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Review

Pedagogy of Emerging Technologies in Chemical Education during the Era of Digitalization and Artificial Intelligence: A Systematic Review

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Abstract: The technological advancement and rapid development of artificial intelligence have led to a growing number of studies investigating pedagogical innovations incorporated with emerging technologies in this digital era. An increasing amount of empirical evidence has suggested the potential benefits of incorporating digital technologies and artificial intelligence in various educational contexts, such as the K-12 education, and a change in learning modality in the unprecedented period of COVID-19. In chemical education, various types of emerging technologies, such as eye-tracking techniques, learning analytics, robotics, virtual reality (VR), and augmented reality (AR), have seen wide applications and promising prospects. In this paper, a systematic review of emerging technologies adopted in chemical education during this era of digitalization and artificial intelligence is presented. The current study aims to identify the major types of technologies adopted in chemical education and analyze the empirical findings from relevant studies. A total of 45 studies between 2010 and 2021 were analyzed through a literature search in three inter-disciplinary databases: Web of Science, Scopus, and the Educational Information Resource Center. Full-text retrieval and analysis of the included studies were conducted. The present study finds that AR and VR applications were most extensively investigated among the identified types of technologies adopted in chemical education, while the major focus areas were associated with virtual chemistry laboratories, visualization and interaction with chemical structures, and classroom hands-on activities. The evidence presented in this study also indicates the promising applications of artificial intelligence and learning analytics in the analysis of students' feedback and behavior, assessment of students' understanding of chemical concepts, and investigations of students' reasoning and cognitive processes during chemical tasks such as spectral interpretation. Furthermore, areas requiring more research, investigations, potential future applications, as well as pedagogical implications of education for sustainable development will be identified based on the evidence presented in this study. The findings of this study are expected to give insight on the evolving areas of chemical education research and technology-enhanced teaching and learning.

Keywords: digital technology; eye-tracking; learning analytics; augmented reality; virtual reality; artificial intelligence; chemical education; sustainability; K–12 education; pedagogy

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1. Introduction

Recent years have witnessed fascinating development in digital technologies and their incorporation in different educational contexts. Remarkable examples of emerging technologies adopted in teaching and pedagogical research include eye-tracking techniques, learning analytics, virtual reality (VR), and augmented reality (AR). For example, three-dimensional VR, providing an immersive experience of a digital environment for users to experience, is considered a contemporary innovative tool with highly promising prospects in education [1]. In fact, a growing body of research studies have suggested that VR applications will bring substantial benefits to K–12 education (from kindergarten to 12th grade, often referring to the combination of elementary, primary, and secondary education for students aged approximately from 5 to 18 years) [2]. Meanwhile, the surging advancement of technology is also important to current education, as exemplified by the rapid transition from traditional classroom teaching into online teaching due to COVID-19 [3]. The change in teaching and learning modalities during the pandemic has been largely supported by the evolving digital technologies. Likewise, technological advancement also plays a critical role in the enhancement of chemical education. In the teaching of chemistry subjects, the use of digital technologies is expected to further enhance the delivery of specific topics which involve extensive use of structural drawings for explanations [4].

In this paper, a systematic review of emerging technologies adopted in chemical education during this digital era is presented. The present study aims to identify different types of technology developed or applied in chemical educational research. The focused application areas and measured aspects of the included studies will be discussed. Analysis on the outcomes and findings of the included studies will shed light on the learning impact brought by technological applications. The pedagogical implications of sustainable education and relevant research perspectives in the era of digitalization and artificial intelligence will be further discussed.

2. Materials and Methods

2.1. Literature Search

The systematic review was carried out with reference to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [5]. The methods included the following major stages:

A Planning: defining the major research questions;
B Search: defining the database sources of the literature search, search strings employed in the search strategies, and inclusion and exclusion criteria, followed by the literature search and selection;
C Literature analysis and report formulation: full-text review and analysis of included studies, data extraction, and interpretation of results.

Searches were conducted in three electronic databases: Web of Science (WoS), Scopus, and ERIC (via EBSCOhost). The review focused on the adoption of emerging technologies in chemical education with topics and content relevant to K–12 education in the age of artificial intelligence (AI), analytics, and the Internet of Things (IoT). The major research questions (RQs) that the current study addresses are the following:

RQ1: What types of technology have been developed or applied to the teaching and learning of chemistry?

RQ2: What are the major application focuses and aspects of measurement for the use of technology in chemical education, as identified from the analysis of the included studies in this review?

RQ3: What are the effects of the adoption of technology in chemical education in terms of the outcomes and findings identified in the present literature review?

The search strategies employed the use of a series of technology terms: "artificial intelligence, learning analytics, Internet of Things, machine learning, deep learning, robotics, cloud computing, big data, eye tracking, smart classroom, augmented reality, augmenting reality, virtual reality, mixed reality, digital technology, AND chemistry education, chemical education".

The search strings were used in combinations in each electronic database, and the retrieved articles were further extracted to EndNote (version 20) (Clarivate, Philadelphia, PA, USA).

2.2. Study Selection

Restrictions on the publication year were applied. The time interval of the publication years was from 2010 to 2021. In addition, any non-English studies were excluded. If a full-text version could not be accessed, the paper was also excluded. The eligibility criteria for the review included evaluation studies of relevant technologies adopted in chemical education during the age of AI, analytics, and the IoT. In the current study, the exclusion criteria were (1) studies that were not chemical education research; (2) studies with scopes outside the current review focus (or not related to fundamental chemistry topics); and (3) non-English articles.

3. Results

Search Results

The PRISMA flow diagram for the current study selection process is illustrated in Figure 1. The search strategy described in Section 2 identified 534 articles through the corresponding searches in the three database systems, and 40 duplicated records were removed. After initial screening, 286 articles were excluded, and 208 records were retrieved for full-text screening based on the inclusion and exclusion criteria described in Section 2. Finally, 45 articles were included in this review. Full-text analysis of the 45 included studies was conducted. The results are presented in the major categories of author and publication year, types of technology, scopes of application, brief descriptions, study focus or aspects measured, sample size or participant details, intervention type or design, and outcomes or major findings. The findings are summarized in Tables 1 and 2.

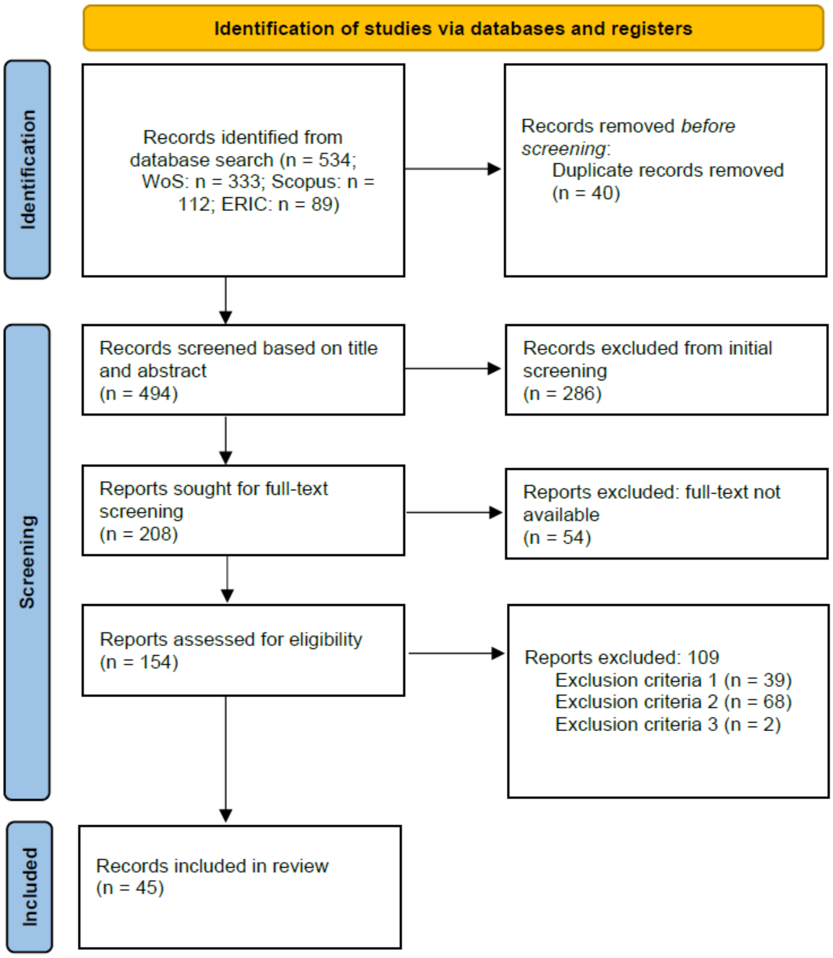

Figure 1. PRISMA flow diagram highlighting the study selection process in this review.

Table 1. Summary of included studies in this review.

Reference Number	Author	Year	Types of Technology	Scopes of Application	Brief Descriptions
[6]	Ali et al.	2014	VR	High school experiments	A multimodal virtual laboratory (MMVL) was developed and evaluations supported a high degree of usefulness and efficiency for practical learning of chemistry in high schools.
[7]	An et al.	2020	AR	General chemistry experiments	Augmented reality in educational laboratory (ARiEL) was used for connecting students to information on scientific equipment through AR technology. Usability evaluations revealed the ease of use and students' preference in using the application to access information on scientific instruments. The findings also supported the use of the application led to reduced anxiety in the course of instrumental operations.
[8]	Aw et al.	2020	AR	Visualization of molecular structures	A mobile application "Nucleophile's Point of View" (NuPOV) was developed to address the limitations presented by two-dimensional representations when teaching molecular structures. The novel app is unique in nature which allows students to have spatial interaction with the molecules by hand in a self-directed learning. The findings supported a good receptivity of the mobile app and increased confidence of students in understanding nucleophilic reactions.
[9]	Badilla-Quintana et al.	2020	AR	Academic achievement in secondary school chemistry	The results of pre- and post-tests showed that the incorporation of AR technology improved the academic achievement in the learning of chemistry by secondary school students. The study also suggested implications for the use of AR as a sustainable technology of inclusive education.
[10]	Chen and Liu	2020	AR	Chemical elements and their reactions	The learning activities incorporated with the use of AR helped to improve the fundamental understandings of chemical elements and lead to long-lasting enhancement of individual interest.
[11]	Edwards et al.	2019	VR	Molecular organic chemistry	A VR Multisensory Classroom (VRMC) was developed to provide an immersive and multisensory learning experience in molecular organic chemistry through natural hand motions (haptic experience) in a virtual environment. Both the quantitative and qualitative usability results supported enhanced motivation and engagement of students through the haptic experience with VR.
[12]	Ferrell et al.	2019	VR	Introductory organic chemistry	A VR learning activity, encompassing real-time and immersive interactive experience of molecular dynamics, was implemented in an introductory organic chemistry subject. Evaluations showed that the use of the VR educational tool and activity enhanced the motivation and learning gains of students.
[13]	Fung et al.	2019	VR	Environmental chemistry	Web-based VR technology was applied for the conduction of a virtual overseas field trip. The results of the evaluation survey indicated good student perceptions regarding the VR application in the virtual field trip.
[14]	Gandhi et al.	2020	VR	Molecular concepts	The SimView system was designed to provide a new type of interactive laboratory learning experience. Student feedback indicated increased interests towards the chemistry curriculum topics regarding molecular chemistry and thermodynamics.
[15]	Kodiyah et al.	2020	AR	Conformation of alkanes and cycloalkanes	Results from the pre-test and post-test analysis suggested improvement of students' spatial ability and understanding of conformational knowledge in alkanes and cycloalkanes.

Table 1. *Cont.*

Reference Number	Author	Year	Types of Technology	Scopes of Application	Brief Descriptions
[16]	Lu et al.	2021	AR	Real-life chemistry	An AR app was developed as a pedagogical tool for the facilitation of students' online self-learning. The survey study of students' attitudes towards the application of AR suggested positive impacts on enhancement of awareness, engagement and understanding in the learning of everyday life chemistry.
[17]	Rodriguez et al.	2021	AR	Molecular structures and reactivity dynamics	MoleculARweb, an open website providing interactive AR apps, was introduced for the exploration of molecular structures, reactivity and dynamic interactions. Results from in-class and online surveys indicated good perceptions from users and supported enhanced learning engagement.
[18]	Shen et al.	2019	AR	Foundation chemistry in junior high school	The incorporation of AR in teaching fundamental concepts of middle school chemistry helped to enhance student learning of microscopic concepts by harnessing the technology to establish connections with microscopic particles and improve the understanding of abstract concepts.
[19]	Suleman et al.	2019	VR	Reaction rates	VR learning media for three-dimensional visualization was developed for the learning of reaction rates in senior high school chemistry. The findings supported that the AR technology adopted would increase students' understanding and motivation.
[20]	Ucar et al.	2017	VR	Chemical bonds	Haptic applications developed in virtual environments were found to have positive effects on the learning of chemical bonding by gifted students of 6th and 7th grades when compared to traditional teaching.
[21]	Chao et al.	2016	Mixed reality	Experiments regarding gas laws	Sensor-augmented virtual labs were employed to promote the learning experience and understanding of gas laws by high school chemistry students. The analytic study of the pre- and post-test results suggested using mixed reality technology enhanced students' connections between macroscopic concepts and processes, thereby leading to learning gains in relevant scientific concepts.
[22]	Duan et al.	2020	Mixed reality	Virtual chemistry laboratory	A virtual laboratory system with specialized display and hand controller devices was developed to get students familiarized with proper procedures and safety issues when conducting chemical experiments. Evaluation study showed that the combination of AR and VR technologies in the system provided students with an immersive virtual environment for laboratory learning.
[23]	Dunnagan et al.	2020	VR	Instrumentation-based organic chemistry experiments	A VR laboratory on infrared spectrometry was designed and evaluated. The results indicated no significant differences were observed in the attainment of learning outcomes between the experimental group and control group of students. The study also supported the feasible use of VR technology for learning chemistry experiments requiring instrumentations in situations when distance education is required.
[24]	Gan et al.	2018	AR	Gas generation reaction experiment	The augmented reality application is employed to simulate the experiment on the redox reaction between hydrogen peroxide and bleach solution. The feedback from high school students was positive. The tool was useful for students to learn experimental skills and led to possible reduction of anxiety when handling chemicals.

Table 1. *Cont.*

Reference Number	Author	Year	Types of Technology	Scopes of Application	Brief Descriptions
[25]	Hu-Au and Okita	2021	VR	Experiment comprehension and safety knowledge	Comparisons were made between students' learning in VR and real-life chemistry laboratories. Results showed that there were no significant differences in terms of laboratory skills, safety knowledge and general chemistry content. However, clean-up behaviours were less common for students engaged in VR learning.
[26]	Isabwe et al.	2017	VR	Basic chemical bonding knowledge and experiments	VR technology was utilized to set up experiments for learning basic knowledge of chemical bonding. Usability evaluations supported the practicability and cost-effectiveness of the technology.
[27]	Jagodziński and Wolski	2015	VR	Junior high school chemistry experiments	Kinect sensor, an example of Natural User Interface, was used to detect and analyze students' hand movement when they were experiencing simulations of performing experiments in a virtual environment. The combination of the techniques has led to increased engagement in learning and improved self-efficacy when working with peers in laboratory work.
[28]	Pan et al.	2021	Mixed reality	Virtual chemical experiments based on the needs model	MagicChem, a comprehensive mixed reality system based on needs theory, was developed to provide a safe virtual environment for students' learning of chemicals. The system was also found to better satisfy the needs model when compared with other MR experimental environments.
[29]	Su and Cheng	2019	VR	Sustainable innovation learning model	A simulation game based on virtual reality chemistry laboratory was developed and a sustainable innovation experiential learning model was suggested and incorporated for investigating the learning effectiveness. The findings from survey analysis and pre- and post-test results found that experiential learning and learning motivation are important for enhancing academic achievement.
[30]	Zhang et al.	2021	AR	Experimental education	A virtual multimedia environment with AR experiment authoring tools was designed and created for experimental education. Evaluation study supported improvement in learning motivation and understanding through the participation of educational activities supported by AR technology.
[31]	Gerber et al.	2017	Robotics	Experimental education	Lego-based robots were designed which could perform liquid-handling functions and expected to support experimental education covering a diversity of science and chemistry experiments.
[32]	Lu et al.	2021	Robotics and VR	Experimental education	The Virtual Reality Remote Education for Experimental Chemistry (VR^2E^2C) system was introduced for remote chemical education incorporated with VR experiments. The system enabled users to opt for controlling the intelligent robot to conduct the experiments or choose for experiment demonstration by the system. The development of the system supported distance learning of experimental topics in a safe and fault-tolerant virtual laboratory setting.
[33]	Connor et al.	2019	Eye tracking	Spectral interpretation in organic chemistry	Students' eye movements during spectral interpretation were tracked. Problematic constraints on reasoning during the interpretation of spectrum were identified by analyzing the statistical results.

Table 1. *Cont.*

Reference Number	Author	Year	Types of Technology	Scopes of Application	Brief Descriptions
[34]	Cullipher et al.	2015	Eye tracking	Structure–property relationships	Quantitative analysis of data from eye-tracking study and qualitative analysis of results adopting a think-aloud interview protocol were used in combination to identify the underlying assumptions concerning structure-property relationships which would put constraints on students' reasoning.
[35]	Karch et al.	2019	Pupillometry	General chemistry	Pupillometric data were used together with gaze data for identifying the cognitive load when student participants were answering Chemical Concepts Inventory (CCI) questions. Measurements of pupil dilation was found to be of promising uses in revealing important information regarding cognitive processing.
[36]	Nehring and Busch	2020	Eye tracking	Chemistry demonstrations	The findings of the study supported that the visual attention focuses of students would be affected by the demonstration set-up including the apparatus sequence direction. This is of particular importance to be considered when the demonstrating experiment contained several processes with steps building upon each other.
[37]	Pienta	2017	Eye tracking	Molecular representations	Eye-tracking studies have been applied to analyze students' use of the visual interface of the web-based tools, and for the study of molecular representations and data interpretation.
[38]	Sweeder et al.	2019	Screencasts, simulations, and eye-tracking	Collision theory and kinetics	Results of eye-tracking studies indicated that students' interest and engagement were strengthened when screencasts were used rather than simulations alone.
[39]	Vandenplas et al.	2021	Screencasts, simulations, and eye tracking	Chemical bonding	Screencasts and simulations were applied in the learning of energy concepts in chemical bonding. Eye-tracking studies were employed to investigate difference of cognitive load for the adoption of screencasts and simulations.
[40]	Tang et al.	2014	Eye tracking	Stoichiometry	Eye-tracking experiments were used to identify students' problem-solving protocols. The results confirmed eye fixation durations were different between student participants having different extents of success in solving chemistry word problems.
[41]	Tang and Pienta	2012	Eye tracking	Gas law problems	Eye-tracking technology is useful for investigating the effect of question difficulty level and cognitive processes when solving gas law word questions. The study found that unsuccessful students spent more time looking into the solution details while recording a longer fixation on the questions as compared to the students having a higher score.
[42]	Williamson et al.	2013	Eye tracking	Ball-and-stick model	A pilot study harnessing the eye-tracking technology was conducted to investigate the time spent on the ball-and-stick images and electrostatic potential maps when addressing different types of chemical questions.
[43]	Adji and Hamda	2019	Learning analytics	Online chemistry courses	Learning analytics were used to assess the extent of student participation in online learning of chemistry subjects. Various items were measured including the number of accesses by each student on tutorial material and number of responses made by each student in the online discussion forum.
[44]	Lim et al.	2017	Learning analytics	Chemistry laboratory	The learning analytics of social media apps such as Instagram and Snapchat were discussed and pedagogical insights on the use of social media for laboratory teaching were highlighted.

Table 1. *Cont.*

Reference Number	Author	Year	Types of Technology	Scopes of Application	Brief Descriptions
[45]	Liu et al.	2018	Learning analytics	Chemistry Virtual Lab tutoring system	A generalizable multi-step approach was developed for more efficient use of temporal data collected from student engagement in a Chemistry Virtual Lab tutoring system.
[46]	Noyes et al.	2020	Learning analytics	London dispersion forces	A coding scheme was adopted to characterize students' answers in explaining the origin of dispersion forces. It was intended for the development of machine learning resources which would enable the analysis of large sample of student participants. The resources developed from the learning analytics would be useful for analytics of more complicated open-ended assessment which served as important reference to improve the learning process.
[47]	Pillutla et al.	2020	Learning analytics	Massive open online courses (MOOCs)	An interaction analysis model (IAM) was developed for tracking the progress of learners in MOOCs. The IAM developed can help instructors identifying learning issues and enhance the attainment of intended learning outcomes in the chemistry courses with large number of participants.
[48]	Russell et al.	2020	Learning analytics	Introductory chemistry	The learning analytics platform Elements of Success was employed to provide students with weekly feedback on their performance. The findings suggested a positive effect on academic performance for at-risk students who used the analytics platform when enrolling in an introductory chemistry course.
[49]	Dittmar and Eilks	2019	Internet forum analytics	Secondary school chemistry	A survey was conducted to investigate the usage of Internet forums by lower secondary school students with regards to chemistry-specific topics. The analytical findings suggested Internet forums may serve as a good educational platform to engage students in learning chemistry.
[50]	Seibert et al.	2019	Information and communications technology (ICT)	High school chemistry experiments	A novel teaching approach, EXPlainistry (experiments explained in chemistry), was presented. The method was primarily based on the use of ICT in the documentation, explanation and visualization of chemical experiments.

Table 2. Summary of included studies in this review.

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[6]	Development of a multimodal virtual laboratory and evaluation of the learning impact based on a selected experiment (standardization of sodium hydroxide)	14 students (10th grade)	Questionnaire	A novel MMVL, supported by a "wiimote" controller as an input device for the virtual hand motions, was developed for the learning of high school chemistry. The system was well perceived by the user participants as a helpful tool with a comprehensible interface and ease of operation. A significant difference between the academic performance of the user and non-user groups was observed in the evaluation study. Students who used the MMVL achieved a mean success rate of 83.5% in learning compared with that of 32.7% for the control group. The analytical findings indicated the usefulness and efficiency of the technological tool to improve learning of chemical experiments and knowledge.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[7]	Development of an AR-application for learning practical chemistry based on a selected experiment (pH measurement)	104 (university students)	Focus group study and attitude measurement survey	Remarkable differences were observed between the pre- and post-survey. A 4% increase was obtained in the intellectual accessibility subscale, while there was a 6% decrease in the anxiety score, indicating higher perceived intellectual accessibility and reduced anxiety when using the instruments.
[8]	Investigation of the learning experience in the visualization of molecular structures through an AR mobile app	87 (university students)	Pre- and post-trial surveys	An AR mobile app allowing students to visualize and interact with 3D molecules was developed to facilitate self-directed learning, and 45% of students felt more confident in their learning of the nucleophilic addition mechanism after using NuPOV to engage in the experience of spatial interactions with the participating molecules in a reaction.
[9]	Immersive learning for students with and without special education needs (SEN)	60 female students in chemistry (12th grade)	Pre-, post- and follow-up tests	Improved academic achievement through integration of augmented reality was supported by an increase of mean values from 3.65 (SD = 1.21) pre-test to that of 5.21 (SD = 1.15) post-test.
[10]	Hands-on AR activities to learn elements and chemical reaction concepts	104 students (9th grade)	Pre-, post- and follow-up tests, questionnaire	The AR activities were found to have more significant enhancement of students' learning of chemical reaction concepts than the control group, with a medium effect size. The results from the follow-up test also supported the long-term beneficiary effects in learning.
[11]	VR Multisensory Classroom for learning molecular organic chemistry	13 users (aged 12–36 years)	Quantitative survey and qualitative open-ended responses	More than half of the participants' ratings were "high" or "very high" for their overall perception in terms of the system's ability to support multisensory instruction, motivation and engagement, haptics, and adequacy of the system as an instructional tool. The qualitative part of the study described the participants' perceptions toward the general design of the system as impressive, interesting, and educative, with promising potential to serve as an instructional tool in the teaching of organic structures and bondings.
[12]	VR lab activity to pull a methane molecule through carbon nanotubes	155 students enrolling in a university introductory organic chemistry course	Questionnaire to experimental group (70) and control group (85)	Students' opinions of the lab activity were assessed. Significant positive results were observed for students that participated in the VR lab activity. There was a 58.8% increase for students strongly agreeing with the usefulness of the lab in understanding the presented materials and 89.7% and 53.1% increase for questions assessing students' interest in organic chemistry and carbon nanomaterials, respectively.
[13]	Application of VR in environmental chemistry education to conduct an overseas field trip	74 university chemistry students	Post-trip survey	Of the students, 64% rated 4 or 5 (good or very good) on a Likert scale their perceptions regarding the virtual field trip experience. Qualitative feedback revealed a general positive reception toward the app with some identified areas for improvement, such as disorientation and app limitations.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[14]	Visualization of molecular dynamics simulations via SimView, an AR/VR tool (teaching of phase diagrams from a molecular perspective)	10 high school students	Post-activity assessment	Most students were capable of correctly answering approximately 80% of the assessment questions. Qualitative feedback on the experience of the SimView workshop included students' views about VR on providing interesting learning of chemistry and enhancing their memorization of chemical knowledge.
[15]	Effect of AR media on improvement of spatial ability	University students of Chemical Education	Pre- and post-tests	The findings showed that the application of AR media on conformation of alkanes and cycloalkanes had positive effects on students' spatial ability. A moderate mean N-gain of 0.58 was reported to support the association between the use of AR media in learning and enhance spatial ability on the conformational structures.
[16]	Students' perceptions on the use of a novel AR software to support flipped and gamified learning	46 university students in an undergraduate chemistry course	Questionnaire	Students' perceptions of the developed AR software were assessed by a questionnaire adopting a 6-point Likert scale ("6" representing "strongly agree" and "1" representing "strongly disagree") for 4 constructs including learning attitude, user satisfaction, cognitive validity, and cognitive accessibility. Among the 4 constructs, the highest score of 4.72 was obtained for cognitive accessibility, while cognitive validity yielded the lowest one at 4.01. The need for further enhancement in the design or content of the AR software for a more fruitful learning experience was also identified in the study.
[17]	Hands-on activities based on AR web apps to learn chemical structures	32 teachers and 99 students participating in the online survey	Website analytics and survey	The website analytics recorded more than 14,500 accesses between May 2019 and January 2021 from all over the world. As for the analysis of the survey findings, regarding the pedagogical effect, 82% of the responses from teachers revealed a positive perception of using the AR web apps to help their students for a better understanding of the materials learned in class. In addition, 83% of the students also indicated that the website was very useful to them for achieving a better understanding of the subject.
[18]	Use of AR to teach atomic weight, molecular weight and mole number	8th grade students	Tests after each stage of teaching	The AR information technology was introduced in the teaching of fundamental chemical concepts and combined with the real-life experience of learners for a proper connection with imagination in the learning process.
[19]	Development of media of three-dimensional visualization using VR in teaching reaction rates	Material expert, media expert, chemistry teachers, peer reviewers, and students	Questionnaire	The media assessment, focusing on the major aspects of learning, material, audiovisual, and software engineering, revealed positive findings and yielded a total ideal percentage of 78%. The developed learning media can serve as a good teaching tool for reaction rates at senior high schools. Identified advantages of the VR application included enhancement of students' motivation in learning and facilitation of teaching demonstrations when there is a lack of equipment or a laboratory.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[20]	Efficiency of haptic applications developed in VR for the learning of chemical bonds by gifted students	52 gifted students	Questionnaire	A significant difference was observed between the experiment and control groups for the answers to the question regarding students' perceptions toward the use of VR applications. The students in the experiment group indicated greater enjoyment (mean = 4.87) from using the force feedback haptic application in VR to learn chemical bonds when compared with that of the control group (mean = 4.23).
[21]	Academic achievement on the learning of gas laws based on sensor-augmented virtual labs	30 students from two chemistry classes in a public high school (most in 10th or 11th grade)	Pre- and post-tests	There were significant gains observed from the test results when comparing between the experiment and control groups. Students learning in the augmented virtual lab environment also had better performance in some of the tested concepts on the physical and molecular properties of gases, which further supported the learning benefits of simultaneously connecting physical and virtual learning experiences.
[22]	Evaluation of mixed-reality chemistry lab for learning of experimental procedures and safety knowledge	45 university chemistry students	Questionnaire and interview	The mixed-reality virtual chemistry lab was evaluated from five perspectives: hardware equipment, immersive experience, educational effects, interaction accuracy, and equipment learning time. Reported advantages included enhanced student enthusiasm, simulation of experiments without actual consumption of chemical reagents and equipment, and repeated practice without overuse of chemicals. Meanwhile, limitations were also identified which included system delay, location perception, sense of reality, and eye fatigue due to prolonged use of VR equipment.
[23]	Learning of infrared (IR) instrumentation under VR or traditional lab conditions	75 university students	Post-test on experimental and control group	There were no significant statistical differences reported for the student performance for the learning of IR instrumentation under VR or traditional lab conditions. It was observed that the interactive VR experience was as effective as a face-to-face lab experience in terms of spectrometer operation and elucidation of simple features of IR spectrums.
[24]	Evaluation of learning experience for an AR experiment on oxygen gas generation	10 senior high school students	Survey	The survey results indicated an overall effectiveness of the AR experimentation tool, which also revealed that all students had rated "strongly agree" (20%) or "agree" (80%) the usefulness of the AR activity to prepare them for performing actual experiments which involved the use of oxidizing chemicals and flammable gases.
[25]	Comparison between the learning experience in real-life and VR chemistry labs	40 graduate students in education or arts	Pre- and post-tests	There were no significant statistical differences between the pre-test results of the experiment group and control group, while students learning under VR conditions showed a significant increase in performance for applying general chemistry knowledge from pre-test (mean = 70.2%) to post-test (mean = 76.5%).

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[26]	Perceived usability of VR prototype for learning chemistry based on a human-centered design process	Students and science teachers from high school	Observational study of user testing	Analysis of video recordings of user tests provided insights for revision of the user requirements and refinement of interaction design. The study also demonstrated a practical approach for the development of a VR prototype at a low cost for users to learn chemical concepts through interactive experimentation.
[27]	Effects of a chemical virtual laboratory on students' chemistry learning experience	100 students from junior and senior high school	Pre- and post-tests, diagnostic survey	The test and survey results indicated that for both junior and senior students using a virtual laboratory, the students' capabilities to solve laboratory problems and design new experiments increased. Students were more motivated to repeat real laboratory procedures and conduct extra experiments. The survey also found that practicing with a virtual laboratory increased their confidence and sense of effectiveness when conducting a real experiment in a physical laboratory.
[28]	User experience and learning effects of MagicChem, a mixed-reality experimental system based on a new needs model for virtual experiments	56 students from the 1st grade of a senior middle school	User test	The results of user tests demonstrated that MagicChem, in terms of system usability, user experience, and learning effects, outperformed two traditional mixed-reality environments, which only met the human-oriented virtual experiment needs model partially.
[29]	Effect of VR chemical experiments on sustainability innovation experiential learning	272 students (10th grade)	Pre- and post-tests, questionnaire	There were significant differences in the post-test between the experiment group (mean = 87.17) and control group (mean = 77.71). Students who learned under the virtual laboratory environment achieved significantly better scores. The findings of the study supported that experiential learning through the use of VR games and experiments engaged students' motivation and improved academic achievement.
[30]	Evaluation of AR-based multi-media environment for experiential education	Teachers and students from secondary school	User test (two question-naires for teachers and students)	From the questionnaire results, both teachers and students perceived the multi-media environment as a helpful tool for teaching and learning. The teachers gave a high rating (mean = 4.5) for the question addressing their willingness to use the authoring tool to create AR experiments. The highest mean score (4.83) was obtained in which students reflected that the AR technology in the experiment was interesting.
[31]	Utility of Lego-based liquid-handling robots in science and chemistry experiments	1st test group: 8 students (5th grade); 2nd test group: 9 middle school students	Two independent user studies	Lego-based pipetting robots based on low-cost household consumables were developed to support science and chemistry experiments. The robot-driven liquid-handling activities were tested in afterschool settings with elementary, middle, and high school students. The participating students were motivated and enjoyed the experiment activities. The overall rating of the robotics-supported course on a 1–5 (very bad–brilliant) Likert scale was 4.2.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[32]	Effectiveness of the VR^2E^2C system application in fundamental chemistry experiment	100 students (19–22 years old; sex ratio: 1:1)	Questionnaire	The VR system was evaluated almost equally well between male and female students. More than 80% of the students learned experimental procedures and methods under the system application, and around 90% of the students indicated their desire to continue the learning mode supported by VR and robotics technology. The findings also revealed that a higher percentage of male students was interested in VR education than female students.
[33]	Investigation of students' reasoning during a series of spectral interpretation tasks	18 university students	Retrospective think-aloud (RTA) interview and eye tracking	The constraints on organic students' reasoning during spectral interpretation were investigated by the RTA protocol paired with eye tracking. The analysis of this pilot study adopting the combined methodology identified 8 heuristic reasoning strategies and 20 invalid chemical assumptions from the spectral interpretation tasks, which were further categorized into 5 main themes. The data collection methodology presented in the work was considered to serve as a valid and promising tool for investigation of students' reasoning when performing complex chemical tasks.
[34]	Investigation of students' reasoning when relating IR spectroscopic responses to molecular structures	20 undergraduate and 6 graduate students	Think-aloud interview and eye tracking	Three implicit chemical assumptions were identified in the qualitative study, including atoms as components (32%), bonds as components (28%), and bonding (40%). The quantitative findings of eye tracking, based on the analysis of the sequences of fixations and areas of interest (AOIs), provided further important information on students' reasoning when addressing the relationships between spectroscopic responses and molecular structures.
[35]	Investigation of cognitive processes when solving chemical problems	22 undergraduate students enrolling in a general chemistry course	Eye tracking (gaze and pupillometric data)	This study investigated the use of pupillometric data and gaze data to reveal useful information about cognitive processes and changes when faced with a chemical problem. The methodology based on pupillometry and epoch analysis served as a promising tool in chemical education research for studying the effects on cognitive load associated with tackling Chemical Concepts Inventory (CCI) questions.
[36]	Analysis of effects on students' eye-movement sequences and patterns due to variations in the sequence complexity and set-up arrangement in teaching demonstrations	146 students from 2 secondary schools	Eye tracking	For the experiment demonstration setting used in the study, there were more eye movement sequences located from left to right (mean = 4.24) than from right to left (mean = 2.39). In addition, it was found that with increasing sequence complexity, the number of eye movement sequences decreased. The findings of the study also supported the assumption that setting up a demonstration according to the left-to-right principle may help to align students' eye-movement patterns with an intended reaction flow.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[37]	Investigation of student behavior, reasoning, and problem-solving skills	University students enrolled in introductory chemistry, general chemistry, and organic chemistry courses	Quantitative analysis of data from browser-based tools and eye-tracking study	Data on the use of the Lewis structure drawing tool were obtained for students enrolling in three different chemistry courses. The percentages of error and drawn structures were analyzed. The findings of the study suggested that structure complexity is related to student success. In addition, eye-tracking studies provided further analysis on students' use of web-based tools as well as the time spent on AOIs when answering the word questions.
[38]	Impacts of screencasts or simulations on students' learning of collision theory and reaction rates; investigation of focused parts between the assignment and electronic resources	27 students for eye-tracking study	Pre- and post-tests, eye-tracking study	The findings of this study suggested that screencasts and simulations were equally effective, both leading to similar learning gains. Furthermore, the study also investigated how students' attentional focus changed when working on an assignment and interacting with a simulation or screencast. Statistically significant correlations were observed between the total fixation time and the number of fixations for both the assignment and electronic resources. It was also found that all students, whether using a screencast or simulation, spent more time (around 60% viewing time) on the resource than with the assignment.
[39]	Effects of simulations and screencasts on the learning of energy concepts in chemical bonding	Classroom study: 302 undergraduates; eye-tracking study: 16 undergraduate students	Pre- and post-tests, eye-tracking study	There was a statistically significant increase in the score (from 1.39 to 1.83 out of 5) from pre-test to follow-up questions for all students in the treatment groups. However, regardless of using simulations or screencasts, students' overall scores were still below 40%. Based on the response analysis of each question, it was suggested that complicated concepts could not be easily mastered with a stand-alone intervention. Meanwhile, the eye-tracking study found that students provided with simulations spent more time viewing the questions compared with those with simulations incorporated with screencasts. This further suggested the use of a screencast as an introductory tool to lower cognitive demand and increase the feeling of easiness when answering the assignment questions.
[40]	Investigation of complexity factors in word problems of stoichiometry and identification of students' problem-solving protocols	Online tool: 2398 attempts from chemistry students at 2 universities; eye-tracking study: 13 university students in a general chemistry course	Online response tool, eye-tracking study	The complexity factors, number format, and unit were identified to have significant effects on students' correctness of answering the stoichiometry word problems. It was also found that the chemical equation complexity factor had a significant influence on the general chemistry group but not the introductory chemistry group. The eye-tracking study reported that less-successful students spent more time viewing the whole question region. The observation that uncommon terminologies in word problems did not distract the participants was explained by the ability to locate and analyze relevant information for solving the questions of familiar types, leading to a probable increase in the working memory load.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[41]	Investigation of the effects of complexity factors on students' ability to solve gas law word problems and the relationship between question difficulty and eye-tracking data	12 university students in an introductory chemistry course	Eye-tracking study	The study revealed that there was a marginally significant difference in the average time spent on each question, with unsuccessful students spending more time on the questions in general. When comparing the time of each problem-solving phase, there was no significant difference for reading or calculation between the successful and unsuccessful groups. The unsuccessful students spent significantly more time on planning. By analyzing the number of fixations on AOIs, the results indicated that the unsuccessful students re-read the question more frequently during the problem-solving phase.
[42]	Evaluation of students' use of ball-and-stick images against electrostatic potential maps when handling organic questions	9 university students in an organic chemistry course	Eye-tracking study	The research team reported on a pilot study to evaluate the use of multiple representations to answer particulate-level questions. It was observed that the students spent more time on ball-and-stick images when faced with the more difficult questions concerning a proton or hydroxide attack. However, in general, the more successful students spent more time on the electrostatic potential maps. Although the validity of the findings may be limited by the sample size of the study, the eye tracker is considered an effective tool in chemical education research, particularly when images are involved.
[43]	Evaluation of student interactions and participation in online learning of chemistry subjects	4 online subjects (2 of them each with fewer than 30 students; 2 of them each with more than 30 students)	Analytics of online learning activities	Analysis was based on major indicators including the number of overview accesses by students on each topic or the learning material, the number of student accesses in the reading of material in the discussion forum, and the number of student responses posted in the forum. Learning analytics provided information about the materials that were most read by students as well as the topics of discussion that were least accessed or responded to by students. The data obtained were useful for the design of program materials and activities to make improvements in teaching and learning.
[44]	Investigation of the learning analytics from the usage of Instagram and Snapchat in chemistry curriculum regarding laboratory learning	104 university chemistry students	Survey and analytics	A mid-semester survey after the incorporation of social technology tools (Instagram and Snapchat) in a laboratory module indicated that the videos and images uploaded to the platform enhanced students' retention of chemical knowledge (88%) and helped them to correct their mistakes (89%). The post-usage study also supported the relevant findings, with a majority of the respondents (87%) agreeing with the benefit of using the applications for their revisions. The findings on learning analytics supported that the incorporation of social technology tools in a chemistry module could enhance students' knowledge gains from visual learning.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[45]	Application of a multi-step generalizable approach to evaluate the learning of students engaging in a chemistry intelligent tutoring system	59 students at a high school enrolled in chemistry classes	Classroom study and multimodal data analysis	A multi-step generalizable approach was described for the qualitative and quantitative analysis of multimodal data collected from a classroom study having students engaged in a chemistry virtual laboratory intelligent tutoring system. First, "focal points" with considerable significance of in-depth analysis were identified based on visual or quantitative analysis of course-level learning trajectories, which were subsequently used for defining a temporal range of activities. The study also described open-source tools which were developed for the facilitation of extracting multimodal data to understand the learning processes when engaging in an intelligent tutoring system.
[46]	Characterization of students' explanations of the origins of London dispersion forces for development of machine learning resources	2030 responses from 4 groups of students from three university institutions	Machine learning	A total of 2030 student responses (explanations of London dispersion forces) from 3 institutions were collected and human coded. The coded responses were applied with machine learning algorithms for developing resources to code new responses as a human coder. In general, good agreement was achieved between the humans and the combined model, although there were errors in the codes of individual student responses. Based on the analytical findings, the developed machine learning tool was recommended for assessing group-level information rather than for high-stakes individual assessment.
[47]	Development of a model for automatic labeling of posts by students and evaluation based on its adoption in a chemistry massive open online course (MOOC)	Discussion data of a chemistry MOOC	Text mining and machine learning	Based on the first phase of the interaction analysis model (IAM), the research team developed a model for automatic labeling of students' posts in a chemistry MOOC. The best combination of parameter values gave a precision of 0.79744. The results suggested that based merely on the text, the developed model was able to infer correctly the IAM category for four out of five posts. The approach was also considered to serve as an intelligent system for generating actionable learning assessment data even with large enrollment.
[48]	Investigation of the relationship between students' use of Elements of Success (EoS) and academic performance of students at risk in General Chemistry I	Student data of General Chemistry I in two cohorts (N = 2864)	Learning analytics	Students' use of the learning analytics platform EoS was high (more than 90%). EoS provided students with updated and personalized subject performance information such as estimated grades. Based on the learning analytics, the study examined the risk of withdrawal and likelihood of obtaining higher final grades for at-risk students (high-risk group and moderate-risk group). For both risk groups, EoS users might have a higher motivation for engaging in the course compared with non-EoS users. A positive relationship was identified between students' use of EoS and their academic performance. In particular, a significant association was observed between the use of EoS by high-risk students and the achievement of higher grades. The learning analytics platform, which provided timely performance feedback, facilitated the decision of moderate-risk students to stay in the course.

Table 2. *Cont.*

Reference Number	Study Focus/Aspects Measured	Sample Size/Participant Details	Intervention Type/Design	Outcomes/Major Findings
[49]	Investigation of Internet forum usage behavior of secondary school students regarding chemistry-specific content	668 secondary school students (aged 12–17)	Survey	A questionnaire was used to evaluate the Internet forum usage behavior of secondary students with regard to chemistry and related science domains. The study reported that nearly all (>90%) of the student participants were well aware of general Internet forums (German language). On the other hand, only a small portion of participants (<10%) was aware of the chemistry-specific forums. Analysis of usage behavior revealed that students used forum sites in their leisure time (40.8%) for the purposes of school (48%) and homework (40.2%) assignments. While only some senior students posted questions (34.4%), the response rate by the students was low (around 14%), indicating passive learning and information gathering. As for the question intended to identify students' areas of interest when using the Internet forums, it was found that the most frequently selected topics were the human body and everyday life (45.2% and 41.5%, respectively), while societal or environmental issues only accounted for 13.1% of the total responses.
[50]	Evaluation of using ICT-based tasks in the method EXPlainistry	52 teachers, 24 student teachers, and 128 students	Survey	The ICT-incorporated method EXPlainstry, providing a new form of experiment documentation and visualization, was presented to 52 teachers, 24 student teachers, and 128 students from different school and university classes. Questionnaires for evaluation were administered to teachers and student teachers only. Statistical analysis indicated participants' positive perceptions toward EXPlainstry as a useful approach for performing similar functions to explanatory videos on the Internet.

4. Discussion

The findings were categorized into several major areas: AR, VR, robotics, eye tracking, and learning analytics. Among the 45 included studies, 25 studies (56%) focused on the use of AR, VR, or mixed-reality applications in the teaching of various chemistry topics, and 10 studies (22%) evaluated the adoption of eye-tracking techniques in chemical education, while the use of learning analytics was associated with 8 studies (18%). Two studies (4%) applied robotics in their investigations (Figure 2).

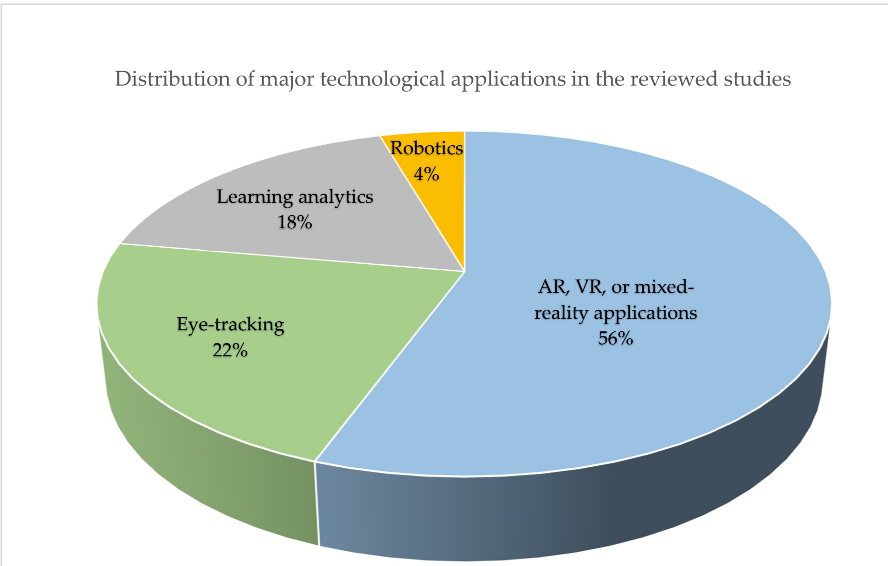

Figure 2. Pie chart showing the distribution of major types of technology adopted in the reviewed studies.

4.1. AR, VR, and Mixed Reality

AR and VR technologies have been commonly observed in the facilitation of molecular visualization, as well as laboratory simulations [30]. Regarding experimental learning, augmented reality in educational laboratories (ARiEL) was used for connecting students to information on scientific equipment through AR technology [7]. Usability evaluations revealed the ease of use and students' preference in using the application to access information on scientific instruments. The findings also supported that the use of the application led to reduced anxiety in the course of instrumental operations. Moreover, the AR application was also employed to simulate the experiment on the redox reaction between hydrogen peroxide and a bleach solution [24]. The feedback from the high school students was positive. The tool was useful for students to learn experimental skills and led to a possible reduction of anxiety when handling chemicals. In addition, VR has been employed in the teaching of high school chemistry experiments [26,27]. A multimodal virtual laboratory (MMVL) was developed, and evaluations supported a high degree of usefulness and efficiency for practical learning of chemistry in high schools [6]. Additionally, a VR laboratory on infrared spectrometry was designed and evaluated [23]. The results indicated no significant differences observed in the attainment of learning outcomes between the experimental group and control group of students. The study also supported the feasible use of VR technology for learning chemistry experiments requiring instrumentations in situations where distance education is needed. It is noteworthy that AR and VR have been used in combination for some reported studies of virtual laboratories, which also led to substantial learning gains [21,22,28].

In 2020, Aw et al. applied AR in the teaching of molecular structures [8]. A mobile application ("Nucleophile's Point of View" (NuPOV)) was developed to address the limitations presented by two-dimensional representations when teaching molecular structures. The novel app is unique in nature, which allows students to have spatial interaction with the molecules by hand in self-directed learning. The findings supported good receptivity of the mobile app and increased the confidence of students in understanding nucleophilic reactions. The results of a recent study showed that the incorporation of AR technology improved academic achievement in the learning of chemistry by secondary school students [9]. The study also suggested implications for the use of AR as a sustainable technology of inclusive education. Another recent study reported that the learning activities incorporated with the use of AR helped to improve the fundamental understandings of chemical elements and led to long-lasting enhancement of individual interest [10]. Very recently, an AR app was developed as a pedagogical tool for the facilitation of students' online self-learning. The survey study of students' attitudes toward the application of AR suggested positive impacts on enhancement of awareness, engagement, and understanding in the learning of everyday life chemistry [16]. Aside from that, it has been reported that the use of AR has led to improvement of students' spatial ability and understanding of conformational knowledge in alkanes and cycloalkanes [15]. There are also reports on the incorporation of AR in teaching fundamental chemistry topics and visualization of simple molecules, which led to enhanced learning engagement [17,18].

VR technologies have been employed in the teaching of molecular and introductory organic chemistry [11,12]. Notably, VR has also been used in the teaching of environmental chemistry [13]. Web-based VR technology was applied for the conduction of a virtual overseas field trip. The results of the evaluation survey indicated good student perceptions regarding the VR application in the virtual field trip. In 2020, Gandhi et al. reported the development of the SimView system [14]. The SimView system was designed to provide a new type of interactive laboratory learning experience. Student feedback indicated increased interest toward the chemistry curriculum topics regarding molecular chemistry and thermodynamics. VR is a versatile technology which has also seen application in the teaching of various topics, including reaction rates [19] and chemical bonds [20].

From the analysis presented in Tables 1 and 2, AR and VR applications focused on major areas such as visualization and interaction with chemical structures, chemical laboratories, and classroom hands-on activities. Overall, the research findings supported the associated benefits of adopting a variety of technologies in the teaching and learning of chemistry. Examples of identified learning impacts include enhanced motivation in the learning of practical chemistry and chemical concepts, as well as improvement in academic achievement. Meanwhile, the development of AR- and VR-based multimodal virtual laboratories can also enhance students' learning experiences and increase their enthusiasm in the learning of practical chemistry. Furthermore, the development of AR and VR virtual laboratories can lead to substantial benefits, including simulation of experiments without actual consumption of chemical reagents and equipment as well as repeated practice without overuse of chemicals. While there are investigations addressing the application of AR and VR in virtual laboratories involving the use of hazardous chemicals, the studies are limited in number. More research investigations and explorations are required for the technological applications in the context of STEM education and green chemistry education for a sustainable future. Similarly, with the limited number of studies in the application of AR and VR for inclusive education, more research studies are imperative in light of the critical issues regarding equity and education for sustainable development.

4.2. Robotics

The adoption of robotics is less frequently reported in chemical education research. In 2017, Gerber et al. reported the design of Lego-based robots which could perform liquid-handling functions and expected to support experimental education covering a diversity of science and chemistry experiments [31]. Very recently, in the study by Lu et al., the Virtual Reality Remote Education for Experimental Chemistry (VR^2E^2C) system was introduced for remote chemical education incorporated with VR experiments. The system enabled the user to opt for controlling the intelligent robot to conduct the experiments or choose an experiment demonstration by the system. The development of the system supported distance learning of experimental topics in a safe and fault-tolerant virtual laboratory setting [32].

4.3. Eye Tracking

Eye-tracking technology has been identified as a useful analytical tool in learning [42]. In the study conducted by Connor et al., students' eye movements during spectral interpretation were tracked [33]. Problematic constraints on reasoning during the interpretation of the spectrum were identified by analyzing the statistical results. In another study by Cullipher et al., quantitative analysis of the data from the eye-tracking study and qualitative analysis of the results adopting a think-aloud interview protocol were used in combination to identify the underlying assumptions concerning structure–property relationships which would put constraints on students' reasoning [34]. That aside, eye tracking has also been applied in the analysis of students' learning of various topics, including molecular representations [37], collision theory and kinetics [38], stoichiometry [40], and gas law problems [41]. Moreover, eye-tracking studies were also carried out on the adoption of screencasts and simulations in chemistry learning [38,39]. It has also been applied to study the set-up arrangement and apparatus sequence in chemistry demonstrations [36]. The findings of the study supported that the visual attention focus of students would be affected by the demonstration set-up including the apparatus sequence direction. This is of particular importance to be considered when the demonstration experiment contains several processes with various steps building upon each other. Furthermore, pupillometric data were used together with gaze data for identifying the cognitive load when student participants were answering Chemical Concepts Inventory (CCI) questions [35]. Measurements of the pupil dilation were found to be of promising use in revealing important information regarding cognitive processing.

4.4. Learning Analytics

Learning analytics were used to assess the extent of student participation in online learning of chemistry subjects. Various items were measured, including the number of accesses by each student of the tutorial material and the number of responses made by each student in the online discussion forum [43]. In addition, learning analytics can be applied to chemistry laboratory subjects. The learning analytics of social media apps such as Instagram and Snapchat were discussed, and pedagogical insights on the use of social media for laboratory teaching were highlighted in the article by Lim et al. [44]. In 2018, a generalizable multi-step approach was developed for more efficient use of temporal data collected from student engagement in a Chemistry Virtual Lab tutoring system [45]. Recently, a coding scheme was adopted to characterize students' answers in explaining the origin of dispersion forces [46]. It was intended for the development of machine learning resources which would enable the analysis of a large sample of student participants. The resources developed from the learning analytics would be useful for further analysis of more complicated open-ended assessment, which served as a important reference to improve the learning process. In addition, an interaction analysis model (IAM) was developed for tracking the progress of learners in MOOCs [47]. The IAM developed can help instructors identify learning issues and enhance the attainment of intended learning outcomes in chemistry courses with large numbers of participants. Another recent report has documented the use of an analytics platform to enhance students' academic performance [48]. The learning analytics platform Elements of Success was employed to provide students with weekly feedback on their performance. The findings suggested a positive effect on academic performance for at-risk students who used the analytics platform when enrolling in an introductory chemistry course. Aside from that, the use of Internet forums and ICT in high school chemistry learning has been investigated. A survey was conducted to investigate the usage of Internet forums by lower secondary school students with regard to chemistry-specific topics [49]. The analytical findings suggested that Internet forums may serve as a good educational platform to engage students in learning chemistry. Furthermore, a novel teaching approach, experiments explained in chemistry (EXPlainistry), was presented in a recent study [50]. The method was primarily based on the use of ICT in the documentation, explanation, and visualization of chemical experiments.

4.5. Pedagogical Implications and Research Perspectives

As discussed in the above sections, the use of emerging technologies in this digital era has led to substantial benefits in the teaching and learning of chemistry. However, mere adoption of technology in chemical education is not sufficient for successful chemical education. Chemistry, being a central science, plays a crucial role in sustainable development [51]. One of the ultimate goals in chemical education is to cultivate responsible citizens and develop awareness and appropriate actions for environmental sustainability. It is noteworthy that pedagogical implications are also important in achieving our educational goals. For example, systems thinking is a very promising pedagogy in chemical education [52]. More efforts and research studies are needed for the incorporation of digital technologies to facilitate the adoption of the systems thinking approach in chemical education for a sustainable future.

In addition, more investigations are recommended to promote active learning in a technology-enhanced learning environment. For example, the game-based learning approach has been established as an effective pedagogy [53,54]. Recently, a simulation game based on virtual reality chemistry laboratories was developed, and a sustainable innovation experiential learning model was suggested and incorporated for investigating learning effectiveness [29]. The findings from the survey analysis and pre- and post-test results found that experiential learning and learning motivation were important for enhancing academic achievement. More research is worth conducting to investigate the integration of new technologies for the innovative design of game-based activities in the learning of chemistry, either in a classroom setting or via an online study mode.

While the emerging technologies have been associated with considerable educational benefits, instructors should also take note of the potential drawbacks that may be encountered. In the study conducted by Hu-Au and Okita, AR was utilized in the simulation of experiments and teaching of safety knowledge [25]. Comparisons were made between students' learning in VR and real-life chemistry laboratories. The results showed that there were no significant differences in terms of laboratory skills, safety knowledge, and general chemistry content. However, clean-up behaviors were less common for students engaged in VR learning.

That aside, with the rapid advancements of technology and artificial intelligence, teacher development programs to enhance digital competency are necessary, while earlier teaching of programming in high school education has already started around the world [55]. In addition, technological advancement should also be used to facilitate chemistry learning in inclusive education.

5. Conclusions

In this paper, a systematic review of emerging technologies in chemical education during the age of AI, analytics, and the IoT was conducted. A search and review of the literature were carried out and applied in the context of technological applications in chemical educational research. The method of content analysis was applied to a total of 45 studies including conference articles, book chapters, and journal articles. The major types of technological applications identified in the reviewed studies included AR, VR, or mixed-reality applications for the teaching and learning of chemistry in various topics, eye-tracking experiments and the use of learning analytics in chemical education research, and robotics applications. Among these major categories, the AR and VR applications received the most interest, while only two studies related to robotics applications and experimentation were included in this review paper. The technological applications focused on major areas such as visualization and interaction with chemical structures, chemical laboratories, and classroom hands-on activities. Overall, the research findings supported the associated benefits of adopting a variety of technologies in the teaching and learning of chemistry. The results also indicated the promising applications of artificial intelligence and learning analytics in the analysis of students' feedback and behavior, assessment of students' understanding of chemical concepts, and investigations of students' reasoning and cognitive processes during chemical tasks such as spectral interpretation. Examples of identified learning impacts include enhanced motivation in the learning of practical chemistry and chemical concepts, as well as improvement in academic achievement. Moreover, eye-tracking technology has been applied in the study of students' reasoning and cognitive processes, while learning analytics have been used for the evaluation of student engagement and learning experiences in MOOCs. These technologies have been considered promising tools for the investigation of pedagogical effectiveness and learning experiences, with their applications in this evolving field expected to be a hot research agenda in the near future. It is suggested that more educational research incorporated with the emerging technologies and artificial intelligence is worth investigating. The major areas of focus include the provision of immersive learning experiences in virtual laboratories, applications of artificial intelligence to analyze students' behavior and feedback, assessment of students' understanding of chemical concepts and solving of chemical problems, as well as pedagogical innovations supported by various tools such as eye tracking and machine learning. Considering the emergence of MOOCs and the prevailing use of Internet and electronic platforms in education, more research studies on the associated learning analytics and machine learning are also recommended. In addition, further research is needed for investigating the applications of technologies in game-based learning, inclusive education, and STEM education. Meanwhile, advances in digital technology also have prospects in the education of green chemistry and simulation of chemical experiments involving the use of hazardous chemicals. These are considered important in the context of sustainable education. It is noteworthy that while technology plays a very important role in chemical education, the pedagogical implications should not be overlooked. The multimodal interactive design and application of technologies and artificial intelligence to support different important pedagogical approaches, such as systems thinking and learning chemistry in Content and Language Integrated Learning (CLIL) classrooms. It is anticipated that effective integration of technology and pedagogy will help move chemistry learning within the context of a sustainable future.

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