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Game-based learning in metaverse: Virtual chemistry classroom for chemical bonding for remote education

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Abstract

Virtual classrooms based on the metaverse or virtual reality are useful and effective for imparting basic chemistry concepts. Interactive and immersive environments can effectively teach fundamental chemistry concepts, such as chemical bonding and formulas, thereby making these otherwise abstract and intangible ideas more accessible and understandable. With the outbreak of Covid-19, e-learning platforms have also been developed for chemistry education. However, these platforms are unable to make learning chemistry interactive and enjoyable. Therefore, there is a need to motivate students to learn basic chemistry concepts in an immersive and interactive environment. In this paper, we propose an immersive virtual reality-based Virtual Chemistry Classroom for Chemical Bonding (VC3B) to facilitate the learning of chemical bonding and formulas through a game-based learning approach. It includes two different games for learning chemical bonding and formulas. In the first game, molecule construction, students reconstruct the structure of molecules by rearranging the atoms in order to learn about chemical bonding. In the second game, chemical formula, students compose the chemical formula of a given compound to help them memorize chemical formulas. The study, conducted on 90 middle school students, employed a randomized controlled study design, dividing participants into three groups. Each group learned about chemical bonding and formulas through three different mediums. After conducting the experiment, the students were given a questionnaire to evaluate the usability of VC3B. The results of the study were positive, with participants finding the VC3B to be more interactive than traditional book and online lecture methods. Participants were also motivated to learn and enhance their knowledge of chemistry.

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1 Introduction

Chemistry is often regarded as one of the most challenging and least popular subjects among school students. Among many reasons, one is that chemistry consists of numerous abstract and obscure concepts, such as chemical bonding, which makes it challenging for students to comprehend and visualize (Stroumpouli and Tsaparlis, 2022). Traditionally, it has been taught in classrooms along with laboratory experiments as an integral part of the learning process to enhance students' interest in the subject matter (Penn and Ramnarain, 2019; Ahmad et al., 2023, 2021). With the increase in distance education and the outbreak of COVID-19, the mode of study has shifted to online platforms (Murphy, 2020). While online platforms have gained popularity, they are limited by their reliance on 2D displays. This limitation hampers the level of engagement and immersion for students who are trying to understand complex concepts, such as chemical bonding and atomic structures (Wang et al., 2022).

To address these challenges, researchers have redirected their attention to the Metaverse, which provides solutions through its technologies, including virtual reality (VR). VR can be used to teach chemistry in an engaging and enjoyable manner. It provides an immersive environment that allows students to access the virtual classroom from remote locations (Edwards et al., 2019; Pan et al., 2022; Ververidis et al., 2022; Castaneda et al., 2018). While acknowledging that various VR-based applications exist for 3D visualization of chemical bonding, molecular structures, and intramolecular interactions (Jiménez, 2019; Febriana et al., 2022), our development of the Virtual Chemistry Classroom for Chemical Bonding (VC3B) is driven by a specific gap in the current literature.

Chemistry, often perceived as a challenging subject, poses unique hurdles for students due to its abstract nature, particularly when it comes to understanding fundamental concepts such as chemical bonding, molecular structures, and chemical formulas. Traditional classroom teaching and laboratory experiments have long been used to enhance student engagement and understanding (Halim et al., 2018; Penn and Ramnarain, 2019). However, the education landscape has undergone significant changes with the emergence of distance learning and the impact of the COVID-19 pandemic (Murphy, 2020; Phattanawasin et al., 2021). The use of 2D screens in current online platforms limits students' complete engagement in grasping complex chemical ideas, even though computer-based visual aids help improve understanding. However, students face difficulties mentally transforming 2D pictures into intricate 3D molecular shapes (Won et al., 2019; Chan et al., 2021; Ahmad et al., 2023). This limitation is what we aim to overcome. The novel contribution of VC3B is its integration of game-based learning and pedagogical principles into the immersive VR environment, which has not been explored in previous VR applications for chemistry. Our VR classroom, especially designed specifically for middle school students, addresses this critical gap by providing a more interactive, engaging, and pedagogically sound method for teaching chemical bonding. This innovative solution enhances chemistry education in a timely manner.

1.1 Virtual chemistry classroom for chemical bonding (VC3B)

In the present study, a Virtual Chemistry Classroom for Chemical Bonding (VC3B) was developed to facilitate remote learning of chemical bonding and formulas for middle school students. This interactive and immersive environment aims to enhance understanding of these concepts. The VC3B utilizes game-based learning techniques to enhance the effectiveness and enjoyment of the learning experience for students. The use of game-based learning in teaching applications has been found to increase student engagement, retention, and improve learning outcomes (Janonis et al., 2020; Uaidullakyzy et al., 2022; Farooq et al., 2022; Sulaiman et al., 2022). It makes education more fun and engaging by allowing students to learn through virtual action, resulting in increased interest in the subject (Alsawaier, 2018; Tsay et al., 2018; Lampropoulos et al., 2022). Similar to other VR labs, VC3B is easily accessible regardless of time and location.

Our proposed system contains two games: 'Molecule Construction' and 'Chemical Formula.' These games are designed to facilitate learning about chemical bonding and formulas, respectively. In the molecule construction game, students must correctly attach the appropriate compounds to accurately build a molecule. In the chemical formula game, students compose the correct chemical formula for the chemical displayed within the virtual environment. The key components of the proposed system architecture are shown in Fig. 1. This system introduces fundamental chemistry concepts, aiding students in establishing a strong foundation at the middle level. Demonstrating these concepts visually in a virtual classroom can make it easier for students to understand. As a result, the emphasis in this study was designed with three aspects in consideration:

1. Create a virtual chemistry classroom for remote education.
2. To design a virtual chemistry classroom using game-based learning techniques in order to enhance learning effectiveness.
3. To enhance the critical thinking and problem-solving skills of middle school students, with a specific focus on chemistry.

We aim to address the following research questions in this study:

- *RQ1:* To what extent does the integration of game-based learning in a virtual reality (VR) chemistry classroom enhance students' understanding of chemical bonding and formulas, compared to traditional and online teaching methods?
- *RQ2:* What are the pedagogical implications and potential benefits of VR and game-based learning in the context of middle school chemistry education, and how does this approach affect students' engagement and motivation in the learning process?

Integrating game-based learning into VC3B represents a innovative advancement over existing applications. By incorporating elements of interactive gameplay such

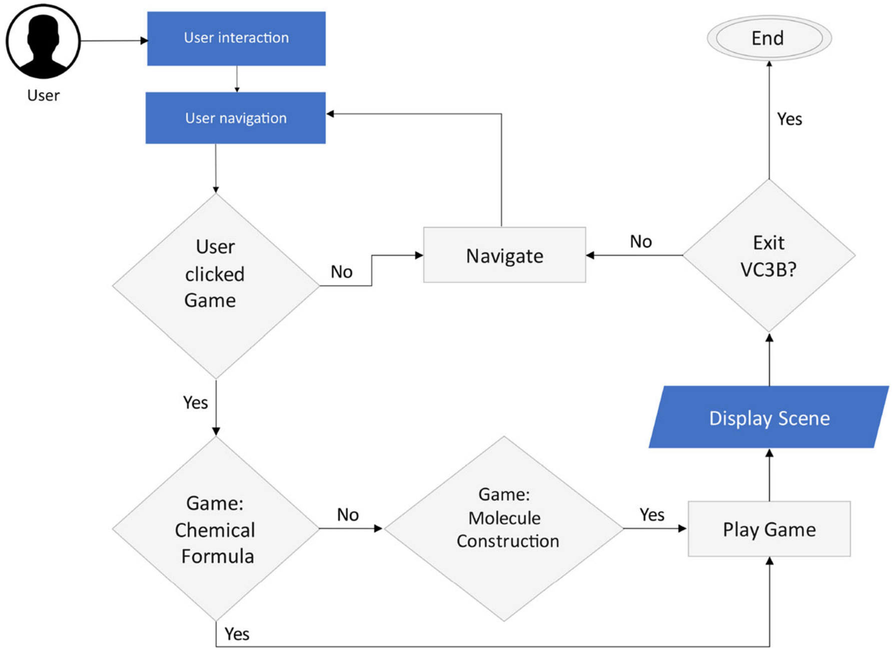

Fig. 1 The architectural layout of VC3B

as 'Molecule Construction' and 'Chemical Formula' games, our approach enhances student engagement, motivation, and active participation. These games provide immediate feedback and allow for an individualized learning path, reinforcing students' understanding of complex chemical concepts. Moreover, the real-world simulations and practical applications of chemistry in the games make the subject matter more relatable, thereby contributing to long-term knowledge retention. The inclusion of a competitive element fosters excellence and prolonged engagement, while the analytics and progress tracking features provide valuable data for educators to effectively tailor their teaching strategies. Game-based learning is a flexible educational method that accommodates diverse learning styles, offering versatility in its approach. In summary, our proposed VC3B system not only leverages the effectiveness of immersive VR but also utilizes the educational benefits of gamification. This addresses a gap in the field and significantly enhances the learning outcomes for students.

1.2 VC3B: A pedagogical tool for chemistry education

In the development of VC3B, we have placed a strong emphasis on the pedagogical principles and theoretical foundations that support effective education. In this regard, our work incorporates pedagogical principles of constructivism, feedback and reflection, active engagement, problem-solving, and critical thinking, differentiation, and assessment (Council, 2000). These principles resonate with VC3B, which incorporates an innovative game-based learning approach. By strategically implementing this technology, we have harnessed the cognitive engagement and active learning strategies (Council, 2000). The TPACK model (Mishra and Koehler, 2006), which intersects technological knowledge, pedagogical knowledge, and content knowledge, has been instrumental in our design process. It guides us in ensuring that our technology is not merely a tool but rather an enabler of enhanced pedagogy. Through this integration, VC3C bridges the gap between pedagogical theory and technological innovation, thereby offering a pedagogically sound and immersive learning experience for chemistry students.

Furthermore, the TPACK model has played a pivotal role in ensuring the effectiveness of VC3B. This model incorporates a balanced approach among technological, pedagogical, and content knowledge, aligning our approach with the best practices in education. In our application, the *T* or technological component, represented by the virtual reality environment, allows students to explore complex molecular structures. Drawing from the guidance provided in Council (2000), we have utilised technology to actively engage students in the learning process. The *P* or pedagogical component is embedded within the game-based learning approach, encouraging critical thinking and problem-solving, consistent with the principles of active learning provided in Council (2000). The *C* or content component reflects our expertise in chemistry education, ensuring that the subject matter is effectively conveyed through technology-enhanced pedagogy. We emphasize that VC3B not only represents an innovative improvement over existing applications but is firmly grounded in the well-established principles of effective education outlined in Council (2000) and Mishra and Koehler (2006). Through this pedagogical approach, we have developed a dynamic and immersive learning environment that not only educates but also inspires and empowers chemistry students in their educational journey.

The structure of the paper is as follows: First, related work is discussed in Section 2, which provides details of the related work. Section 3 presents the proposed methodology. Section 4 provides a detailed analysis of the system evaluation and discussion. Lastly, Section 7 presents the conclusion of the study.

2 Related work

2.1 Chemical bonding education using virtual reality

A comprehensive understanding of chemical bonding is crucial for learning chemistry, given its fundamental role in the subject. Numerous VR-based applications have been developed to facilitate the learning of chemical bonding in an interactive and immersive environment. For instance, Edwards et al. (2019) developed the VR Multisensory Classroom (VRMC), a haptic virtual reality immersive environment, to teach hydrocarbon bonding and molecule formation. The results of the study revealed that VRMC has the potential to promote high engagement, motivation, interest, and learning in organic chemistry, accommodating the diverse learning styles of users. In another research (Nasharuddin and Umar, 2021), researchers developed a VR mobile application with the aim of helping students visualize the process of chemical bonding. The researchers found that this approach enhanced students' comprehension and interest in the subject. The application featured a mini-game to evaluate learners' retention of knowledge, and the results demonstrated a positive impact on students' knowledge progression, confirming the effectiveness of the application.

Similarly, another study (Astuti et al., 2019) assessed the effectiveness of VR technology in enhancing students' scientific attitudes toward chemical bonding. The findings revealed a significant distinction in scientific attitudes among different classes. The group that utilized VR in combination with hybrid learning and a physical laboratory (EG-2) showed significantly improved results compared to the other classes (CG and EG-1). Another study introduced a novel educational VR activity known as interactive molecular dynamics in virtual reality (iMD-VR) (Ferrell et al., 2019), was designed and implemented to demonstrate chemical concepts and engage students in exploring dynamic molecular structures, motions, and interactions. In the first semester of the introductory organic chemistry course, 70 students participated in a task that involved manipulating a methane molecule through a carbon nanotube using the iMD-VR software. Assessment of this activity revealed significant motivational benefits and measurable improvements in learning.

A study by Ucar et al. (2017) investigated the effects of haptic VR applications with forced feedback on the learning of chemical bonding among gifted students. They developed a haptic application in virtual reality for this purpose. The study revealed that the experimental group, which used a force feedback haptic device in a VR environment, exhibited a more positive attitude towards VR haptic applications compared to the control group that received traditional teaching methods. The findings indicated that VR haptic applications in education could offer greater benefits and potentially enhance productivity.

2.2 Chemistry education using virtual reality

Other than chemical bonding education in a VR environment, several studies have been conducted on teaching chemistry using VR (Patle et al., 2019; Howard and Van Zandt, 2021). A study (Hu-Au and Okita, 2021), assessed the differences in student learning and behaviors when comparing real-life chemistry laboratories to virtual reality (VR) laboratories. The researchers found similar learning performance; however, participants in the VR laboratory demonstrated a significant improvement in applied knowledge and scores. In another study, WondaVR was used to develop a VR chemistry lab to teach students how to use infrared spectrometers. The results revealed that a VR laboratory can be utilised in distance learning, as there were no significant differences in learning outcomes between the traditional laboratory group and the VR laboratory group (Dunnagan et al., 2019).

Various research has also proven the cost-effectiveness of VR chemistry laboratories for distance learning. Narupa is a virtual reality application developed for real-time interactive molecular dynamics simulations (O'Connor et al., 2019). It has diverse research applications, including studies on protein-ligand interactions, investigations into transport dynamics, and sampling of biomolecular conformations.

Researchers compared the effectiveness of paper-based and virtual laboratory experiences in improving hands-on chemistry practical skills among secondary school students in the Dodoma region of Tanzania (Manyilizu, 2023). A virtual chemistry laboratory was developed and implemented at Dodoma Secondary School to provide practical exposure to students who had not previously had access to laboratory sessions. The results indicated that students who experienced the virtual laboratory before the real one performed better in the real laboratory than those who started with traditional paper-based practical methods.

A recent study (Fombona-Pascual et al., 2022) developed a virtual chemistry laboratory that incorporated advanced molecular and atomic visualization. The findings revealed that virtual laboratories can create immersive digital environments, enabling students to visualize molecular actions that would otherwise be intangible. This visualization of intangible chemistry concepts in a virtual environment significantly increased students' motivation to learn and improved their understanding of chemistry. Robert and Piotr Wolski and Jagodziński (2019) developed a virtual chemistry laboratory that utilizes hand movement recognition for middle and secondary school students. The results obtained showed that the students who worked in the VR laboratory retained information better and performed better in solving chemical problems than the other students. In Ali et al. (2023) researchers introduced the concept of an adaptive aids virtual reality chemistry laboratory which enabled the users to enhance their performance and successfully conduct chemical experiments by following correct procedures. The results of the study demonstrated that the proposed system led to incremental improvements in students' performance, particularly a significant enhancement in the performance of weak students, surpassing that of good and average students.

VR-based chemistry applications have emerged as flexible, cost-effective, and valuable tools for learning and education in schools and universities. Particularly in remote learning scenarios where physical attendance is not possible, these applications offer additional advantages. To address the need for immersive game-based learning in chemistry, this study introduces the Virtual Chemistry Classroom for Chemical Bonding (VC3B). VC3B is a VR-based classroom that incorporates game elements, allowing students to learn about chemical bonding and formulas remotely. This innovative approach not only facilitates remote learning but also motivates students to deepen their knowledge in the subject. By accessing VC3B, students can engage in interactive and immersive experiences that enhance their understanding of chemical bonding and formulas. The following section elaborates on the methodology employed for the development and evaluation of VC3B.

3 Methodology

3.1 VC3B architecture

The architecture of VC3B is demonstrated in Fig. 1.

3.1.1 User interaction in immersive VC3B environment

The first component of the proposed system enables the user to navigate the immersive VC3B environment, allowing them to engage with the interactive virtual space of VC3B.

3.1.2 Game modules of VC3B

After the user enters the immersive virtual environment of VC3B, they can select whether they want to play molecule construction or chemical formula game modules.

3.1.3 Molecule construction game of VC3B

When the user selects the molecule construction game module to play, they now have to complete all ten levels of this game module in order to progress to the next game.

3.1.4 Chemical formula game of VC3B

When users complete all ten levels of the molecule construction game, they will have the option to choose from the menu whether they want to play the chemical formula game or exit the environment. If users choose to play the chemical formula game, they will complete ten levels and advance further. At the end of the game, the user can exit the environment by accessing the menu within the immersive interface.

3.2 Software and hardware requirements

Several software programs were used in the development of the application. Blender 3D visualization software was used to model the 3D environment and objects. The 3D models were then integrated into the Unity 3D game engine, where interactivity with the objects was implemented. Scripts were used to add functionality to the objects. The Oculus Quest plugin has been integrated into Unity 3D. The application was then exported to the Oculus Quest 2 and validated.

In our study, Unity3D was employed to facilitate a comprehensive virtual environment. It served as the foundational platform enabling the creation of the immersive virtual setting within the VC3B, development and integration of interactive elements, 3D models, spatial layouts and the implementation of game-based learning modules. It facilitated the creation of a dynamic, visually stimulating and interactive space where students engaged with chemical bonding concepts through diverse activities, including ’Molecule Construction’ and ’Chemical Formula’ games. These elements leveraged Unity 3D’s capabilities to offer a multifaceted educational experience in a VR environment.

3.3 The VC3B

When the virtual system experience begins, the user uses the controller to press the start button. VC3B immerses the user. Inside VC3B, the game will begin when the user clicks on it. Our proposed system contains two games: “Molecule Construction” and “Chemical Formula,” designed to facilitate the learning of chemistry concepts. In the molecule construction game, the user will have to correctly attach the appropriate compounds in order to accurately build a molecule. In the second game, Chemical Formula, the user will compose the correct chemical formula for the chemical displayed within the virtual environment. Once users have finished playing, they can either return to navigating VC3B or exit from the application.

3.3.1 Navigation and interaction within the environment

The users can navigate their surroundings using the controller or by employing free or natural locomotion. Furthermore, users can interact with the environment by grabbing objects and learning how to use Oculus Quest controller. The classroom setting designed in Unity3D is shown in Fig. 2. Game-based learning is the primary learning technique used in this experience.

The design of the screens within VC3B was meticulously crafted to optimize interactivity and foster an engaging learning environment. Each screen and its layout were purposefully structured to align with pedagogical principles and enhance user engagement. For instance, the ’Molecule Construction’ (Fig. 3) and ‘Chemical Formula’ (Fig. 5) game screens were designed with a user-centric approach, aiming to provide an intuitive interface that allowed students to manipulate and interact with 3D molecular structures effortlessly. The incorporation of a user-friendly interface ensured easy navigation and manipulation of objects within the virtual space, promoting an immersive and dynamic learning experience.

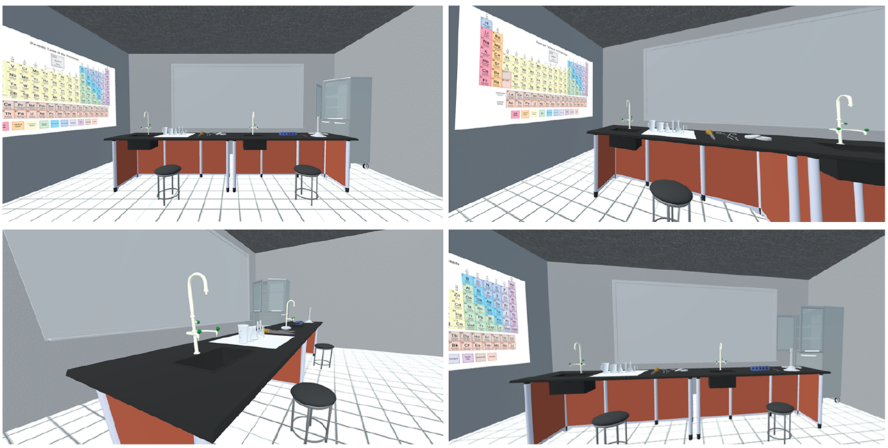

Fig. 2 The inside of the classroom is designed in Unity 3D. Students can navigate and interact with the environment

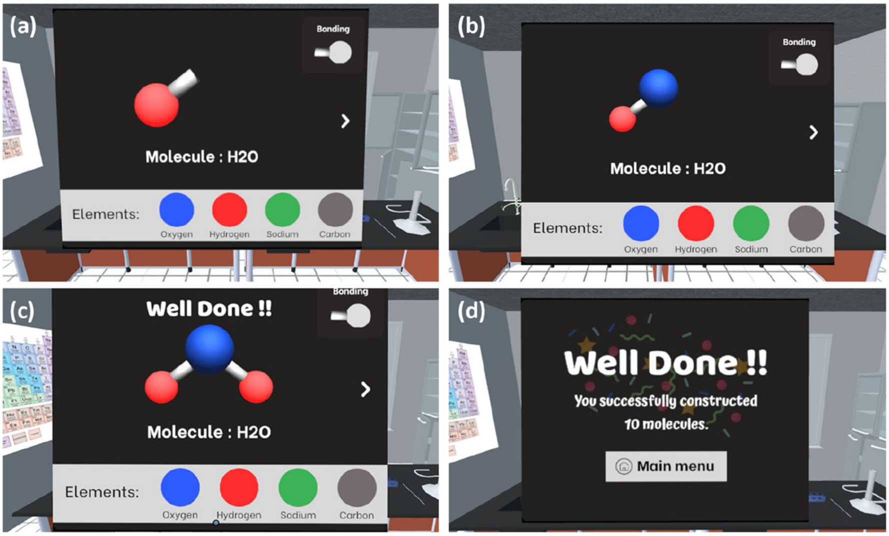

Fig. 3 Molecule Construction game in VC3B. (**a**) Main scaffolding with hydrogen atom. (**b**) Place oxygen atom in the scaffolding. (**c**) Positioning other atoms and compound formed. (**d**) Well Done! message for students after completing the whole game

Moreover, the rational behind screen design stemmed from fostering active participation and learning retention. The visual layout and interaction elements were tailored to encourage students' critical thinking an problem-solving skills. In the 'Chemical Formula', for example, the design encouraged students to assemble chemical formulas, promoting a hands-on approach to learning and enhancing memorization through interactive engagement. Additionally, the incorporation of real-time feedback mechanisms within the screens aimed to provide immediate responses to students actions, reinforcing their understanding of chemical concepts.

3.4 Game-based learning approach with gamification elements

In our game-based learning approach, we have integrated gamification elements to enhance the educational experience and increase student engagement.

1. *Points and Scoring:* Students earn points for completing tasks and providing correct answers, which promotes achievement and friendly competition.
2. *Leaderboards:* Individual scores are showcased, providing students with more motivation to improve.
3. *Feedback and Rewards:* Immediate feedback and rewards for correct choices motivate and encourage continuous learning.
4. *Progress Tracking:* Empowers students to monitor their educational journey, observe improvements, and set personal learning goals.

Collectively, these gamification elements work in harmony to create a captivating, interactive, and effective platform for learning through games. Our approach specifically focuses on overcoming the challenges associated with chemistry education,

Table 1 List of chemical elements used in VC3B

S.No.	Chemical elements
1.	Hydrogen
2.	Sodium
3.	Oxygen
4.	Carbon
5.	Phosphorus
6.	Iron
7.	Hydrochloric acid
8.	Nitric acid
9.	Methane
10.	Sodium phosphate

allowing students to comprehend complex subjects more easily. By incorporating these elements, we ensure a dynamic, immersive, and enjoyable learning environment for students. This enables them to develop a deeper understanding of abstract and complex concepts, such as chemical bonding and formulas.

3.4.1 Molecule construction game

Molecule Construction is the first game created specifically for the purpose of basic molecular construction. The objective of this game is to teach students chemical bonding in an engaging and immersive VR environment. In this game, the students will be given the name of a compound along with a list of its components. They must construct the structure by rearranging the atoms (balls) in their proper positions. The level of difficulty is minimal since it is specifically designed for middle school students. There are 10 levels designed, each of which includes the construction of 10 compounds.

The chemical elements used in VC3B are given in Table 1. All elements are color-coded in the element bank provided at the bottom of the screen. Students will need to select an element from the bank and connect it to other elements. The color scheme includes blue for oxygen, red for hydrogen, green for sodium, gray for carbon, purple for phosphorus, and orange for iron.

After submitting the model, the learner will receive either a 'Well Done!' message, in case of success, or a 'Try Again!' message, in case of failure. The student can leave the game at any moment and return to the main virtual classroom by clicking on the home menu located in the corner of the room. The level of enjoyment is directly proportional to the duration and frequency of gameplay, which reinforces the learning process. Students can enhance their memorization of molecular structures by constructing molecules. Additionally, if they may experience stress during the exam period, they will have a visual representation of the molecules in their mind, aiding in the recall of the compounds. Figure 3 illustrates the construction of molecules in the virtual environment. Figure 4 shows students learning about chemical bonding and formulas in VC3B using the Oculus Quest 2.

Fig. 4 Students learning chemical bonding and formula in VC3B

3.4.2 Chemical formula game

In this game, students must compose the chemical formula for the given material. The objective of this game is to assist students in memorizing the basic chemical formulas. A picture of a chemical will be provided along with its name. The chemical formula game will display the initial part of the formula, and students can click on the empty space to access a virtual keyboard. From the virtual keyboard, users can select the appropriate alphabets and numbers to complete the chemical formula (Fig. 5).

Considering the middle school level, the chemicals included in this game are salt, sucrose, caffeine, baking soda, ammonia, bleach, nail polish remover, vinegar, glycerin (glycerol), and natural gas (methane). These elements are selected because they are familiar to almost everyone and are commonly used in everyday life. Images are also carefully selected so that students can differentiate between them, as some chemicals may appear very similar, such as salt and sugar. The start of each chemical formula is provided to students because it is intended to be a learning experience rather than a test. When the student enters the formula for each chemical, the game ends, and the results display the student's score. If the student accurately answers 5 out of 10 items, the message 'Satisfactory' appears and one star is awarded. When the student receives a score of 7 out of 10, they are awarded a 'Good Job' message and two stars. When all the questions are answered correctly, the message 'Excellent' is displayed with three stars.

This game aims to assist students in memorizing fundamental chemical formulas. Similar to the 'Molecule Construction' game, which has been designed and developed

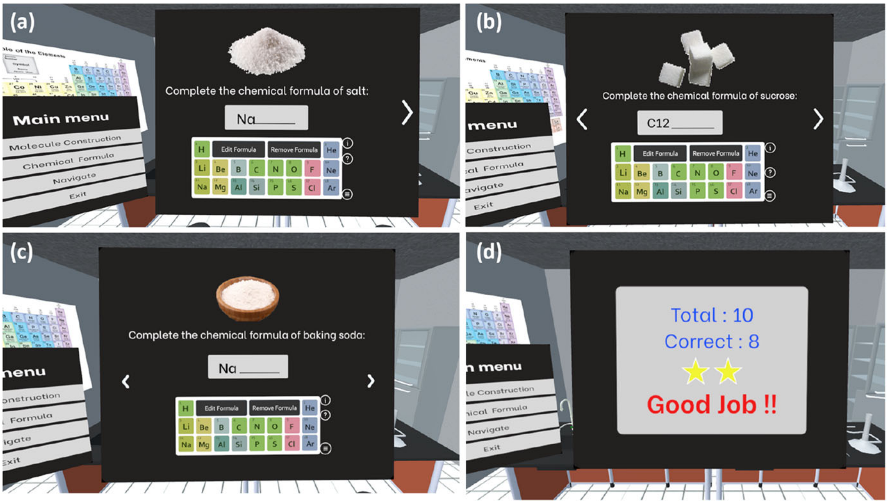

Fig. 5 Chemical Formula game in the VC3B. (**a**) A substance picture is shown, with a hint of its chemical formula, and a student is required to complete it. (**b**) An image of sucrose is shown. (**c**) The virtual keyboard is shown, and the student using the controller enters data. (**d**) End result of the game is presented on screen

within a VR environment, 'Chemical Formula' game is also developed within a VR environment. The development of a 3D VR environment for the chemical formula game enhances learning by providing an immersive and interactive experience that aligns with pedagogical principles. It offers active learning, a learner-centered approach, 3D spatial learning, immediate feedback, multi-sensory experiences, and adaptability. These advantages surpass traditional methods, making the VR game an innovative and pedagogically rich approach to learning chemical formulas.

The decision to incorporate ten levels in both the 'Molecule Construction' and 'Chemical Formula' games in VC3B was guided by several considerations. These ten levels offer a structured and progressive learning experience, reinforcing specific concepts of chemical bonding and chemical formulas. They sustain student engagement over an extended period and provide a variety of scenarios and formulas related to chemical bonding, making the subject matter more relatable and applicable. The content of each level aligns with the learning objectives, ensuring that students encounter a wide range of chemical scenarios and gradually develop their knowledge. In conclusion, the inclusion of ten levels in both games aims to offer a comprehensive, progressively challenging, and engaging learning experience that caters to the diverse needs and abilities of middle school students.

3.5 Participant selection

Participants for this study were recruited from a local private school with prior permission from the school authorities. The selected participants were in the 8th grade and their ages ranged from 12 to 13. The student body consisted of three sections: A, B, and C, with each section comprising 30 students. The selection process was inclusive, involving students from different sections to ensure diversity among the study participants. Participation in the study was voluntary and carried out with the permission and cooperation of the school authority. Students willingly participated in the study, and their involvement was voluntary.

The participants were divided into three groups based on the learning medium from which they received lecture on chemical bonding and chemical formulas. These 90 students were divided into three groups: G1, G2, and G3. The learning mediums of all three groups are as follows:

1. G1 used the textbook.
2. G2 used the online lecture.
3. G3 used VC3B.

The assignment of students to their respective groups was performed using a random allocation process. This method ensured that students were assigned to groups without bias, facilitating a fair distribution among the traditional, online, and VR groups.

3.6 Measurement tools

3.6.1 Learning outcome quiz

The measurement tools for assessing students' learning outcomes included a paper-based quiz, as shown in Table 2. This paper-based quiz was designed to assess the knowledge acquired from the lecture delivered to all three groups during the study experiment. This quiz was designed by subject expert teachers from the school where participants were recruited, ensuring the validity of this measurement tool. The first four questions in the quiz test students' knowledge of chemical bonding, while the next five questions test their knowledge of chemical formulas. The expert subject teachers rated the learning outcome performance of students from all three groups. This ensured the validity of the measurement tool that was developed. G3 participants

Table 2 Questions for assessing learning outcome of students

Q.No.	Questions
1.	How many oxygen atoms are in carbon dioxide?
2.	How many hydrogen atoms are in a water molecule?
3.	How many hydrogen atoms are in baking soda?
4.	How many chlorine atoms are present in sodium chloride?
5.	Na3PO4 is the formula of which chemical?
6.	C3H8O3 is the formula of which chemical?
7.	What is the formula of salt?
8.	What is the formula of water?
9.	NaClO is the formula of which chemical?

were required to assign ratings to each question using a rating scale ranging from 1 to 5, with 1 indicating ‘strongly agree’ and 5 indicating ‘strongly disagree’.

The learning outcome scores achieved by G1, G2, and G3 were compared using the developed quiz. In this study, the decision to compare VC3B using VR with traditional textbook learning and online lectures was carefully considered. Comparing VR to these established methods serves as a baseline for assessing the innovative aspects of VC3B. This approach addresses the real-world scenario where traditional methods are still widely used. It allows us to evaluate how VR bridges the gap between conventional education and advanced technological approaches. Furthermore, our primary focus is to assess the pedagogical implications of VR and game-based learning. We aim to align these innovative technologies with established pedagogical theories in order to understand their potential benefits in enhancing students’ understanding and motivation in the context of chemistry education.

3.6.2 Usability evaluation questionnaire

Users’ opinions Table 3 regarding the proposed VC3B system were analyzed using a survey questionnaire. A 5-Likert scale questionnaire was developed based on the Five Usability Principles of Human-Computer Interaction (Table 5) for evaluating system usability. The items of the questionnaire were developed based on the System Usability Scale (SUS) (Brooke, 1996).

3.7 Experimental setup

On the first day of the experiment, the students in the VR group (G3) received training on how to use the Oculus Quest 2 HMD, navigate the VR environment, and interact with the 3D chemical models within the VR environment. For this purpose, a total of five Oculus Quest headsets were made available. Based on the availability of HMDz, six experimental sessions were held, each consisting of five students, to ensure comprehensive training. To accomplish this, the experimental sessions were conducted over two days. Three sessions were held on the first day, and the remaining three were held on the following day. After each session, the students were given a subject-related quiz designed to evaluate their learning outcomes. G3 students were informed about cyber sickness and were asked to alert investigators immediately if they experience any symptoms. G3’s participants played the games “Molecule Con-

Table 3 VC3B usability evaluation questionnaire

Q.No.	Questions
1.	How much would you rate VC3B for learning chemical bonding and formulas?
2.	Is the molecule construction game effective for learning chemical bonding?
3.	Were you motivated to learn chemical bonding through VC3B?
4.	Do you feel VC3B is a smooth-running interface for learning chemical bonding?
5.	Are you satisfied with the interface of VC3B?

struction" and "Chemical Formula" in VC3B. Finally, they were required to complete a questionnaire to evaluate their level of satisfaction with VC3B. The experimental sessions lasted for total 40 minutes following the class schedule of the school, with 30 minutes allocated for teaching via VC3B and ten minutes for subsequent quiz to assess learning outcome.

Concurrently, the traditional (G1) and (G2) groups engaged in lecture sessions that paralleled the sequence of the VR group's learning. The sessions were also conducted within the same 40 minute time frame, comprising a 30 minute lecture segment followed by a 10 minute quiz assessing the learning outcomes. It is noteworthy that all three groups were instructed by the same subject teacher. This approach ensured consistency in content delivery and instructional quality across groups, minimizing potential biases arising from varying teaching methodologies, consequently enhancing the study's internal validity.

The experimental procedure was meticulously designed to address the research objectives. The study aimed to assess the efficacy of VC3B in comparison to traditional and online teaching methods. This research was motivated by the need to explore the potential advantages of integrating virtual reality (VR) and game-based learning into middle school chemistry education. Specifically, it sought to enhance student engagement and comprehension by offering a novel learning approach.

3.8 Statistical analysis

SPSS v23 was used to perform the statistical analysis of the data. First, the descriptive statistics were calculated for the measurement scores of each group on the quiz. The success rate of each group was also calculated as in (1). To measure the differences in scores of each group, an ANOVA was performed. Similarly, percentages of VC3B usability for each response on each item of the questionnaire. When comparing the learning outcomes of all three groups, a significant difference in their results was observed. The success rate of students in the quiz was assessed as:

$$SuccessRate = \frac{CorrectAnswers}{TotalQuestionsAsked} * 100 \tag{1}$$

Table 4 Results of of learning outcome of study groups (n = 90)

Group	Mean	SD	Percentage(%)
G1	5.40	2.21	60.6
G2	5.63	2.04	66.36
G3	8.97	0.18	81.51

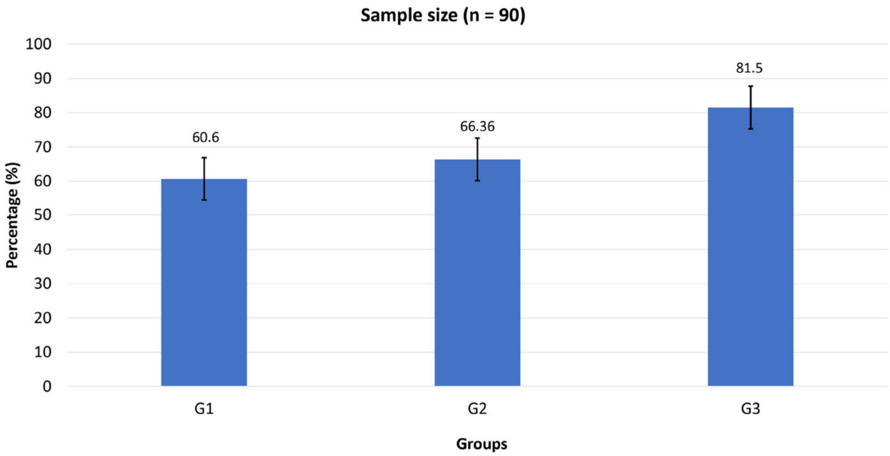

Fig. 6 Mean success rates of G1, G2 and G3

4 Results

4.1 Student's learning outcomes

The results of the learning outcome quiz revealed that G3 outperformed G1 and G2. The mean success rate of G3 was 81.51% (mean = 8.97 and standard deviation = 0.18), while G2 was 66.36% (mean = 5.63 and standard deviation = 2.04). Lastly, G1 had a success rate of 60.6% (mean = 5.40 and standard deviation = 2.21) as shown in Table 4 and Fig. 6.

The results of ANOVA demonstrate a significant difference in the performance of G1, G2, and G3 (Table 5). Results demonstrate significant mean differences across the groups on students' performance with $F(2, 87) = 39.48$, $p = .000 < .001$, $\eta^2 = 0.47$, 95% confidence interval. Findings revealed that students in Group 3 who used VC3B performed better than students in G1 and G2 who used textbooks and online lectures, respectively.

Table 5 Mean, standard deviation and ANOVA results of G1, G2, and G3

Group	Mean	SD	F (2, 87)	p	η^2	95% CI [LL,UL]
			39.48	.000***	0.47	
G1	5.40	2.207				[-4.66, -2.47]
G2	5.63	2.04				[-4.43, -2.24]
G3	8.97	0.18				[2.24, 4.43]

***p<.001

Table 6 Results of VC3B evaluation by G3 for each question

Q.No.	Poor	Satisfactory	Good	Very Good	Excellent
1.	0	13.9	24.5	22.4	39.2
2.	0	11.9	18.2	28.4	41.5
3.	0	16.3	19.3	26.5	37.9
4.	0	8.0	16.5	27.7	47.8
5.	0	4.4	12.9	32.8	49.9

Note: Each cell displays percentage value

4.2 Analysis of VC3B usability

The results obtained are presented in Table 6 and illustrated in Fig. 7.

The first question was about having sufficient information on chemical bonding and formulas. In response, 39.2% of students rated it as 'Excellent', 22.4% as 'Very good', and 24.5% as 'Good'. Hence, this implies that VC3B provides adequate information for learning about chemical bonding and formulas. The second question assessed the effectiveness of a molecule construction game for learning about chemical bonding. The 41.5% of students rated it as 'Excellent', 28.4% as 'Very good', and 11.9% as 'Good'. This implies that visually presented information in VC3B about chemical bonding is useful for enhancing the understanding of chemistry concepts. The third question was related to the interface of VC3B for learning chemical bonding and formulas. In response, 37.9% of the students rated it as 'Excellent', 26.5% as 'Very good', and 16.5% as 'Good'. Furthermore, 47.8% of students rated the fourth question as 'Excellent', 27.7% as 'Very Good', and 16.5% as 'Good'. For the last question, regarding the satisfaction level of students with VCB, 49.9% rated it as 'Excellent', 32.8% as 'Very good', and 12.9% as 'Good'.

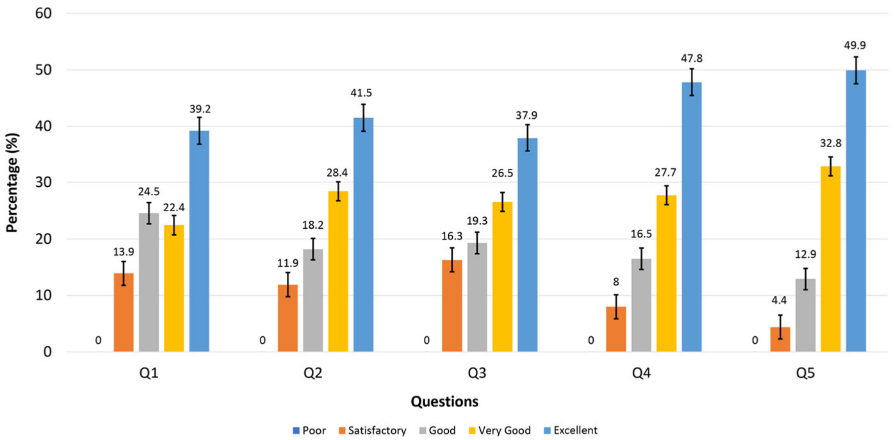

Fig. 7 VC3B usability evaluation results

5 Discussion and implications

5.1 Key findings

Our study aimed to evaluate the effectiveness of a Virtual Chemistry Classroom for Chemical Bonding (VC3B) in enhancing students' understanding of chemical bonding and chemical formulas compared to traditional and online teaching methods. The key finding of our study is that VC3B, a virtual reality-based classroom, is a highly effective educational medium, surpassing traditional and online platforms. Our results revealed that students who utilized VC3B as their learning medium outperformed those who relied solely on textbooks or online video lectures. The average success rate of the VC3B group was 81.51%, significantly higher than that of the traditional group (60.6%) and the online group (66.36%). This finding underscores the potential of immersive virtual reality and game-based learning in enhancing students' comprehension of complex chemistry concepts.

The results of our study imply that VC3B, with its immersive virtual environment and game-based learning approach, can significantly enhance students' understanding of chemical bonding and chemical formulas. The incorporation of gamification elements, immediate feedback, and interactive gameplay in VC3B led to increased engagement, motivation, and active participation among students. The positive outcomes of this approach can be attributed to the fact that it aligns with pedagogical principles, such as constructivism, feedback, active engagement, problem-solving, and critical thinking.

Furthermore, the TPACK model played a pivotal role in the development of VC3B, ensuring a balanced approach to technological, pedagogical, and content knowledge. VC3B bridges the gap between pedagogical theory and technological innovation, providing students with a pedagogically sound and immersive learning experience. The inclusion of ten levels in both the 'Molecule Construction' and 'Chemical Formula' games in VC3B offers a structured and progressively challenging learning experience, which contributes to long-term knowledge retention.

The findings resonates with prior research emphasizing virtual reality's (VR) potential to enhance learning outcomes. it echoes previous literature, showcasing VR's engagement and effectiveness in teaching chemistry and emphasizing improved comprehension and knowledge in chemical bonding (Edwards et al., 2019). Moreover, our findings resonates with with studies showcasing VR's role in boosting motivation, problem-solving skills and enhanced students' performance (Fombona-Pascual et al., 2022; Ali et al., 2023).

5.2 Enhancing student understanding with game-based learning

The first research question *(RQ1)* in our study aimed to investigate the impact of integrating game-based learning in a VR chemistry classroom on students' comprehension of chemical bonding and chemical formulas, in comparison to traditional and online teaching methods. Our findings indicate that the integration of game-based learning, specifically the Virtual Chemistry Classroom for Chemical Bonding (VC3B) has a significant positive impact on students' comprehension and performance.

Traditional teaching methods, often limited by 2D displays, have faced challenges in effectively communicating the intricacies of chemical bonding, molecular structures, and chemical formulas. However, our approach of using VR-based games bridges this educational gap. By incorporating gamification elements such as 'Molecule Construction' and 'Chemical Formula' games, we successfully fostered active engagement and enhanced the immersive learning experience. This approach enabled students to comprehend and apply intricate chemical concepts, ultimately leading to significantly enhanced learning outcomes.

Our results reveal that students who utilized VC3B (Group G3) outperformed their counterparts in the traditional textbook (G1) and online video lecture (G2) groups. The average success rate of Group G3 was significantly higher, demonstrating the substantial benefits of VC3B's game-based learning approach. Students who utilized the potential of the immersive VR environment, coupled with interactive gameplay, displayed an enhanced understanding of chemical bonding and formulas. The immediate feedback, individualized learning paths, and real-world simulations within VC3B were instrumental in reinforcing the students' understanding of these complex concepts.

These findings underscore the ability of VC3B to significantly enhance students' thinking and problem-solving skills, thereby effectively contributing to the overall efficacy of learning through game-based techniques. VC3B represents a paradigm shift in chemistry education by successfully integrating technology, gamification, and pedagogical principles to enhance students' understanding and performance in this challenging subject.

5.3 Pedagogical implications and enhanced engagement

The second research question *(RQ2)* explored the pedagogical implications and potential benefits of using VR and game-based learning in middle school chemistry education. It also examined the impact on students' engagement and motivation in the learning process.

VC3B was developed with a strong focus on pedagogical principles, aligning with educational best practices. It incorporates constructivist approaches, feedback mechanisms, active engagement, problem-solving and critical thinking, differentiation, and assessment. Through this integration, VC3B emerges as an innovative and pedagogically sound tool that offers students an immersive and dynamic learning experience. The utilization of the TPACK model has been crucial in ensuring that technology serves as a facilitator of improved teaching methods, effectively bridging the gap between theory and innovation.

The findings from our study suggest that students were highly satisfied with VC3B as a pedagogical tool. They found the VR interface engaging and effective for learning complex chemical concepts. This reflects the success of VC3B in effectively combining technological, pedagogical, and content knowledge. The inclusion of gamification elements increases students' motivation and engagement, developing a deeper interest in the subject matter.

In developing VC3B, our study drew upon extensive research in VR-based education, underscoring its impact on chemistry learning. Studies like Edwards et al. (2019) showcased VR's engagement and effectiveness in organic chemistry, echoed by others Nasharuddin and Umar (2021), Astuti et al. (2019) emphasizing improved comprehension and knowledge in chemical bonding. Additionally, investigations into WondaVR Dunnagan et al. (2019), Narupa O'Connor et al. (2019), and virtual labs (Hu-Au and Okita, 2021; Manyilizu, 2023) highlighted VR's efficacy, especially in distance learning settings. Recent works (Fombona-Pascual et al., 2022) emphasized VR's role in visualizing abstract concepts, boosting motivation and problem-solving skills, while adaptive aids in VR labs (Ali et al., 2023) showed promise in enhancing weaker students' performance. These studies collectively underline VR's flexibility, cost-effectiveness, and value in advancing chemistry education.

In conclusion, the integration of game-based learning and pedagogical principles within the VC3B system represents a significant advancement over traditional teaching methods. It not only utilizes the potential of immersive VR but also exploits the educational benefits of gamification. The results of this study reveal the significant positive impact of VC3B on students' understanding, engagement, and motivation in the context of middle school chemistry education. By promoting interactive, engaging, and pedagogically sound approaches to teaching complex chemical concepts, VC3B serves as an innovative and timely solution that significantly improves learning outcomes.

6 Limitations and future work

While our study highlights the effectiveness of VC3B, several limitations exist. The research focused on middle school students, which may limit its generalizability to other age groups or educational levels. The controlled environment and short duration of the study may not fully capture the long-term impact of VC3B. To advance our findings, future research should explore the platform's sustained effect on knowledge retention, encompass diverse student populations, expand the content coverage of VC3B, and continually incorporate feedback for ongoing improvement. Furthermore, conducting comparative analyses with existing diverse VR platforms in chemistry education would offer valuable insights into the relative effectiveness and unique attributes of VC3B. This extension would provide crucial insights into VC3B's relative efficacy, guiding its improvement and understanding its distinct contributions.

7 Conclusion

The Virtual Chemistry Classroom for Chemical Bonding (VC3B) represents a significant advancement in education, offering an innovative approach to teaching complex chemistry concepts. Our study has demonstrated that VC3B, with its fusion of immersive virtual reality and game-based learning, outperforms traditional and online teaching methods. It enhances student engagement, motivation, and comprehension of challenging subjects such as chemical bonding and formulas. VC3B's success is rooted in its alignment with pedagogical principles, such as constructivism, feedback, and problem-solving. By integrating technology, pedagogy, and content knowledge through the TPACK model, VC3B offers a dynamic and immersive learning environment. It bridges the gap between pedagogical theory and technological innovation, empowering students on their educational journey. Based on the results of the presented study, the VC3B may be successfully utilized for teaching the chemistry curriculum in remote education. This system also has the potential to enhance students' cognitive abilities, such as critical thinking and problem-solving, through its game-based learning technique. In the future, the proposed system will incorporate advanced chemistry concepts for higher levels of education. Furthermore, an immersive virtual classroom, similar to VC3B will be developed for various fields of study, such as biology and physics.

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Declarations

Competing interests The authors have no conflicts of interest to declare that are relevant to the content of this article and journal.

Ethical Approval All of the methodologies employed in the relevant study were compliant with the institutional and national research committees' codes of conduct and appropriate ethical standards.

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