bretz, 2013 and Vladušić et al., 2016), students cannot distinguish between ionic and covalent bonding, while other studies (Taber, 2013) show that they are unaware of the chemical bond's electrostatic nature. Additionally, students conflate intramolecular and intermolecular forces, according to Luxford & Bretz (2013) and Uyulgan et al. (2014), while having misconceptions regarding the geometrization and polarity of molecules. These demonstrated the claim by Nahum et al. (2004) that students had trouble seeing and comprehending abstract concepts like chemical bonding.

Recently, reports show that the most challenging topic in chemistry is chemical bonding. This was a result of a study conducted to investigate (i) the problems encountered by the students and lecturers during the teaching and learning of matriculation chemistry subject, (ii) the most challenging topics in the matriculation chemistry syllabus, and (iii) the needs for the development of the teaching and learning module. That is why the report, after analyzing how the chemical bond is taught, that traditional instruction contributes to learning difficulties. As a result, they proposed a new method of teaching chemical bonds based on current scientific knowledge, new pedagogical content knowledge and technological integration in chemistry teaching and learning. Inorganic and organic chemistry's understanding of reactivity and analytical chemistry's comprehension of spectroscopy depend on an understanding of chemical bonding (Vladušić et al. (2016). This is because it is focused on particle combinations, and the type of particle bonding can be used to explain a substance's chemical and physical properties.

According to Lee (2022), chemical bonding is currently the most challenging area of chemistry. This report was the outcome of a study conducted to assess (I) the issues that both learners and instructors encountered while learning and teaching chemistry, (ii) the most difficult topics on the syllabus, and (iii) the requirements for the development of the teaching and learning module. In the cause of a similar problem, Nahum et al. (2010) claimed that traditional training exacerbates learning issues after investigating how the chemical bond is taught. They consequently put up a fresh approach to teaching chemical bonds based on modern pedagogical content knowledge, current scientific understanding, and technological integration in chemistry teaching and learning.

Educational processes in Technology Enhanced Learning Environments (TELE) are mainly constructivist inquiries that foster an understanding of science and technology concepts and develop research skills. In such environments, the students construct knowledge in science and technology through practice in creating and operating technological tools. Digital technology in the 21st century is regarded as an effective tool for innovation in learning systems. Learning environment adopting digital technology positively contributes to students' cognitive and affective processes, which can finally result in a high attitude toward learning (Nababan et al., 2019).

Objectives of the Study

Because of the difficulties that both students and teachers have had in learning, understanding, and teaching chemical concepts that are either macroscopic, submacroscopic, or symbolic, many researchers have turned their attention to using technologically advanced tools to facilitate classroom instruction and laboratory experiments. Thus, the study examined several forms of technology academics utilize to facilitate chemistry classroom instruction and laboratory experiments in the 21st century.

The study is intended to pull out any relevant digital software tools used in the 21st century to ease the teaching and learning of chemical concepts at home, in the classroom, or the laboratory. The study's findings will categorically indicate chemical concepts taught to the students by chemistry educators when teaching with the aid of specific digital technology. Thus, this will help chemistry teachers understand technological tools that could be used to address specific chemical concepts. If effectively used, the problem of complex concepts and misconceptions in chemistry caused by textbooks, chemical models, or even teachers themselves can be easily overcome.

Method

The study adopted a systematic review of related work executed by scholars between 2010 and 2022. It is believed that during this period of 12 years, a lot has changed regarding the instructional approach for teaching and learning chemistry at both secondary and tertiary levels of education. Many databases and journals were visited to source relevant information for the study, including Google Scholar, Elsevier, ScienceDirect, Web of Science, SAGE journals, Springer, Semantic Scholar, the Journal of Chemical Education, and the International Journal of Interactive Mobile Technologies. The keywords searched include "chemistry and technology," "chemistry and mobile learning," "virtual chemistry laboratories," "chemistry and robotics," "chemistry and learning management systems," "chemistry and digital games," and "chemistry and web-based learning."

The search results, amounting to over 22,169 articles, were scrutinized and screened through set criteria. The first criterion is screening out those articles intended for areas other than the teaching and learning of chemistry. This criterion excludes articles from consideration for laboratory and clinical research. Secondly, articles not related to the teaching and learning of chemistry specifically were also eliminated. Further exclusion and inclusion are represented in Figure 1, which reveals that 58 articles qualified for the review.

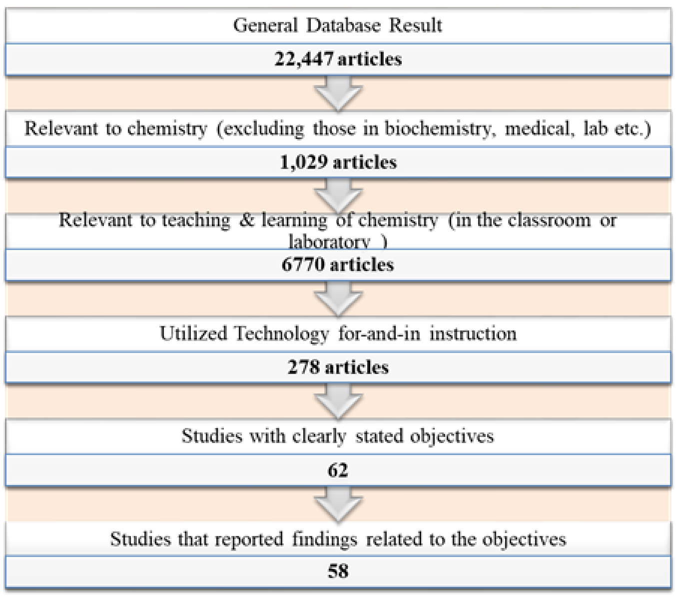

Figure 1. Criteria for Screening Qualified Research Work

Result and Discussion

Over the years, several technological resources were used by researchers and chemistry teachers to facilitate classroom instruction and laboratory experiments, especially during the COVID-19 pandemic. The outcome of this review demonstrated the variety of electronic resources and digital technologies used for facilitating the learning and teaching of various chemical concepts concerning the objective intended to be addressed. Thus, the analysis is hereby presented to address different forms of technologies and e-resources used by the researchers, including robotics, learning management systems, virtual laboratories, computer and mobile software applications, videos, and digital games.

Robotics for Chemistry Instructions

For more than a decade, a combination of robotic automation and artificial intelligence (AI) has made great advances in chemistry to improve yields and reproducibility, cut costs, prevent health hazards, and accelerate the discovery of new materials. Most of the relevance here indicated is associated with advancement in the industrial sector. Despite claims that many schools train students to employ automation technology while some have already discontinued teaching traditional manual techniques, very few robotics (indicated in Table 1) are created to facilitate chemistry classroom instruction and laboratory research (Verner & Revzin, 2019). Robotic technologies are thought to be able to increase the effectiveness and accessibility of laboratory experimentation, offering considerable educational benefits, particularly in supporting constructivist inquiry-based learning and in developing students' higher-order thinking skills.

Table 1. Robotics Used by Chemistry Instruction by Researchers

SN	Authors	Publishers	Software application	Scope of chemical activities
1	Lu et al. (2021)	Journal of Chemical Education	VR^2E^2C system	General chemistry experiment: the synthesis of gold nanocrystals (AuNCs)
2	Li et al., (2018)	Journal of Physical Chemistry	Authentic Intelligent Robotics for Chemistry (AIR-Chem)	Inorganic chemistry
3	Verner & Revzin (2019)	Springer	LEGO-based automation device	Inorganic chemistry

As indicated in Table 1, while two studies are related to inorganic chemistry, one concerns general chemistry. Thus, researchers use robotics to facilitate the learning of general and inorganic chemistry. This does not limit other experts from utilizing robotics in other areas of chemistry, including analytical and physical chemistry. Researchers (Li et al., 2018; Lu et al., 2021; Verner & Revzin, 2019) report that robotics was interesting and engaging and contributed to significant outcomes in learning chemistry. There is no specific robotics designed for chemistry education. Teachers need to determine more relevant tools that fit their students' intellectual development and ensure the attainment of instructional objectives.

Web-Based Learning Resources for Chemistry Education

The web-based learning resources are categorized into learning management systems and virtual laboratories. Thus, this section is divided into two sub-sections, including (a) web-based learning via learning management systems and (b) a virtual laboratory in chemistry education.

Web-Based Learning Via Learning Management Systems

The software used to deliver, monitor, and process training and learning is a learning management system (LMS).

Similarly, creating teaching materials for learning that use the LMS application is thought to pique students' desire and interest more, fostering a positive attitude toward chemistry and enhancing their metacognition abilities (Nababan et al., 2019). According to Putro et al. (2022), it is envisaged that the learning management system (LMS) for chemistry teaching will consist of a collection of resources, virtual lessons, quizzes and practice problems, and a collection of formulas, as well as extra animations and virtuals to make it easier to grasp. As indicated in Table 2, some of the LMS used in teaching and learning include Edmodo, Moodle LMS, Google Classroom, Teachmint, TalentLMS, iSpring Learn, TalentCards, Eduflow, Skillcast LMS, 360 Learning, Gurucan, Sakai, Xperiencify, GyrusAim, Tovuti LMS, LearnWorlds etc.

Table 2. Web-Based Technologies Used in Chemistry Instruction

SN	Authors	Publishers	Software application	Scope of chemical activities
1	Agnello et al., (2020)	Journal of Chemical Education	ULg Spectra	Spectrometry (organic chemistry experiment)
2	Marchak et al. (2021)	Journal of Chemical Education	Framework	General chemistry
3	Hagos et al. (2022)	Journal of Chemistry Education Research	Technology Integrated Formative Assessment (TIFA)	chemical equilibrium
4	Fosu et al. (2019)	Technology Integration in Chemistry Education and Research (TICER)	Twitter and a campus-based learning management system (LMS)	General chemistry
5	Putro et al. (2022)	Journal of Physics: Conference Series	Moodle LMS	General chemistry
6	Imaduddin & Astuti (2022)	Bulletin of Community Engagement	Google Classroom	microscopic concepts i.e. sub macroscopic concepts like atom, radioactivity etc.
7	Hsiung (2018)	Journal of Interactive Mobile Technologies	Moodle e-Learning platform	General chemistry
8	Al-nawaiseh & Alwraikat (2020)	European Journal of Business and Management	e-learning made from LMS	General chemistry
9	Siqueira de Oliveira & Nichele (2020)	14th International Technology, Education and Development Conference	Facebook as a Learning Management System (LMS)	Organic chemistry
10	Muchtar et al. (2021)	Jurnal Pendidikan Kimia	Google Classroom	General chemistry
11	Wolfa et al. (2012)	Proceedings of the SPDECE-2012. Ninth Nultidisciplinary Symposium on the Design and Evaluation of Digital Content for Education	ILIAS-learning software	Practical chemistry (organic & inorganic)
12	Kurniawan et al. (2021)	2nd Annual Conference on Blended Learning, Educational Technology and Innovation (ACBLETI 2020)	Moodle	General chemistry
13	Suherman et al. (2022)	International Journal of Educational Research & Social Sciences	Learning management system	General chemistry
14	Rohyami & Huda (2020)	AIP Conference Proceedings	Google classroom	Analytical Chemistry (stoichiometric aspects of volumetric analysis)
15	Flynn (2015)	Chemistry Education Research and Practice	Blackboard Learning system	organic chemistry and spectroscopy
16	Napitupulu et al. (2020)	International Journal of Mobile Technology	LMS Schoology	Metal Inorganic Chemistry
17	Varela & Leal (2015)	Proceedings of the 5th International Technology, Education and Development Conference (INTED)	Moodle	Carbon compounds; Chemical reactions; Separation processes from mixtures; Chemical bond; etc.
18	Fakngern et al. (2022)	Asia Research Network Journal of Education	online Chemistry learning management	General chemistry
19	Parbuntari & Ikhsan (2014)	International Conference On Research, Implementation And Education Of Mathematics And Sciences	Edmodo	Acid Base Chemistry
20	Nababan et al. (2019)	AIP Conference Proceedings	Thermochemistry-based Learning Management System (LMS)	General chemistry

As can be seen from Table 2, there were about eight general chemistry studies, four organic and inorganic chemistry studies, two analytical chemistry studies, one radioactivity study, and one physical chemistry study conducted by researchers with the aid of a web-based learning management system or as an instructional tool. Since web-based learning tools are employed to reciprocate face-to-face instruction, researchers focus on the chemistry curriculum's theoretical (non-practical) aspects, like general, organic, and inorganic chemistry. Experts mostly use web-based resources to address certain educational or instructional objectives. As a result, the type of web resource that is integrated with an LMS, such as Google Classroom, Edmodo, Mooc, Moodle, and others, is the one that is utilized the most frequently..

The findings of review studies emphasize the advantage of web-based learning resources in developing/enhancing/encouraging student motivation (Fosu et al., (2019; Hagos et al., 2022; Hsiung, 2018; Kurniawan et al., 2021 and Parbuntari & Ikhsan, 2014), learning outcomes (Rohyami & Huda, 2020 and Wolfa et al., 2012), attitude of students toward learning (Nababan et al., 2019), metacognition of the learner (Hagos et al., 2022; Nababan et al., 2019), user satisfaction (Muchtar et al., 2021), and scientific thinking & process skills (Agnello et al., 2020 and Al-nawaiseh & Alwraikat, 2020). Other web resources include ChemTeach & ChemSage, Discovery and Naming of the Chemical Elements, Khan Academy, VIAS Library GenChem, LibreTexts Chemistry, General Chemistry Online, Mark Bishop's Introduction to Chemistry, Virtual Chembook, General Chemistry Virtual Textbook, Chemogenesis Webbook, WikiBooks, AUS-e-TUTE, ChemPaths, KnowledgeDoor, ChemCollective, Doc Brown's Chemistry Clinic, Wyzant, etc.

Virtual Laboratory in Chemistry Education

A "virtual laboratory" is a three-dimensional, realistic virtual environment created using cutting-edge technologies including high-resolution screens, multi-sensor interaction, artificial intelligence, multimedia, and three-dimensional graphics production. Modern sensors that are integrated with technology, as well as high-performance computer hardware and software, are all completely utilized (Geng & Wu, 2021). As indicated in Figure 2. users can replicate their hearing, touch, vision, and other senses to observe items in three dimensions as if they were physically there.

Figure 2. An Analogue of Virtual Chemistry Laboratory

(Retrieved from https://www.labster.com/simulations/introductory-lab/)

Students can obtain a more realistic experience and achieve better learning results while engaging in interactive virtual learning or performing a simulation experiment in a virtual laboratory (Geng & Wu, 2021). Thus, as shown in Table 3, researchers focus on utilizing various distinct virtual laboratories to fulfill varying aims for understanding related chemical processes.

Table 3. Virtual Laboratory Used in Chemistry Instruction

SN	Authors	Publishers	Software application	Scope of chemical activities
1	Winkelmann et al. (2017)	Journal of Chemical Education	Second Life (SL) created and operated by Linden Lab	General chemistry
2	Edwards et al. (2018)	Virtual Reality,	Virtual Reality Multisensory Classroom (VRMC)	Organic chemistry
3	Soong et al. (2021)	Journal of Chemical Education	open-source remote titration unit	Analytical chemistry (titration)
4	Ferrell et al. (2019)	Journal of Chemical Education	interactive molecular dynamics in virtual Reality (iMD-VR)	Molecular chemistry
5	Dunnagan et al., (2020)	Journal of Chemical Education	VR laboratory experience	Spectrometry (organic chemistry lab experiment)
6	Davenport et al. (2018)	Journal of Chemical Education	ChemVLab+	General chemistry
7	Clark & Chamberlain (2014)	Journal of Chemical Education	PhET interactive simulation	General Chemistry laboratory
8	Lancaster et al. (2013)	ACS Symposium Series	PhET interactive simulation	General Chemistry laboratory ((e.g. atoms, photons, electrons))
9	Wright & Oliver-Hoyo (2021)	Journal of Chemical Education	Hydrogen Nuclear Magnetic Resonance MoleculAR Application	Spectrometry energy levels, symmetry, molecular geometry, chemical bonding, reaction mechanisms, etc.
10	Moore et al. (2011)	Journal of Chemical Education	PhET interactive simulation	General Chemistry laboratory
11	Moore (2016)	Journal of Chemical Education	PhET interactive simulation	General Chemistry Instruction
12	Aguirre & Selampinar (2020)	Journal of Chemical Education	Blackboard Learning System (BLS)	General Chemistry laboratory
13	Buchberger et al. (2020)	Journal of Chemical Education	Blackboard Collaborate Ultra	analytical chemistry
14	Dunnagan et al. (2019)	Journal of Chemical Education	VR laboratory experience created using WondaVR	analytical chemistry
15	Tatli & Ayas (2013)	Educational Technology & Society	virtual chemistry laboratory (VCL)	Physical Chemistry (chemical changes)

As you can see from Table 3, there are seven general chemistry studies, five analytical chemistry studies, one organic chemistry study, one molecular chemistry study, and one physical chemistry study conducted via a virtual learning platform. This result reveals that chemistry teachers most often use virtual laboratories to convey laboratory activities involving general and analytical chemistry. These concepts (general and analytical chemistry) are important content of the secondary and undergraduate curriculum that learners must cover, learn, and gain skills before graduating. For example, secondary school chemistry curriculum and assessments frequently prioritize numerical problem-solving activities and practice with symbolic operations, such as balancing chemical equations and building Lewis structures. These steps assume students will learn chemistry fundamentals by manipulating numbers and symbols. By assisting students in drawing links to real-world situations, realistic and context-based instruction via virtual laboratories fosters deep learning of chemical processes.

Another example of the importance of virtual laboratories is their animated and interactive interface, which allows for the exploration of various atomic models, including Dalton's billiard ball, Thomson's plum pudding model, Rutherford's classical solar system model, the Bohr and de Broglie models, and finally Schrödinger's quantum mechanical model. Some of the most frequently used virtual laboratories include the Virtual Reality Multisensory Classroom (VRMC), Blackboard Learning System (BLS), PhET interactive simulation, ChemVLab+, and Interactive Molecular Dynamics in Virtual Reality (iMD-VR).

The advantages of virtual laboratories for students operating and experimenting with chemical and physical processes include promoting student's motivation, interest, and learning (Edwards et al., 2018; Lancaster et al., 2013), encourages intuitive interaction (Lancaster et al., 2013), overcoming learning difficulties (Davenport et al., 2018), learner satisfaction (Ferrell et al., 2019; and Winkelmann et al., 2017), student's self-efficacy (Ferrell et al., 2019), minimizes cognitive load (Lancaster et al., 2013), enhancement of student's performance (Ferrell et al., 2019; and Winkelmann et al., 2017), development of manipulative and science process skills (Chabra 2020 and Clark & Chamberlain, 2014), allow students to connect learning to real-world situations (Lancaster et al., 2013). Virtual environments let students observe the process in more detail, compared to board and chalk activities of the traditional classroom or partially completed experiments in a real laboratory environment (Tatli & Ayas, 2013). Other significant virtual chemistry laboratories not found in this review include Reactor Lab, Virtlab, ScienceMedia, Model ChemLab, and Model ChemLab.

For example, Model ChemLab is a real-time two-dimensional simulation of a chemistry lab in which the user interacts with animated lab equipment in a large number of experiment modules, including Charles' Law, Acid-Base Titration, Atomic Weight of Magnesium, Bond, Cation, and Anion Reactions, Determination of Specific Heat, Electrochemical Cell, Flame Chemistry, Fractional Crystallization, Gas Compression, Gravimetric Analysis of Chloride, Reaction Kinetics, Iron (II) Redox Titration, LeChatelier's Principle, Oxidation and reduction, Nuclear Chemistry, and Paper Chromatography.

Computer and Mobile Software Applications in chemistry instruction

Some software applications are designed to operate on computer devices and mobile phones due to their portability and numerousness. Today, almost every grown individual in this 21st-century society has, if not both, at least a computer device or a mobile phone used for business, leisure, or education. As a result of that, there are many software applications (indicated in Table 4) that run on computers and mobile phones to facilitate the teaching and learning of chemical concepts.

Table 4. Computer and Mobile Software Applications for Chemistry Instruction

SN	Software/Application	Publishers	Scope of chemical exploration	Authors
1	Elements 4D	Journal of Chemical Education,	Periodicity (General chemistry)	Yang et al. (2018)
2	MoleculAR, available in Android and iOS stores	Journal of Chemical Education,	Spectrometry (Analytical chemistry)	Wright & Oliver-Hoyo (2021)
3	iMolview Lite, available in Android and iOS stores	Journal of Chemical Education,	Organic chemistry	Toscanini et al., (2021)
4	Mathematica and MATLAB programming environments	Journal of Chemical Education	Spectrometry (Analytical chemistry)	Jones et al. (2021)
5	Matlab framework.	Journal of Chemical Education	Spectrometry (Analytical chemistry)	Fisher (2019)
6	CHEMTrans	Journal of Chemical Education	Chemical equations	Li et al., (2022)
7	Courseware	2018 IEEE 10th International Conference on Engineering Education (ICEED)	Acid-Based chemistry	Talib et al. (2018)

As indicated in Table 4, while three studies related to analytical chemistry are executed with the aid of computer and mobile software applications, two general, one inorganic, and one organic chemistry use similar technological resources. Some applications and software researchers use include Elements 4D, MoleculAR, iMolview Lite, MATLAB, Courseware, and CHEMTrans. Most of these methods are used by researchers to encourage students' creativity while facilitating active learning, which shows that the activity assists students in absorbing chemical concepts more thoroughly. Some of the reported by researchers include the development of a positive user experience (Wright & Oliver-Hoyo, 2021), a positive attitude toward learning (Yang et al., 2018), gain a deeper understanding of the chemical concept (Fisher, 2019; Jones et al., 2021; Li et al., 2022 and Toscanini et al., 2021).

Other chemistry-specific apps include AutoChrom, Katalyst D2D, Luminata, Method Selection Suite, MS Fragmenter & NMR Predictors, Spectrus JS, ChemOffice (the new version includes ChemDraw Ultra, Chem3D Ultra, E-Notebook Ultra, ChemFinder, CombiChem, Inventory, BioAssay, and The Merck Index), Spectrus Processor, Gaussian, Structure Elucidator Suite, ChemSketch, Hyperchem, Betwixt, Odyssey, ChemBuddy, Monte Carlo Gas Simulator, SAVANT Laboratory Training, Atomic orbitals CD-ROM, Chemical Thesaurus, CHEM-IT, Newbyte, WinTorg, CHEMIX School, Kintecus.

Video-Based Learning Technology in Chemistry Instructions

Videos can be used to support chemistry lessons if they are appropriately integrated with crucial elements that help teaching and learning (Gallardo-Williams et al., 2020). Videos are frequently used in chemistry to describe chemical processes and demonstrate instruments, procedures, and skills pertinent to the lab. In order to instruct experiments to people learning the practical parts of chemistry, movies are frequently employed. As demonstrated by using problem-solving videos for general chemistry, learners can learn at a self-regulated pace. They may review the content whenever necessary with video technology. Managing the cognitive load of the video, maximizing the engagement of the video, and fostering active learning from the video are three factors that instructors should consider when using video as a teaching method (Brame, 2016). Videos may be a powerful educational tool because they are often the foundation of blended learning strategies. Various techniques and delivery methods are used in video-based chemistry laboratories, such as straightforward video footage, storylines lab compilations, and real-time delivery (Karayilan et al., 2021).

Table 5. Video-based Technology in Chemistry Instruction

SN	Authors	Publishers	Scope of chemical activities
1	Altowaiji et al. (2021)	Chemistry Education Research and Practice	General chemistry
2	Box et al. (2017)	Journal of Chemical Education,	Organic Chemistry
3	Cresswell et al. (2019)	Journal of Chemical Education,	Organic and analytical chemistry
4	Pulukuri & Abrams (2020)	Journal of Chemical Education,	Solubility
5	Jones et al. (2021)	Journal of Chemical Education	General chemistry laboratory courses (CHEM 1211, 1212, & 1310)
6	Nadelson et al. (2015)	Journal of Science Education and Technology	Organic Chemistry
7	Howitz et al. (2020)	Journal of Chemical Education	General & Organic Chemistry
8	Demissie et al. (2013)	American Journal of Chemistry Education	General & Organic Chemistry
9	Ranga (2017)	Journal of Chemical Education	General Chemistry
10	Delaviz & Ramsay, (2018)	Proc. 2018 Canadian Engineering Education Association (CEEA-ACEG18) Conf	engineering chemistry

The authors employed videos to facilitate instructions in several chemistry topics, as shown in Table 5. According to this review, researchers use five video technologies related to general chemistry, four to organic chemistry, one to analytical chemistry, one to physical chemistry, and one to engineering chemistry.

It is obvious that most teachers use videos for common practical and non-practical areas of the curriculum, like general and organic chemistry. For example, a video-modified platform called “Edpuzzle” was used by Pulukuri & Abrams (2020) to teach the concept of solubility in a chemistry classroom at Boston University. Moreover, Nadelson et al. (2015) researched to determine the influence of the addition of instructional videos on student preparation, performance, and achievement associated with their engagement in organic chemistry laboratory activities with the aid of instructional videos. Furthermore, at the University of California, Irvine (UCI), Howitz et al. (2020) replaced general & organic chemistry experimental work with videos.

The findings of studies involved in this review reveal that videos improve the comprehension ability and performance of students in the subject (Demissie et al., 2013), deep learning and improve students' ability (Box et al., 2017), better prepare for the laboratory activities (Altowaiji et al., 2021); highly suitable for teaching purposes (Cresswell et al., 2019)

Digital Game-Based E-Resources for Chemistry Instruction

Using games to teach ideas or impart skills to students who would otherwise struggle in a regular classroom is known as game-based learning (GBL). Students can study a subject, review the rules, and locate patterns based on the correctness or errors in their responses when games help them understand complex concepts (Gupta, 2019). The easiest games to make and utilize for teaching and learning are physical ones, such board games, puzzle games, and card games. These games can be created with common things and require little technical expertise. For people of all ages, digital gaming has become one of the most exciting types of entertainment. Video games and computer-based games' elements are combined in digital educational games, which are software programs. Digital educational games are a fundamental education innovation that can improve students' learning and skill development.

The reasons why people find digital educational games appealing include their entertaining elements combined with a pleasant environment, their aesthetic quality (graphics, effects, and music), the presence of a structured framework, their learning objectives (also presented as problems requiring solutions), and the presence of the gaming element (also causing the strong participation of the learner). Digital educational games don't make having fun and enjoyment their primary goal, but its setting incorporates educational material in a pleasant and challenging style that encourages active learning.

As shown in Table 6, the review studies facilitated learning and teaching chemical topics using Kahoot!, Molebots, and the Symperid board game. Chemical symbols, nomenclature, elemental periodicity, Molecular weight, elemental quantum chemistry, acid-base and reduction-oxidation equilibrium, colligative properties of solutions, and reaction kinetics are some ideas. The results show that including game elements in lessons results in learner satisfaction, motivation, and interest stimulation, offering an alternative method of presenting subject matter and inspiring students regardless of their gender, age, or educational level (Aliyu, 2022; Aliyu et al., 2021; and Gupta, 2019).

Table 6. Game Element in Learning/Teaching of Chemistry Concepts

SN	Authors	Publishers	Technological Resources	Scope of Exploration
1	Aliyu (2022)	4th International Göbeklitepe Scientific Research Congress. Organized by International Science and Art Research Center (ISARC)	Kahoot!	Philosophy of Chemistry
2	Gupta (2019)	ACS Symposium Series	Molebots	Nomenclature, or naming chemical compounds
3	Aliyu et al. (2021)	International Journal of Asian Education,	Symperiod Board Game	chemical symbols and periodicity of elements
4	Murciano-Calles (2020)	Journal of Chemical Education	Kahoot!	elemental quantum chemistry, acid-base and reduction-oxidation equilibrium, colligative properties of solutions, and reaction kinetics
5	Sanga Lamsari Purba et al. (2019)	Jurnal Pendidikan Kimia	Kahoot!	General chemsitry
6	Youssef (2022)	Journal of Chemical Education	Kahoot!	General chemistry
7	María et al. (2018)	4th international conference on higher education advances (HEAD'18)	Kahoot!	General chemistry
8	Ghawail & Yahia (2022)	Procedia Computer Science	Kahoot!	Molecular weight

Other instructional games that can facilitate learning of chemical concepts include ChemCompete, Chemistry Gears, Build a Molecule (Molecularium), ChemCaper, CheMoVEr, Bingo, Old Pro, Common Sense Media, and Sheppard.

Conclusion

The study is a systematic review that looked at several technological tools used by academics to support 21st-century chemistry classroom instruction and lab experiments. Different databases, search engines, journals, and libraries were searched to obtain the most recent and relevant studies from 2012 to 2022. The result reveals that the VR2E2C system, Authentic Intelligent Robotics for Chemistry (AIR-Chem), and LEGO-based automation device were the robotics tools used by researchers to facilitate classroom instruction of chemical concepts, including inorganic and general chemistry. It also reveals that the type of web resource that is integrated with an LMS, such as Google Classroom, Edmodo, Mooc, Moodle, and others, is the one that is utilized most frequently. Furthermore, the findings reveal that the virtual laboratories used for facilitating chemistry instruction include the Virtual Reality Multisensory Classroom (VRMC), Blackboard Learning System (BLS), PhET interactive simulation, ChemVLab+, and Interactive Molecular Dynamics in Virtual Reality (iMD-VR). Other findings reveal that computer and mobile device software applications used by researchers include Elements 4D, MoleculAR, iMolview Lite, MATLAB, Courseware, and CHEMTrans. The study concluded that technological advancement in the twenty-first century revolutionized chemistry instruction, making it more realistic than abstract.

Recommendations

The study recommends that all chemistry teachers learn how to use these online resources for the instruction of laboratory concepts to supplement if not completely replace, face-to-face or direct laboratory experiments in school laboratories. Moreover, researchers need to test other digital software tools yet to be presented in academic journals and databases. Some could be more relevant and effective in facilitating classroom instructions or laboratory experiments.

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