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Review Paper

Game-Based learning in chemistry education: An overview of the literature

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Abstract

Technology has been significantly incorporated into chemistry curricula more recently to boost students' scientific thinking and reverse the trend of declining interest in the subject. Game-based learning "GBL" is one of the ideal teaching strategies because it emphasizes "hands-on" as well as "minds-on" exercises in chemistry classrooms. The purpose of this study is to present empirical data on the use of GBL in the literature on chemical education. To achieve this, we carried out an in-depth analysis of the 48 empirical research papers that were published between 2011 and 2022 in three different electronic databases: Google Scholar, ERIC, and Scopus. This review highlights the most recent GBL trends in chemical education while highlighting the gaps in the literature, challenges, and barriers. Additionally, it increases the opportunities for potential future research directions. It gives future researchers a framework and perspective on subject matter, educational levels, theoretical models, results, methodologies, game elements, and assessment tools. The results demonstrate that educational games help students understand chemistry concepts conceptually and enhance their desire to learn and enjoy themselves while doing so.

Keywords: Chemistry gaming, games in chemical education, digital gaming in chemistry, game-based learning in chemistry.

Introduction

Novel and interesting approaches to enable learners to meet the rising demands of education are constantly being produced by rapid technological development. Meanwhile, tried-and-true instructional methods, including modern software, frequently prove to be insufficient, if not completely ineffective[1]. Science education is widely recognized as among the most of important facets of contemporary education because it is responsible for producing citizens who are scientifically literate and developing essential 21st-century abilities such as critical thinking[2]. Consequently, instruments, techniques, and educational theories which encourage scientific thinking have garnered a lot of attention[3,4].

Game-based learning (GBL) has received a lot of attention recently from researchers across a variety of disciplines, including science education[5,6]. According to Kapp[7] GBL is the use of game design elements, game-play mechanics, aesthetics, and game thinking for non-game applications to motivate students. The fundamental tenet of GBL is the assumption that the motivational power of game elements can be applied to educational setting[8]. Many researchers have found the application of gamification in science education to be fascinating because it is something that students are familiar with while also piquing their interest[9,10]. Additionally, GBL can encourage rational thinking that is consistent with established scientific principles, methodologies, and instructional strategies related to education[11]. Despite the fact that the use of GBL has typically been deemed as effective in terms of learner engagement,[12] its implications on educational objectives has quite often been disputed, with research findings differing among participants, raising concerns about its advantages. Thus, the need to investigate the specific educational processes to ascertain their effects has been further increased by their growing popularity coupled with the mixed results.

According to Eilks, I. et al.[13] and Nzeyimana & Ndihokubwayo[14], learner-oriented, dynamic, and collaborative learning strategies are essential for meaningful learning in chemistry classrooms[15,16]. These study techniques have their roots in social cognitive and constructivist theories. Social constructivist idea asserts that effective learning can only emerge when students can interact and provide their knowledge context[17]. Cognitivists agree that pragmatic, hands-on activities assist in aiding students understand and remember the material[18]. Examples include laboratory exercises, motion graphics, simulations, and videos. It is important to use active learning techniques in the classroom, such as cooperative learning[19], game-based learning[20], problem-solving strategies[21], and others. This is the reason why social constructivism has been heavily incorporated into chemistry classes at all educational levels. Many instructional strategies, such as cooperative learning, and GBL, have been used to successfully teach and learn chemistry concepts[22-24]. This is attributed to the fact that these teaching approaches will unquestionably involve students' bodies, social interactions, and thoughts. The result of this is eventually a positive outlook, greater interest, and motivation to learn chemistry. Constructivism has a relation to games in education because it gives students real-world tasks that allow them to take what they've learned and apply it to new situations[25].

In a nutshell, educational games aid students in understanding concepts more thoroughly as well as inspiring them to learn and providing an opportunity for them to make sense of the material they have learned[26-28]. Even though many review studies on game-based learning have been conducted[13], few of them have specifically targeted particular chemistry subject areas[22]. However, the reviews were restricted to summarizing the various game-based learning programs. The reviews lacked in-depth, systematic analysis. The most recent GBL trends in chemical education are highlighted in this review, along with any gaps in the existing research, difficulties, and barriers.

Methodology

We surveyed the literature to identify, select, as well as link relevant research to research questions in order to offer a thorough useful understanding of GBL in chemistry learning. The search protocol employed to choose articles has been previously discussed[29].

Research questions: i. What methodology and evaluation tools were used in the first study? ii. What are the subjects covered, what are the educational levels, and what are the settings? iii. What pedagogical principles are used, and what gaming elements are present in gaming applications? iv. What were the educational and/or motivational outcomes?

Inclusion criteria: The study must be empirical and carried out in a classroom setting using either quantitative, qualitative, or mixed methods, At least one unique game component was used in the study's gamified practice, empirical data must be present and students had to have been subjected to the practiced) The study was carried out in a setting that was either primary, secondary, or higher education, Chemistry must be a sub-discipline covered by the study, It is a conference paper or a peer-reviewed article, and only articles published between 2011-2022. From each article reviewed, the following key details were extracted: grade level (MS, HS or H.Ed.), chemistry content (bonding, geometry etc), learning outcome (cognitive, affective or skill based), assessment tools (survey, questionnaire, test etc), learning theories, objective(s) of the study, overall outcome, gaming elements, gaming type (2D, 3D, AR, or non-digital), study type (comparative or evaluative), affective domain attributes (interest, attitude, self-efficacy etc).

Results and discussion

The basics: Findings suggest that studies were conducted at high school 66.7% (n=32), higher education 43.8% (n=21), and middle school levels 8.3% (n=4). A study may have examined more than one grade level, so percentages may not add to 100. Findings also suggest there were significantly more digitally based games (n = 33, or 68.8%) than non-digital games (n = 11, or 22.9%). 8.3% (n = 4) of the cases (games) had both non-digital and digital game implementations.

Learning outcomes: In the empirical studies reviewed, the three types of learning outcomes that were measured were cognitive, affective, and skill based[30]. A participant's cognition is referred to as their "cognitive domain," which involves declarative knowledge (factual knowledge), procedural knowledge, and conditional knowledge[31]. A participant's subjective response is referred to as their "affective domain," which includes their mindset, functionality, and self-efficacy. The term "skill-based domains" describes the practical skills of the participants, such as their laboratory practical skills.

Figure-1 displays the proportion of evaluation methods that were used in comparative and evaluation studies. As shown in Figure-6, more evaluative studies frequently evaluated participants' affective outcomes (n = 25, 52.1%), while a higher proportion of comparative studies measured cognitive outcomes (n=14, 29.2%). This is because these studies evaluate participant perceptions and the functionality of the virtual laboratory. Of all the studies considered in this review, the skill-based outcome has received the least attention (n=1, 2.1%). Declarative knowledge (n=32, 66.7%), attitude (n=17, 35.4%), and usability (n=15, 31.3%) the cognitive and affective contexts, which are the most evaluated learning outcomes, respectively. Figure 2 graphically displays the outcomes.

Data evaluation: A combination of evaluation methods has been used to measure learning outcomes (cognitive, evaluative and skills) in order to assess the effectiveness of GBL Figure-3. The most popular method of evaluation for comparative studies (n=15, 32%) is testing, whereas the most popular methods for evaluative studies (n=11, 23% and 9.19%, respectively) are surveys and questionnaires. Comparative studies also appear to have employed survey methods to measure participants' affective outcomes (n=6, 13%). The prevalence of mixed-method investigations is important because it can help us comprehend the findings and the justification for them. For instance, linking micro and macro domains through the triangulation of datasets can improve the accuracy of the conclusions[32-34].

A quantitative and mixed-method approach has also been found to be effective in studies that collect and use data from gaming applications in addition to the data tools already mentioned. Numerous studies (Figure-4) where this was seen combined user feedback with input from the gamification platform or application with other traditional assessment methods, such as quiz scores[35], reports[36] or time spent in the application[37].

Learning theories: The underlying theoretical models are a major part of how a GBL application with gaming components is designed. Understanding the motivational mechanisms that underlie cognitive and behavioral changes, specifically the learning theories, is crucial for correlating game design elements and results[38]. Figure-5 presents the percentages of learning theories. A summary of each learning theory is included in Table-1, along with any that are specifically mentioned in the text or used as keywords in the publications under review. Our study found that among the most popular learning theories for game-based learning were constructivism (n=5, 10.4%), problem-based learning (n=5, 10.4%), inquiry-based learning (n=4, 8.3%), and experiential learning (n = 4, 8.3%). However, a sizable portion of the articles (n=28, 58%) did not mention any specific learning theory. Even though the theoretical framework was only used in a small number of studies, all of them found that either learning outcomes or motivational outcomes were improved.

Gaming elements: GBL entails selecting and using just one or a few different combinations of game design elements[39]. Because game elements play such a fundamental role in a game-based learning environment, many researchers have proposed a link between game elements and learning outcomes[40-41]. Thus, it's imperative to go over the main game mechanics and components utilized in GBL environments. Figure 6 presents the percentages of all the game's elements.

We found that the most frequently used game mechanics and components in GBL environments for chemical education were animation and sounds, levels, quizzes, puzzles, and rewards. Together, these elements increase competition in the environment. Competitive settings can boost motivation, encourage commitment to the learning process, and produce a fun learning atmosphere[42]. In a gamified environment, competition has a positive influence on students' behaviour and helps them get over their anti-competitive attitudes[43]. Figure-7 presents a bar graph representing the nature of chemistry content addressed through the studies on GBL. A higher percentage of studies focused on fundamental chemistry topics such as chemical reactions, chemical nomenclature, periodic table and elements, intermolecular forces etc.

Representative GBL's: Chairs!: This game was created to instruct high school and college organic chemistry students about the ring conformations of cyclohexane. The game was found to improve students' conceptual understanding of conformational isomers and strengthen their spatial reasoning[44].

ChemEscape: ChemEscape is an educational game that combines practical laboratory work, ongoing multi-player competition, and traditional escape room concepts. Puzzles were created by Clapson et al. with the help of engineering students and students in grade levels 4 through 12. The participants believed ChemEscape to be an effective teaching tool. It improved their ability to work together and solve problems, it improved their ability to apply their knowledge in new situations, and it helped them visualize and put into practice scientific concepts. This game also seems to encourage "hands-on and minds-on" learner-oriented exercises in chemistry lessons[45].

CheMakers: CheMakers helped students become more confident in their ability to handle challenging questions while also encouraging higher level thinking, originality, and problem-solving abilities. Feedback from the students revealed that CheMakers was a useful teaching tool for fostering debate and competition. CheMakers allowed learners to memorize information. Finally, the authors asserted that, despite the game's testing with undergraduates, it could be adapted for use in chemistry classes at both the introductory and advanced courses[46].

Chemory: Chemory games were found to significantly increase student motivation when contrasted with conventional didactic instruction. The students' weekly self-study time was also found to have increased. In addition, learners could earn bonus points for successfully completing the game also helped to lower the failure rate on the final exam[47].

Ion Hunters: Ion Hunters was created as a chemistry education game for university-level students to practice writing the formulas for ions. The students found the game to be more enjoyable, engaging, and entertaining. Ion Hunters markedly raised students' motivation for learning, which ultimately led to a better comprehension of anions and cations. Additionally, the authors claimed that this game could also be applied to any chemistry lesson that covers ions[48].

Molebots: Molebots is a first-person shooter video game that emphasizes chemical nomenclature. It was evaluated among US college students enrolled in a general chemistry course during the first semester. The online course where the announcement of the game was made was conducted using a learning management system called Desire to Learn (D2L). According to survey findings, students preferred playing games to other forms of media and enjoyed playing the game, with the textbook coming in last among their least preferred teaching strategies[49].

Alkihimia: Alkihimia was created for the chemistry curriculum in high schools. Dual high-ability classrooms were given the game, with one class of 40 students placed in the intervention group and the other class of 38 placed in the control condition. An attitude survey was also administered before and after intervention. According to the study, students who received the intervention performed better on the separation task than their equivalents in the control group in terms of conceptual understanding. The intervention was successful because it changed the culture of the traditional classroom to one that is characterized by critical and interrogative thinking[50].

Game Based Approach: Samide et al. used a variety of games to instruct undergraduates in analytical and organic chemistry. Along with having fun, they discovered that using games as a teaching tool helped students sharpen their critical thinking and interactive skills. Overall, the authors made the case that it was preferable to use a variety of games to teach one unit, as opposed to numerous earlier studies that utilized games alone to teach content. Despite requiring a lot of time to prepare and execute, results demonstrate that including multiple games in a single lesson will inevitably provide a context that is appropriate for students with a range of interests and cognitive abilities[51].

Element Cycles: Even though the researchers were unable to compare the outcomes of participants with those of non-participants, they still came to the conclusion that those who took part significantly improved on their retention of important information on the post-test. It was also mentioned that the game could be adjusted to suit various chemistry topics and grade levels. The game was a great way to learn and teach chemistry because it was entertaining and enjoyable[52].

Discussion: To give a summary and perspective into the published research literature on GBL in chemical education, a comprehensive review of the pertinent literature was undertaken. According to our review of the literature, GBL is utilized more frequently in high school and higher education settings than in primary grade settings. This is in line with other previous research reviews that claim that the achievement gap between primary and secondary, and higher education is closing[53]. Numerous studies that use independently developed GBL applications show how much easier it has become to create such applications, but more importantly, they highlight the significance of gaming elements and the necessity of customizing and designing the GBL application.

We were able to learn helpful information about the use of assessment tools, data collection, and data use from this study's analysis. Although most of the research utilized more traditional methods like tests, surveys, and interviews to collect their data, a few of them also obtained information from GBL applications. Modern interactive digital technologies and GBL applications might be able to give us prompt and helpful feedback.Data from game scores, final assessments, or gaming experience can support and enhance research findings. According to several studies[54–56], removing the pressure of evaluation frees up both students and researchers from having to keep an eye on the process constantly. Teachers and researchers can collect user-specific information which is more comprehensive and multifaceted during a "non-invasive form" of assessment because students self-report their learning progression and demands[57,58]. Insightful assessment techniques like eye tracking, motion tracking, or mouse tracking might be supported by a GBL application as well, which could give researchers access to data that is not otherwise possible. Recent research[10,59,60] suggests that these techniques could result in a very accurate and complete record of students' gestures, inclinations, thought processes, and overall learning growth. Numerous studies also employed mixed and quantitative assessment methods, which enhances the reliability of their judgments and choices made considering the information gathered[61]. We discovered that the game mechanics and components that were most frequently used in GBL environments were animation and sounds, levels, quizzes, puzzles, and rewards.

These elements all work together to increase competition in the environment. Even though most of the articles did not go into detail about the theoretical framework upon which they were built, a small percentage of them did establish a theoretical framework to represent the motivational processes that lead to changes in cognition and behaviour. In the articles that were examined, "motivation" was one of the words that was used the most. The relationship between player ambition, game elements, and learning objectives was very challenging to interpret because most studies lacked a solid theoretical underpinning[62]. All of the studies that used a theoretical framework supported the idea that GBL can improve students' learning, even though not all of them presented findings for both motivation and engagement. Critical knowledge about the improved intrinsic and extrinsic motivational elements was provided by the studies that reported both learning and motivational consequences. The motivational component was evident in studies grounded in self-determination theory[63].

Our in-depth analysis of the literature leads us to believe that the use of GBL environments and the development of these environments may increase students' motivation by encouraging learning-related mentalities and substantial academic gains. There is proof that the interaction of intrinsic motivation and extrinsic motivators can influence the development of skill set, mastery, and a deeper understanding of scientific ideas[61,64]. The current study's findings also point to the possibility that GBL in chemistry instruction may improve students' academic results[57] and games are by their very nature engaging and enjoyable for students. According to our research, using gaming elements like levels, points, leader boards, and competitive environments can help students become more intrinsically motivated while also having a positive influence on their behavior[57] students who are intrinsically motivated are more likely to engage in class activities and give their full attention to the instructors' lessons. After conducting a literature review, we found that incorporating modern instructional methods, such as inquiry oriented or flipped instruction, as well as game elements designed to influence motivation (intrinsic and extrinsic), has shown promise in improving students' academic performance[63]. Baek et al. highlighted that using games to teach chemistry can motivate students[26].

Games are now being used in classroom studies more frequently, which may be due to the use of blended learning. The Covid-19 curriculum specifically called for teachers and students to adapt to ICT (information and communication technology)-related media. Online education is now crucial during times of crisis, such as the one currently affecting the entire world (the COVID-19 lockdown). The findings of a recent study by Barko, T., & Sadler, T. D.[66], which compared teaching methods involving digital and analog games, and conventional lectures with middle school students in China, are compelling in this respect. They discovered that game-based learning techniques outperformed more traditional teaching methods. Other researchers have suggested that the interactive learning environments provided by digital games are characterized by several advantages, such as the chance for active learning, the reduction of workload, and the development of scientific understanding[67,68]. It has also been demonstrated that using digital games to teach students allows them to have fun while doing so. The school curriculum emphasizes the ongoing blending of digital and smart technologies into education to support learning[8].

The study's findings are consistent with the notion that well-articulated GBL application can enhance motivation and possibly enhance academic outcomes by carefully integrating gaming components and mechanical design based on theoretical underpinnings with instructional methods. All gamification-related limitations and issues were found to be caused by students' differing learning objectives from those that were established, their inability to complete the challenges, their encountering technical issues, or their lack of preparation for using the GBL environment, all of which might indicate a lack of multidimensional literacy and learning, digital or gaming literacy[69]. GBL implementation does require a certain level of digital literacy and gaming technologies because it is easy for students to become disengaged due to a lack of gaming skills[69].

Table-1: Representative list of learning theories

Learning theory	Description	n
Multimedia theory	According to the theory, a learner has a textual and a visual information processing platform	1
Experiential learning	Experimentation, conceptualization, observation, and experience are all parts of the four-stage cycle of experiential learning that leads to knowledge acquisition	4
Problem based learning	A teaching strategy that presents difficult problems for the students to solve. The learner is encouraged to develop their critical thinking, problem-solving abilities, and metacognitive knowledge	5
Inquiry based learning	A constructivist teaching strategy that encourages students to conduct research. They must adhere to the scientific method, which includes formulating hypotheses, examining, and analyzing the evidence, explaining the results, and evaluating their own arguments.	4
Constructivism	Knowledge is constructed in the mind of the learner	5
Knowledge in Pieces	The notion that knowledge is made up of small cognitive units as opposed to broad concepts	1
Flow theory	Highlights intrinsic processes to enhance engagement and learning through a balance between difficulty and student aptitude and the use of appropriate game elements that enrich the learning process	1
Learning by doing	Improving the learner's skill development through real-world applications. Engaging in realistic tasks and interacting with the learning environment enforces learning	1
Self-determinant theory	Provides crucial insight into the relationship between gaming elements, motivation, and learning goals. Describes and connects motivation (intrinsic and extrinsic) while still combining basic psychological necessities to gaming elements.	1
Unspecified		28

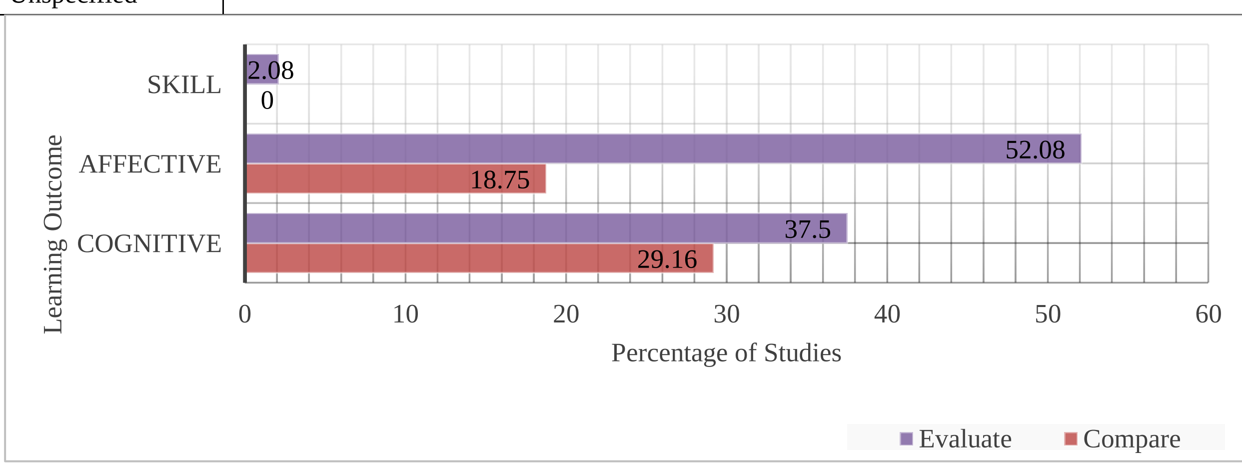

Figure-1: Bar graph showing the percentage of the learning outcomes measured in evaluates vs comparison.

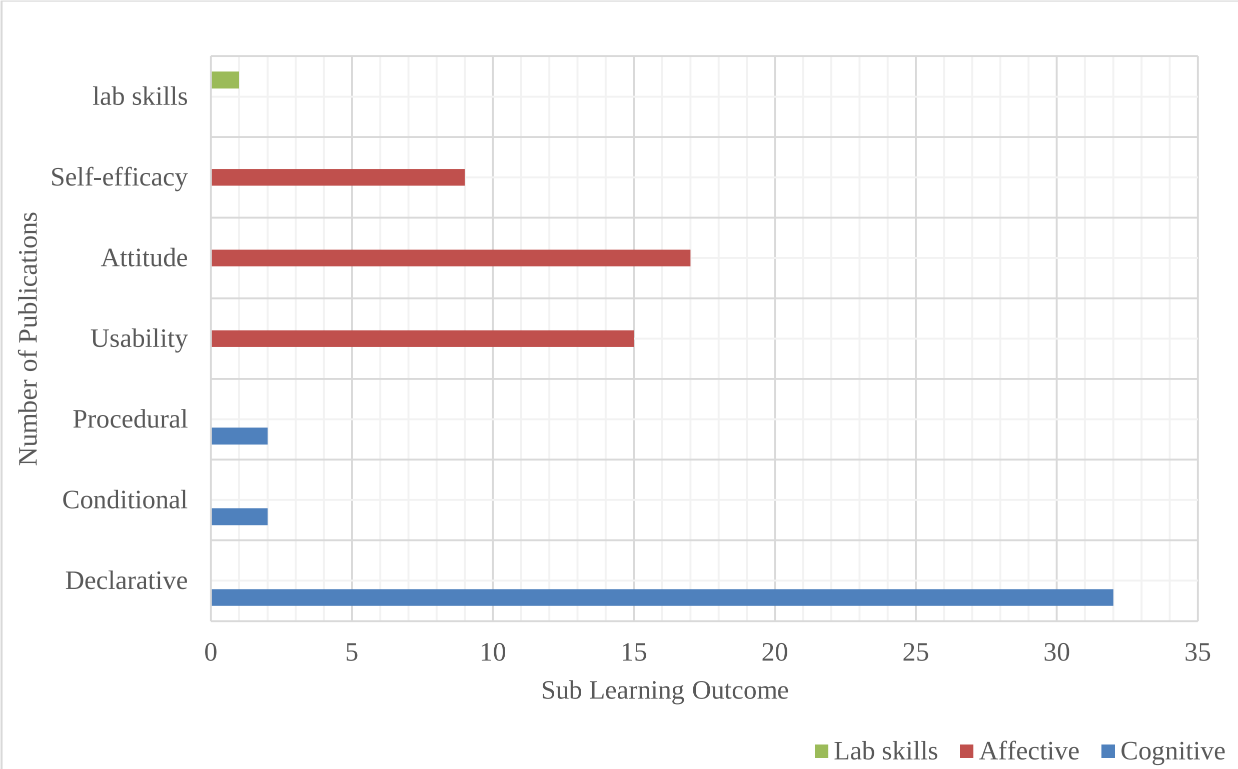

Figure-2: Bar graph showing the percentage of the learning outcome sub-categories measured in the cognitive, affective, and skills domain respectively.

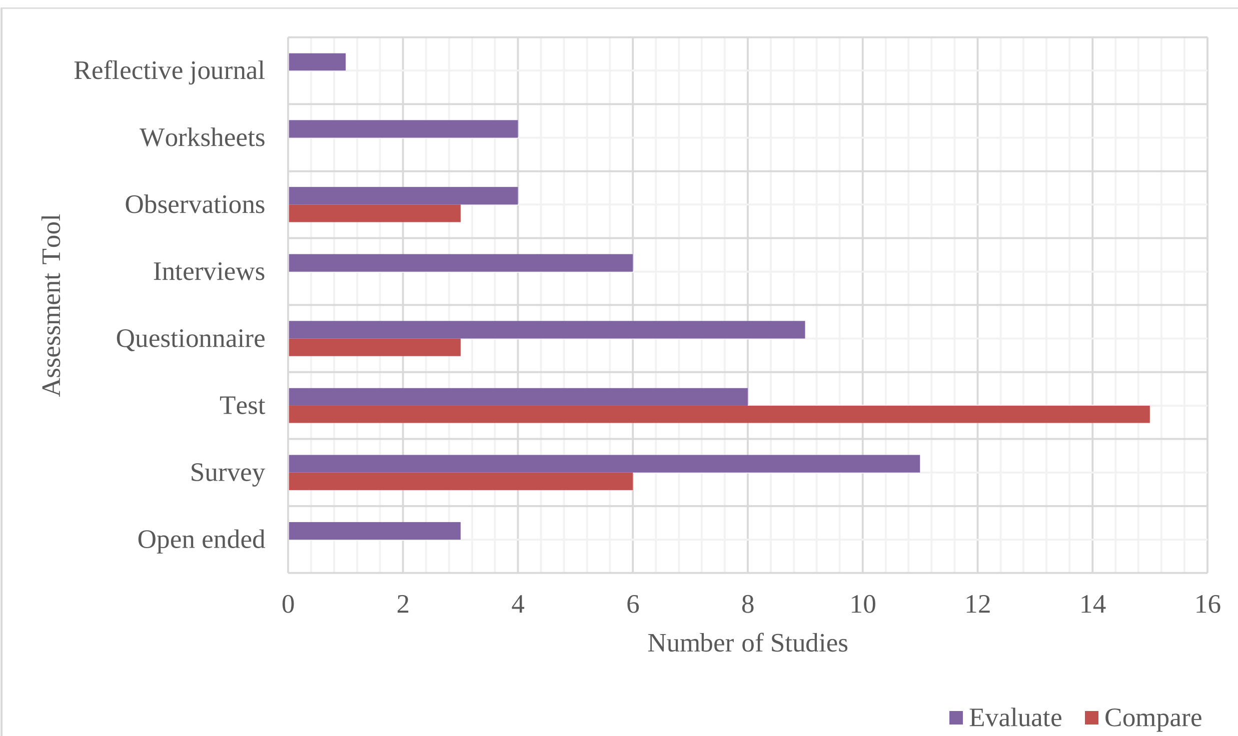

Figure-3: Bar chart representing the nature of data assessment tools used in GBL studies.

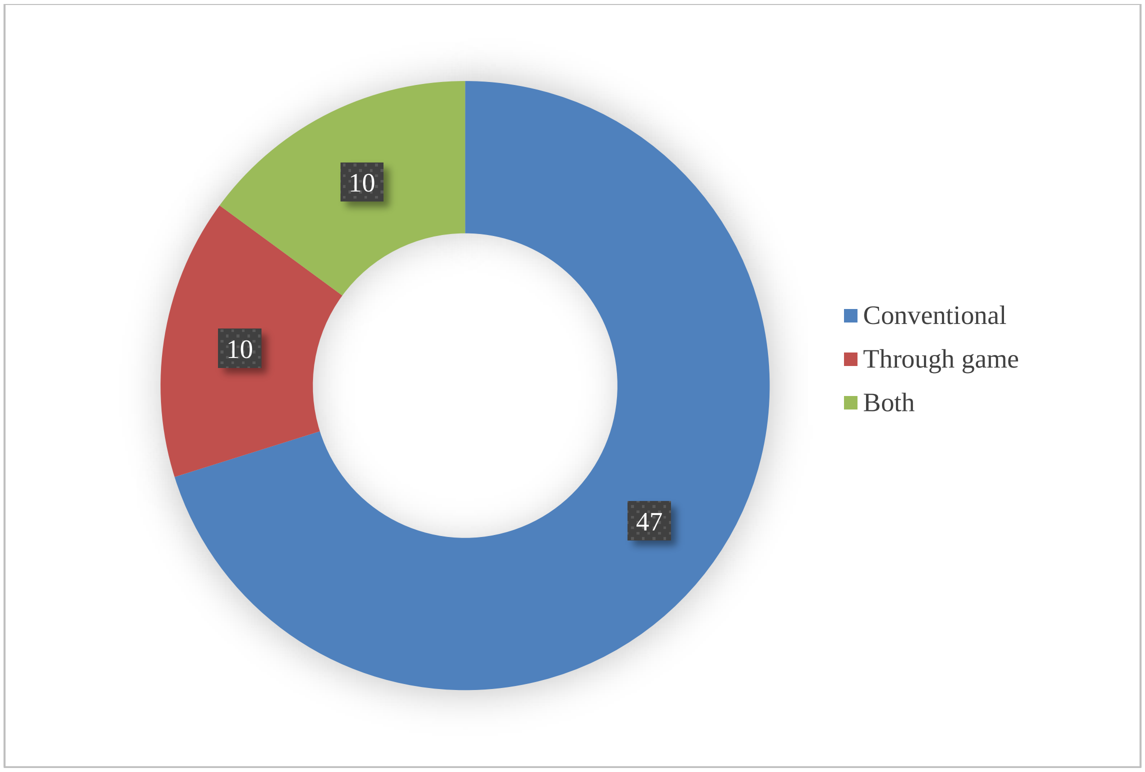

Figure-4: Pie chart showcasing the number of studies obtaining assessment data through the game, conventional method, and both.

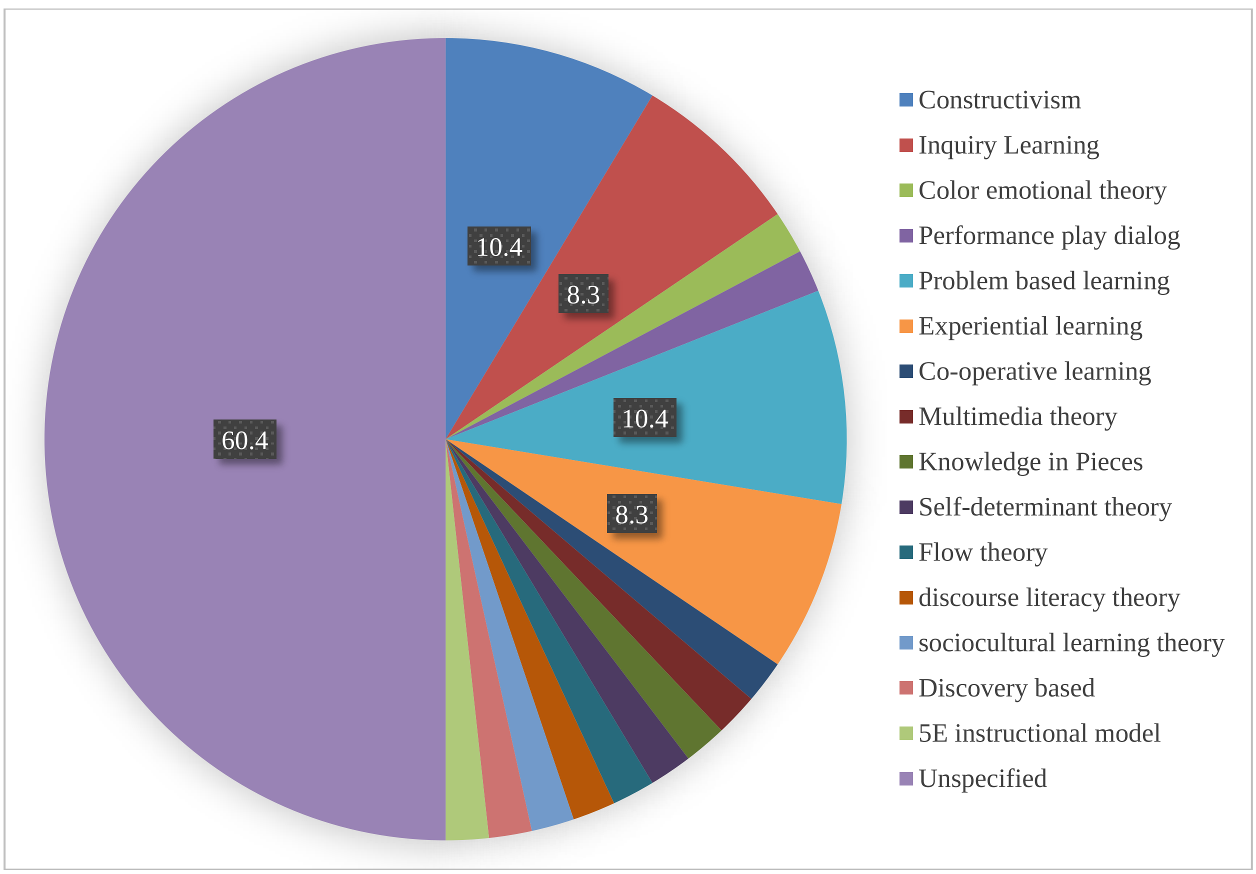

Figure-5: Percentages of learning theories reported in reviewed articles.

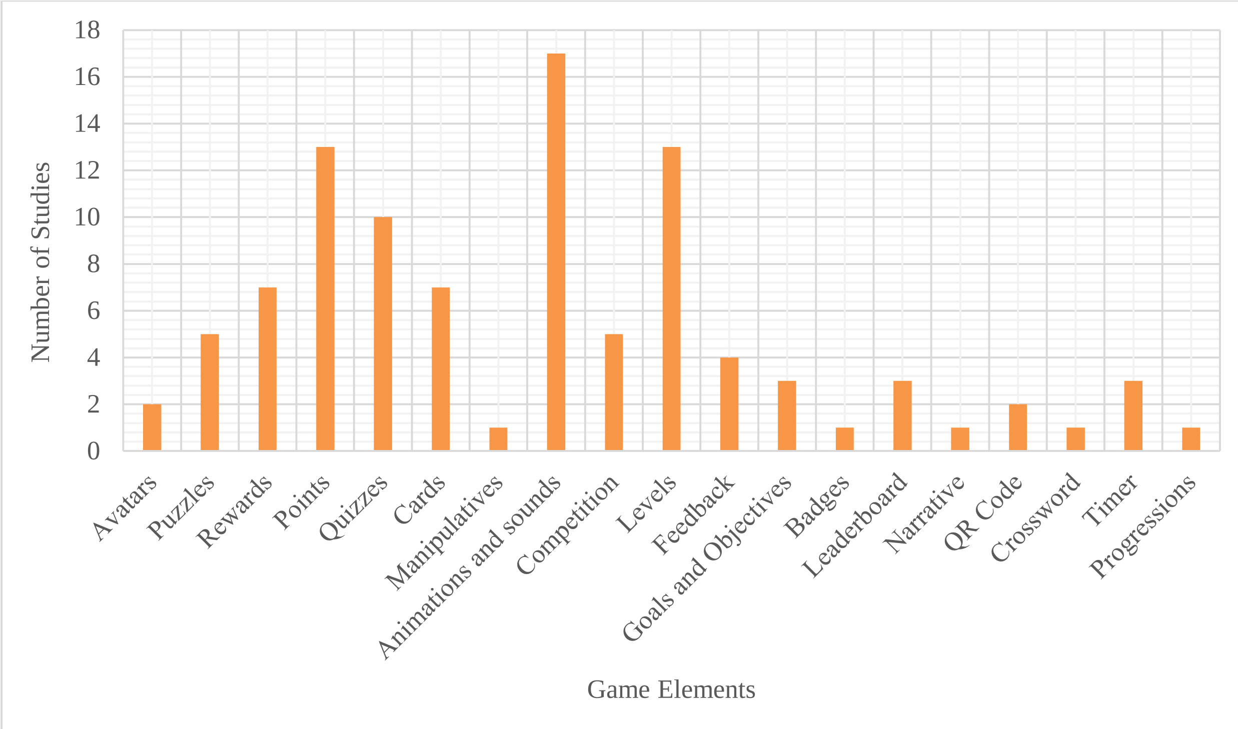

Figure-6: Bar chart showcasing the nature of gaming elements used in the GBL applications.

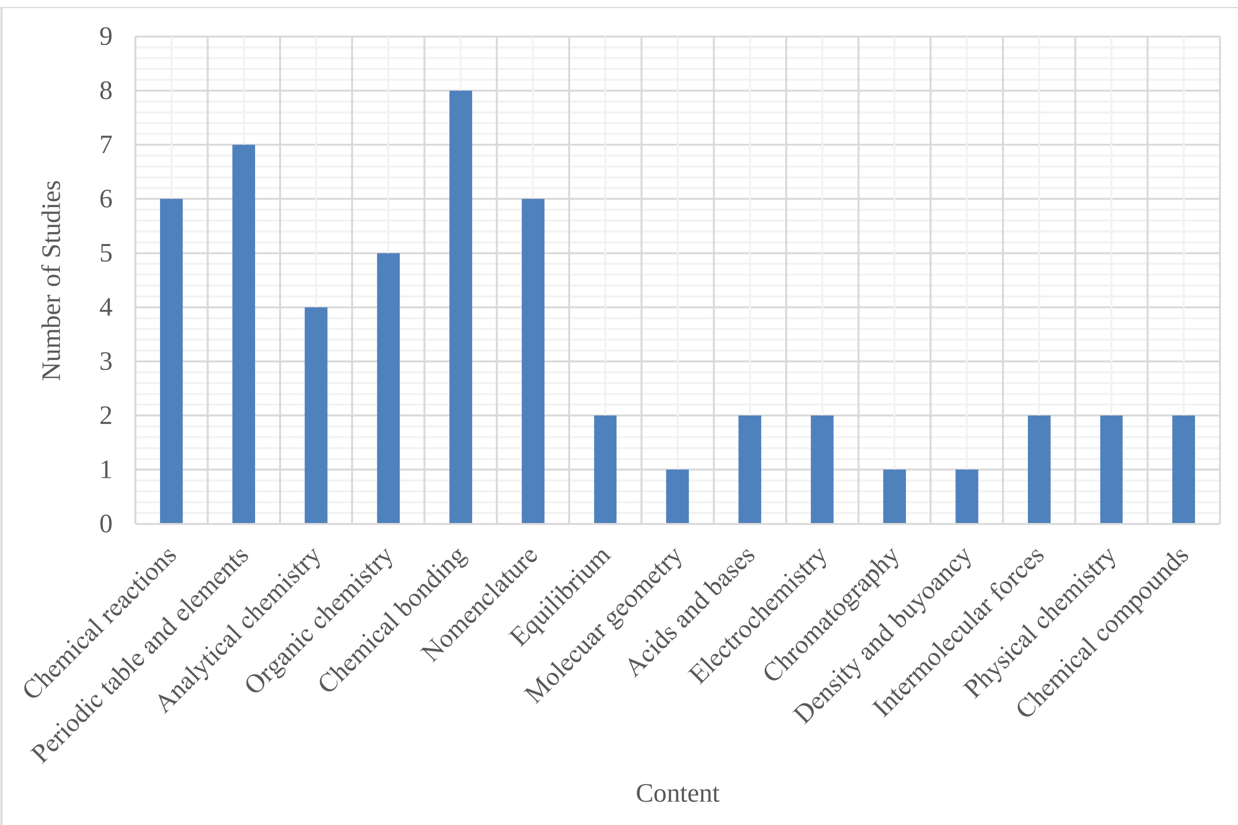

Figure-7: Bar graph representing the nature of chemistry content addressed through the studies on GBL.

Conclusion

This study's goal has been to present the current state of GBL research in chemistry education, as well as the relationship between learning theories, gaming components, and learning outcomes.

In this study, a comprehensive review of the literature was undertaken to investigate how GBL has affected chemical education from 2011 to 2022. We received insightful information from the review's findings, which also improved the body of literature in several ways. We gained a better understanding of the contexts and applications of GBL in chemistry instruction. The most popular content areas, educational levels, and most recent advancements in GBL environments were all identified. This study also made a significant contribution by demonstrating how GBL can improve user data collection for research studies by integrating novel assessment methods. GBL can give more information about the learning processes that are taking place in the classroom by increasing the quantity and quality of data. The main gaming elements that are currently used in chemical education were also identified by this study. Academic success, social interaction, and motivation and engagement were found to be the three main learning outcomes that were most affected. Students who struggle with chemistry frequently express negative feelings and have trouble understanding concepts. Both digital and analog GBL environments can significantly affect how students learn. This study suggests that GBL improves chemistry instruction and raises student motivation, engagement, and learning outcomes.

According to the literature review, many games have been assessed in chemistry classes at the high school and collegiate levels. It's encouraging to know that most of these game designers have said that these games could be modified to fit chemistry education at lower levels. Future studies should investigate how well-rounded these strategies are in terms of meeting curriculum requirements. Teachers have not been seen to use games very frequently when instructing. This may be due to several factors, including insufficient game-based learning educators, a lack of funding, and inadequate science classes and laboratory facilities. Despite taking a lot of time to prepare for and carry out, GBL has been hailed as a technique that helps students understand chemistry concepts.

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