

Effects of Computer Simulation on Chemistry Learning: A Systematic Review of PhET and Vlab Use in Classroom

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Introduction

The science of chemistry contains lots of abstract concepts that cause problems in the conceptualization of instruction in chemistry lessons (Akram et al., 2017; Gabel, 1999; Park & Oliver, 2008; Prosser et al., 1994). Chemistry teaching and learning at all levels of education have been marked with several challenges, many students have difficulties embodying chemistry lessons that contain so many abstract concepts (Nakhleh, 1992). Learning chemistry involves understanding phenomena at three levels: the microscopic level which encompasses molecules, atoms, ions, subatomic particles, and kinetic (moments of particles); the macroscopic level embraces real and observable chemical phenomena (i.e tangible, edible, and visible, etc); and the symbolic level describes chemical structures and process with graph, chemical formulas, equations, symbols, and stoichiometry (Johnstone, 1993; Tang & Abraham, 2016). Correct understanding and applying concepts of particulate nature is very essential for chemistry learning students. Nevertheless, the particulate theory of matter is one of the most difficult topics due to the abstract nature of atoms and molecules, which requires students' ability to logically operate on information and symbols beyond personal experience and concrete cases in the real world. Learning at the submicroscopic level often requires the aid of models and images. The basic concepts that are used to understand chemical phenomena would rely on how molecules are made and what molecules do (Mammino, 2008).

Chemists formulate mental visualization concepts for molecules and the changes they undergo, through this, the internal representations are expressed externally using different forms such as equations, concrete models, graphs, drawings, and tables (Al-Balushi & Al-Hajri, 2014; Gilbert, 2005; Kozma & Russell, 2005). Representing chemical molecules with a two-dimensional representation that serves as a three-dimensional phenomenon distorts mental models and hampers desirable learning outcomes (Stieff et al., 2005). Scholars pointed out that shallow experiences of students with the microscopic level of representation lead the students to miss comprehend the relationship among the three levels of representing phenomena (Johnstone, 1993; Treagust & Chandrasegaran, 2009). The students also fail to link visual and conceptual information of representations and are faced with misconceptions about chemical concepts (Al-Balushi & Al-Hajri, 2014; Özmen et al., 2009).

Scholars suggested different teaching strategies (like a computer simulation, animation, using computer-based visualization tools, and manipulation of 3D concrete models) to alleviate these epistemological problems and make students familiar with the three levels of representation in chemistry particularly in the microscopic level of representation (Kozma & Russell, 2005; Mocerino et al., 2009). Computer simulations are dynamic models that indicate simplified models of real-world components, phenomena, or processes, which include animations, visualizations, text, images, video clips, and interactive laboratories (Bell & Smetana, 2011). The greatest contribution of the computer simulations was the enhancement of learners' understanding of abstract chemistry concepts (Sentongo et al., 2013).

Computer-based animations and simulations can provide visual representations of particulate structures and processes that may help students build mental models or imaginations (Tang & Abraham, 2016). Mapping or configuring three levels of representation can be enhanced by using computer technologies that are used in the teaching-learning process as instructional media. It makes up for the deficiencies of the traditional instructional approaches concerning time, place, speed, consideration for individual differences, safety, and overall efficiencies. Oladejo (2018) emphasized the principal role of technology-based instructional media is to improve the overall efficiency of instruction by increasing the quality of learning or the degree of mastery; decreasing the time taken for learners to attain the learning outcomes; increasing the efficiency of teachers in terms of the numbers of learners taught without reducing the quality of learning; reducing cost, without affecting quality; and increasing the independence of learners and the flexibility of education and training provisions.

Technologies enhance the cognitive powers of human beings during thinking, problem-solving, and learning and hold great potential for students to develop deeper knowledge and execute reflective thoughts (Jonassen, 1996). This is why computer simulation has emerged as one of the most popular instructional tools for delivering quality instruction for the chemistry teaching-learning process. The use of realistic simulation often requires students to apply newly acquired skills while motivating them toward advanced learning (Moreno & Mayer, 2007; Weller, 2004). Different studies demonstrated that computer-based animations and simulations can increase students' conceptual understanding of chemistry and enable them to develop mental models of chemical processes at the molecular level (Abraham, 2005; Abraham et al., 2004). Other studies have shown that animations can help students develop an integrative understanding of chemical phenomena across macroscopic, submicroscopic, and symbolic representations (Kozma, 2003; Salame & Makki, 2021). Simulations have long been recognized as important in the teaching and learning of chemistry. With increased access to technology in the classroom, interactive visualization tools have emerged as powerful for transforming chemistry education. Interactive simulations deliver dynamic access to multiple representations, make the invisible aspects to be visible, scaffold the inquiry process, and allow for many trials and immediate feedback while being engaging and fun for students and teachers (Moore et al., 2014). Computer simulations have been used in different teaching situations, especially as a substitute for, or complement to, the chemistry laboratory (Akaygun & Jones, 2013). It emphasizes representing phenomena at the atomic and molecular levels. The dynamic information and

character, which increases the information-processing demand is the main feature of simulation (Lewalter, 2003). Lewalter also indicated that dynamic visuals may reduce a load of cognitive processing by supporting the construction of a mental model, but they may cause a higher cognitive load because of their temporal nature (Avramiotis & Tsaparlis, 2013). Computerized simulation chemistry experiments allowed the students to correctly solve problems related to the experiments and provide feedback for the simulated experiments in a linear sequence. Another advantage of computer-simulated experiments over the traditional approach is that the students dealt with data in a controlled setting. The data obtained under the traditional laboratory conditions were not fully reliable because of uncontrolled variables or measurement errors. The students using the computer-simulated experiment might have understood the concepts and problems conducted in those experiments better because they had the option of reexamining each part of the experiment. Because of the time constraint, the traditional approaches were not reexamined (Al-Balushi & Al-Hajri, 2014; Geban et al., 1992).

Having this background, the researcher attempted to review the effects of computer-based simulation on the chemistry instructional process. In this regard, my review was guided by the following research questions:

1. What is the most commonly used research design?
2. How many of the reviewed articles were done via PhET simulation and Vlab simulation?
3. To what extent does simulation-based instruction enhance the chemistry teaching-learning process?

Data to address the stated research questions were collected via the narrative review method. This was done by conducting a literature search to gather published articles on the effects of simulation-based teaching and learning chemistry. Google Scholar and CORE search engines were used to search relevant articles published between 2003 and 2022. Initially, 32 articles were collected from these database sources in the restricted time frame. After doing some preliminary analysis of the downloaded articles, some articles were excluded because of at least one of the following reasons:

1. If the article was published before 2021 and hadn't been cited or has very small citations.
2. The article hadn't been published in a reputable journal and publishers are not indexed by Scopus.
3. The articles were done with a qualitative research approach.

By using the above exclusion criterion, 23 research articles were removed and only 9 articles that satisfy the inclusion criteria were retained to conduct the review process. The researcher identified the included articles' purpose, study design, target groups, country of the study, publication year, and the chemistry concept catered for.

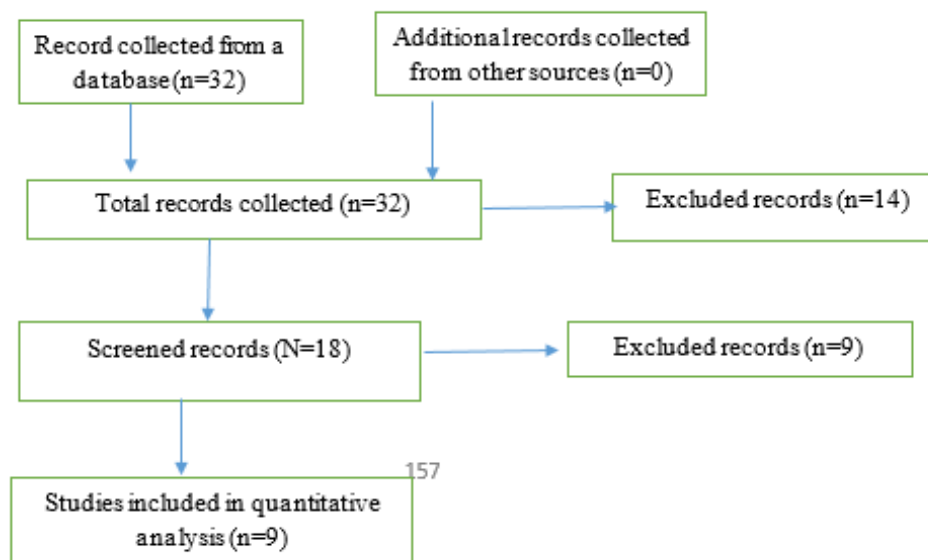


Figure 1. Exclusion steps of downloaded articles

Table 1. General Description Of Included Articles

	Purpose of study	publis her	# cite	Stud y area	Research design	Research analysis	Targeted group	Sample size	Chemistry concepts
1	Enhancing students' understanding of the macroscopic level of matter using computer simulation (Tang & Abraham, (2016).)	ACS	31	USA	Quasi-experime ntal	t-test	university students	170	Macroscopic level and particulate level of matter
2	Investigating the Effectiveness of Computer Simulations on Chemistry Learning (Plass, Milne, Homer, Schwartz, Hayward, Jordan, & Barrientos, (2012).)	Wiley	146	USA	Quasi-experime ntal	ANOVA	High school students	718	Kinetic molecular theory of gases
3	Comparing virtual and traditional laboratories for teaching electrochemistry (Hawkins & Phelps, 2013)	RSC	140	USA	Quasi-experime ntal	t-test, ANOVA	University students	167	Electroche mistry
4	examine the effect of using computer simulations in teaching chemical bonding (Sentongo Kyakulaga, & Kibirige, 2013)	Tayler & Francis	26	Ugan da	Quasi-experime ntal	Mann Whiteny U-test, ANCOVA	High school students	115	Chemical bonding
5	To examine the influence of computer-assisted instruction on students' conceptual understanding of chemical bonding and attitude toward chemistry (Ozmen 2008)	ELSE VIER	161	Turk ey	Quasi-experime ntal	percentage , t-test	High school students	50	Chemical bonding
6	To explore the impact of associating animations with concrete models on students' comprehension of different visual representations in organic (Balushi & Al-Hajri, 2014).	RSC	66	Sulta nate of Oma n	Quasi-experime ntal	ANCOVA	High school students	50	Organic chemistry

7	To examine the effects of virtual laboratories on students' achievements and attitudes toward chemistry (Tuysuz, 2010)	acarindex	477	Turkey	Quasi-experimental	Paired-sample t-test and independent-sample t-test	High school students	341	Separation of matter
8	To determine the effect of a virtual chemistry laboratory on student achievement in chemical changes (Tatli & Ayas, 2013)	jstor	294	Turkey	Quasi-experimental	t-test, one-way ANOVA	High school students	90	Chemical changes
9	To examine the effects of PhET simulation on students' attitudes and learning in general chemistry Salame and Makki (2021)	ijese	12	USA	Descriptive survey	Likert scale Questionnaire, open-ended question	College students	158	General Chemistry II

As vividly shown in Table 1, the overviews of the descriptive features of the 9 empirical studies were included in this review. The publication year for the articles included in the review was between 2008 and 2016 and the methodology of the studies was a quantitative research approach with an experimental research design.

Regarding research question one, identify the most common research design used for simulation-based chemistry teaching. As Table 1 displays, the commonly used research design used in the screened articles was quasi-experimental. It used a non-randomization approach to select participants and used intact or existing classes as experimental and control groups. Due to the use of naturally existing classes, the two groups may not be equivalent. As a design, it has the advantage of having better external validity to generalize the results compared to the true experimental groups but faced with different extraneous variables which affect the internal validity. Most of the screened articles were analyzed using ANCOVA to reduce the effects of the extraneous or confounding variables which affect the internal validity. From the initially collected 32 articles 20 of them were done using quasi-experimental, 2 of them were done with randomization design (true experimental), 1 of them was done with descriptive survey and 9 of them were done using qualitative research designs. But eight of the screened articles were done using a quasi-experimental and 1 descriptive survey research approach.

Regarding the second research question, the articles reviewed indicated that most of them 6(66.67%) were done using PhET simulation, and the rest 3(33.33%) were done using Virtual lab visualization computer-assisted chemistry instruction. The chemistry concept (content) taught using PhET simulation was chemical bonding, the molecular structure of organic compounds, chemical kinetics (molecular theory of gases), and the particulate nature of matter (PNM). The PNM is mainly focused on representing matters at the macroscopic level, microscopic level, and symbolic level. The macroscopic level is an observable phenomenon that is narrated through everyday experiences. It can be explained by the use of theories and models. The microscopic level is an explanatory model and theory. Representing the explanatory model through interactive computer simulation provides students with an active learning experience allowing them to engage in simulations presenting visualizations of particles that might be impossible. The symbolic representation of simulation design texts, graphs, and symbols are important elements (Milne et al., 2010; Plass et al., 2012).

Regarding the third research question, varieties of researchers investigated the effects of simulation-based instruction on students' chemistry achievement. The different articles indicated that simulation-based instructions have positive effects on the achievements of the students in the chemistry teaching-learning process. Virtual laboratory applications render students active thinkers instead of passive observers and thereby construct an effective and meaningful learning process (Tatli & Ayas, 2013). Different Studies stated that virtual laboratories facilitate the formation of conceptual models by providing activities that improve cognitive skills. The virtual laboratory software was shown to be at least as effective as real chemistry laboratories. Through research, it was determined that students in the experimental group could complete the experiments with reasonable results; they felt self-confident; they could associate the experiment with daily life; and they had the opportunity to examine macroscopic, microscopic, and symbolical levels of each experiment. It is anticipated that virtual chemistry laboratories will be adopted as supplementary and supportive elements in the future. This will provide not only an effective learning environment but will also minimize school expenditures and the time spent on such activities to a large extent (Tatli & Ayas, 2013). Virtual laboratories are a tool that can be very beneficial to the teaching-learning process of chemistry, as the conclusion of the study, virtual lab simulation was as good as normal hands-on general chemistry laboratories at teaching concepts (Hawkins & Phelps, 2013).

Research articles done by Tüysüz (2010) indicated that a virtual laboratory developed by interactive computer animation about the topic of separation of matter enhances the achievements of the students. The author of the article concluded that a virtual laboratory enriched with visual representation and used to make concrete difficult and abstract concepts increases the achievement, motivation, and interests of the students. However, as the author remarked that active will of the students to participate during the instruction plays a great role to lead the process to be effective (Hawkins & Phelps, 2013; Tüysüz, 2010).

Another scholar investigated the learners' achievement when using computer simulation in addition to the manual hands-on activities to compare achievements with using only hands-on/manual/ activities during the teaching-learning process of chemical bonding. The result revealed that understanding of the chemical bonding concept was enhanced from a pre-test to a post-test in the experimental group, and any significant change in the achievement accounted for the intervention of the computer simulation instruction. Computer simulation-based teaching-learning processes enhance the recalling process, comprehension, and analysis of chemical bonding concepts. Practically, computer simulations allowed learners to visualize chemical reactions at a microscopic level (Sentongo et al., 2013). Researchers claim that computer-assisted instruction enhances the transfer of learners' alternative conception compared to the conventional teaching method and enhance understanding of scientific conceptions (Al-Balushi & Al-Hajri, 2014; Jimoyiannis & Komis, 2001).

Other reviewed articles point out that computer-assisted instructional intervention positively impacted the attitudes of the students towards chemistry, understanding, and remediation of alternative conceptions of chemical bonding (Özmen, 2008). Some studies have indicated that students exposed to simulations performed significantly better in assessments and demonstrated better conceptual understanding than students who only viewed computerized static representations

(Aldahmash & Abraham, 2009). This is because dynamic chemical processes are usually more complex than statistical phenomena and simulated visualizations can help students develop appropriate mental models to comprehend the concepts and processes. Another result in the reviewed articles indicated that computer simulations improved students' conceptual understanding at the particulate level, but more specifically indicated that dynamic simulations at the particulate level helped the students understand the microscopic nature of matter involving dynamic chemical phenomena(Tang & Abraham, 2016).

According to Salame and Makki (2021), PhET interactive simulation had an overall positive impact on student's attitudes and perceptions about learning. PhET simulations helped students to create a better understanding of chemistry concepts and the content covered in the lecture. It promotes and facilitates learning and understanding of abstract concepts and also provides clear instruction which is easy to follow. Another reviewed article indicated that animation of submicroscopic organic molecules enhanced the utilization of concrete models in the teaching of organic chemistry, animation helped the students to comprehend the spatial aspects of organic molecules (Al-Balushi & Al-Hajri, 2014).

Chemistry teachers must make an effort to create an ideal environment for teaching and learning, including technological tools. Instead of using technological tools for a short-term educational program, students will benefit more from a longer period of learning (Pekdağ, 2010).

Conclusion

This study aimed to conduct a narrative review of the use of simulations in chemistry education. Based on the article selection process of inclusion and exclusion criteria, 32 articles published from 2003 to 2022 were listed. Using the exclusion and inclusion criterion 9 research articles published from 2006 to 2016 were selected for this narrative review. The research method, data collection tools, sampling methods, sample sizes, and data analysis method of these articles were displayed in a table for the review. According to the results of the analysis, the commonly used research design was quasi-experimental with a pretest-posttest control group design method. The data analysis was inferential statistics mainly independent and paired sample t-test, one-way ANOVA, ANCOVA, and Whitney U test. Most of the results in the articles indicated that interactive simulation-based chemistry teaching had an overall positive impact on students' achievement, motivation, attitude, and perceptions about the chemistry teaching and learning process.

Another important finding from the articles, computer simulation-based instruction can be a solution for schools which has overcrowded classes and inadequate chemistry laboratory. Sometimes virtual laboratory simulation-based instruction will be an alternative approach to physical laboratories in terms of cost, safety, repeatability, and comprehension.

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Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of paper titled “**Effects of computer simulation on chemistry learning: A systematic review of PhET and Vlab use in classroom**” belongs to the authors.