

# Systematic Literature Review: Visualizing of Molecular Structures and Chemical Reactions Through Augmented Reality (AR)

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**Abstract:** This article explores molecular structures and chemical reactions in augmented reality (AR) created between 2021-2025. The goal of this research is to identify the most advanced forms of augmented reality, materials related to molecular structures and chemical reactions that have been developed as augmented reality, and the benefits of augmented reality in the study of these topics. This study's methodology is a systematic review of the literature. Three steps are involved in conducting a systematic literature review: planning, implementation, and reporting. This article have 16 publications were found using the criteria based on the study's findings, and additional analysis was done. The analysis's findings demonstrate how different kinds of augmented reality, both marker-based and markerless, are generated molecular structures and chemical reactions. The most advanced useful is hybrid AR for molecular structures and chemical reactions. The most advanced content in the form of instructional games includes geometry and symmetrical molecules, which have been demonstrated to enhance students' molecular comprehension.

**Keywords:** Augmented reality; Chemistry; Molecular; Systematic literature review

## Introduction

Students often consider chemistry to be a difficult and complex subject (Ardura et al., 2021). This perception can affect students' academic performance and their future professional decisions (Vilia & Candeias, 2020). The study found that spatial visualization is crucial for understanding the concept of submicroscopic, which can lead to serious misconceptions in chemistry education (Coduto et al., 2024). In chemistry, both scientists and students interact with various external representations, such as text and images found in educational materials or research papers. Combining graphical and verbal representations is useful for explaining complex cause-and-effect systems in science (Castro-Alonso et al., 2019). Conceptually, understanding molecular structures and chemical reactions relies on the ability to represent submicroscopic objects – such as atoms, chemical bonds,

and molecular geometry – which are abstract and cannot be observed directly. These representations are typically visualized using ball-and-stick or space-filling models for molecular structures, as well as changes in bond configurations to illustrate the dynamics of chemical reactions. Augmented reality (AR) enables the real-time integration of three-dimensional digital objects into the real world, allowing users to observe and interact directly with molecular models and chemical reaction simulations from various perspectives. Through this capability, AR bridges the gap between the static two-dimensional representations found in conventional learning and a more intuitive three-dimensional spatial understanding, thereby potentially strengthening students' conceptual understanding of abstract and dynamic chemical phenomena (Laohapornchaiphan & Chenprakhon, 2024).

According to empirical studies, positive attitudes, student enjoyment, and their achievements in chemistry

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are strongly correlated. Since many students lose interest in science before they reach more in-depth material in high school and college, it is essential to engage students in chemistry through child-friendly educational approaches (Mellander & Lind, 2021). Representations have an important role in science communication (Rau, 2017). Chemical phenomena can be expressed using a variety of representations, including wedge-dashnotations, ball-and-stick models, and symbolic representations such as chemical equations or structures (Habig, 2020). Four types of external representations and provide examples. (a) Verbal-textual: This sort of representation combines written text with verbal information. (b) Symbolic mathematics: Examples in chemistry include element symbols, structural formulas, and ball-and-stick models. (c) Visual-graphical: This style of representation refers to real-world macroscopic phenomena. (d) Action-operational: Example from the context of chemistry are hands-on experiments and inquiry-based actions.

Misconceptions among students. Conventional physical molecular models used as alternatives also have limitations, such as relatively high production costs, fragility, and an inability to display the dynamics of chemical reactions in real time. On the other hand, although augmented reality (AR) has the potential to overcome these limitations, its implementation still faces challenges such as platform variations, hardware requirements, and teacher readiness. This situation is exacerbated by research fragmentation, in which studies on AR for chemistry are scattered across various fields (education, HCI, computational chemistry) without an integrated synthesis; therefore, a systematic review is needed to comprehensively map the development of this research (Horikoshi et al., 2023).

Augmented Reality (AR) technology enhances physical environments with digital aspects (Keller et al., 2021). Augmentation involves integrating virtual computer-based things into real-world environments in real time. AR used to require big headmounted displays, but now it can be used with smartphones or tablets (Nechypurenko et al., 2018). Azuma proposes three qualities that all AR systems must have, regardless of their technical implementation. Second, real-time interaction with the items on screen, such as manipulation or rotation, is required. The most significant feature of augmented reality is the integration of the physical and virtual worlds. This distinguishes augmented reality from virtual reality, which masks the real-world surroundings completely (Lund et al., 2016).

Despite its inclusion in the IUPAC top 10 emerging technologies in chemistry for 2022 and the growing body of research indicating the advantages of using AR to teach abstract concepts (Gomollón-Bel, 2022). To our

knowledge, there is only one study that uses AR to introduce a reaction mechanism such as in organic chemistry, and there have been very few studies on the use of AR to teach organic chemistry (Chang et al., 2022). AR can help students understand the processes and spatial structures of molecules, which are more difficult to understand through traditional teaching techniques (Fatemah et al., 2020). Prior research examined learning difficulties in chemistry reactions topics with and without AR support (Keller et al., 2021). By displaying more complex digital overlays in the real world, such as visualizations of abstract concepts like atoms, molecules, and phenomena chemical reactions. Augmented reality (AR) can aid children's learning in STEM subjects (Mazzuco et al., 2022).

A recent study, conducted by Mazzuco et al. (2022), examined the use of augmented reality in the context of chemistry education. However, the study did not discuss in detail the development of AR technology, the evaluation methods used, or the effectiveness of these methods in improving students' understanding of scientific concepts. Most previous studies still exhibit a number of limitations, including the lack of a systematic mapping of the AR platforms used, a lack of synthesis regarding the pedagogical impact of AR implementation, and the absence of a clear classification of the types of interactions employed (marker-based, markerless, or web-based AR), as well as a lack of mapping regarding the scope of the visualized chemistry content. These gaps represent areas of research that have not yet been fully integrated into a single study. Therefore, this article seeks to comprehensively link all these aspects within a single systematic research framework.

By making the material easier to understand, more interactive, and more engaging, augmented reality games can be a useful tool for overcoming conceptual challenges related to chemistry and fostering a positive outlook on the field (Chen & Liu, 2020). In addition, the interactive and adaptive nature of AR allows for the customization and enhancement of learning scenarios through the use of multimodal and multisensory learning experiences (Ponticorvo et al., 2019). This study employs a systematic approach with a specifically defined range of publication years and focuses on two aspects that have traditionally been studied separately: the visualization of molecular structures and chemical reactions.

## Method

One of those scientific studies that needs to be legitimate, trustworthy, and reproducible is a literature review. There are two types of literature reviews: those

that serve as background information for a study and those that stand alone as literary works (Xiao & Watson, 2019). Systematic literature reviews (SLR) are independent reviews of the literature that follow rigorous, methodical guidelines (Okoli & Schabram, 2012). If the research questions are developed, pertinent papers are found, their quality is evaluated, and the data is summarized using a clear methodology, the review is considered systematic (Khan et al., 2003). There are three stages carried out in this SLR research, namely the

planning stage, the conducting stage, and the reporting stage.

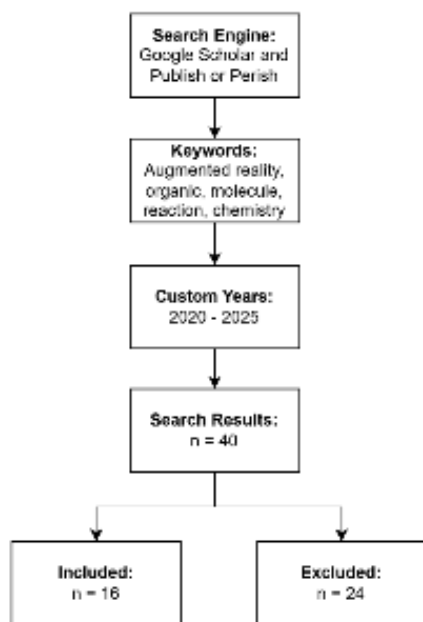
#### Planning Stage

Setting the scope—more especially, the subject of augmented reality for chemistry education—was the first step in the study process. The selection criteria for the articles to be included in the SLR were then specified by the researchers and are listed in Table 1.

**Table 1.** Article Criteria Used in SLR

| Criteria | Description                                                                                                                                                                                                                                                                                                                                                    |
|----------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Included | <p>The article that will be used discusses the augmented reality on chemistry learning</p> <p>The articles used are articles that have been published in the 2021-2025</p> <p>The articles used are articles published in journals indexed by Scopus</p> <p>Articles with participants are secondary and undergraduate students</p> <p>Articles accessible</p> |
| Excluded | <p>Literature review, nomenclature, and proceedings articles are not included</p> <p>Articles not about augmented reality on chemistry learning are not included</p> <p>Articles not indexed by Scopus are not included</p> <p>Articles with primary school student participants are not included</p> <p>Article inaccessible</p>                              |

#### Conducting Stage



**Figure 1.** SLR conducting stage flow

Articles were gathered from Scopus-indexed sources, including Google Scholar and Publish or Perish, adhering to the previously defined criteria. The search focused on the 2021-2025 period using keywords such as "augmented reality", "structure", "molecule", "reaction", and "chemistry." The collection process initially identified 40 potentially relevant articles. A rigorous analysis and grouping process was then applied to these 40 articles, separating them into included and excluded groups based on the criteria. This resulted in a final corpus of 16 included articles and 24 articles that were excluded. The methodology's step-by-step flow is provided in Figure 1.

#### Reporting Stage

Reporting on SLR outcomes is now done in accordance with previously formulated research questions. Articles that fit into the included category are currently labeled M (Marker), ML (Markerless), and PB (Projection-Based). Table 2 lists the articles that were utilized in this SLR.

**Table 2.** Articles Used in SLR

| Article Title                                                                                                 | Writer                                                        | Year | Code | Source                             |
|---------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------|------|------|------------------------------------|
| Development and use of augmented reality models to teach medicinal chemistry                                  | Chase Smith, Carolyn J. Friel                                 | 2021 | M    | (Smith & Friel, 2021)              |
| Augmented Reality, a Review of a Way to Represent and Manipulate 3D Chemical Structures                       | Alba Fombona-Pascual, Javier Fombona and Rubén Vicente        | 2022 | M    | (Fombona-Pascual et al., 2022)     |
| Online tools to easily build virtual molecular models for display in augmented and virtual reality on the web | Fabio Cortés Rodríguez, Matteo Dal Peraro, Luciano A. Abriata | 2022 | ML   | (F. Cortés Rodríguez et al., 2022) |

| Article Title                                                                                                                                                       | Writer                                                                                                                                                                                                                                                          | Year | Code | Source                                |
|---------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------|------|---------------------------------------|
| Fostering Motivation toward Chemistry through Augmented Reality Educational Escape Activities. A Self-Determination Theory Approach                                 | Daniel Elford, Simon J. Lancaster, and Garth A. Jones                                                                                                                                                                                                           | 2022 | M    | (Elford et al., 2022)                 |
| Application of Augmented Reality for Learning Material Structures and Chemical Equilibrium in High School Chemistry                                                 | Wernhuar Tarng, Yu-Cheng Tseng and Kuo-Liang Ou                                                                                                                                                                                                                 | 2022 | M    | (Tarng et al., 2022)                  |
| Augmented reality and worked examples: Targeting organic chemistry competence                                                                                       | Daniel Elford, Simon J. Lancaster, Garth A. Jones                                                                                                                                                                                                               | 2023 | M    | (Elford et al., 2023)                 |
| Effect of an augmented reality app on academic achievement, motivation, and technology acceptance of university students of a chemistry course                      | Monica Silva, Karina Bermúdez, Karina Caro                                                                                                                                                                                                                      | 2023 | M    | (Silva et al., 2023)                  |
| Tracking visual attention during learning of complex science concepts with augmented 3D visualizations                                                              | Fang-Ying Yang, Hui-Yun Wang                                                                                                                                                                                                                                    | 2023 | M    | (Yang & Wang, 2023)                   |
| Teaching with Augmented Reality Using Tablets, Both as a Tool and an Object of Learning                                                                             | Sabrina Syskowski, Chantal Lathwesen, Canan Kanbur, Antje Siol, Ingo Eilks, and Johannes Huwer                                                                                                                                                                  | 2024 | M    | (Syskowski et al., 2024)              |
| Teachers' attitudes and self-efficacy toward augmented reality in chemistry education                                                                               | Melanie Ripsam and Claudia Nerdel                                                                                                                                                                                                                               | 2024 | M    | (Ripsam & Nerdel, 2024)               |
| Augmented reality interactive experiences for multi-level chemistry understanding                                                                                   | Sandra Camara Olim, Valentina Nisi, Teresa Romao                                                                                                                                                                                                                | 2024 | M/ML | (Cámara Olim et al., 2024)            |
| Development and Evaluation of a Marker Arrangement-Based Mobile Augmented Reality Application for Learning Covalent and Ionic Bonding in the High School Curriculum | Young-Eun Jeon, Joon-Yong Ji, and Hun-Gi Hong                                                                                                                                                                                                                   | 2024 | M    | (Jeon et al., 2024)                   |
| A Cognitive Load Approach to Molecular Geometries: Augmented Reality Technology and Visuospatial Abilities in Chemistry                                             | Conor Desmond Kenneally and Brendan Bentley                                                                                                                                                                                                                     | 2024 | M    | (Kenneally & Bentley, 2024)           |
| A Mobile Device Application for Visualizing Molecular Symmetry and Orbitals in Augmented Reality                                                                    | Marc A. Zambri and John R. De Backere                                                                                                                                                                                                                           | 2024 | M    | (Zambri & De Backere, 2024)           |
| An Investigation into whether Applying Augmented Reality (AR) in Teaching Chemistry Enhances Chemical Cognitive Ability                                             | Vu Thi Thu Hoai, Pham Ngoc Son, Dang Thi Thuan An, Nguyen Viet Anh                                                                                                                                                                                              | 2024 | M    | (Hoai et al., 2024)                   |
| MolecularWebXR: Multiuser discussions in chemistry and biology through immersive and inclusive augmented and virtual reality                                        | Fabio J. Cortés Rodríguez, Gianfranco Frattini, Sittha Phloi-Montri, Fernando Teixeira Pinto Meireles, Dana'e A. Terrien, Sergio Cruz-Leon', Matteo Dal Peraro, Eva Schier, Kresten Lindorff-Larsen, Taweetham Limpanuparb, Diego M. Moreno, Luciano A. Abriata | 2025 | ML   | (F. J. Cortés Rodríguez et al., 2025) |

## Result and Discussion

*Q1. What are the trends in the development of Augmented Reality (AR) technology in the visualization of molecular structures and chemical reactions in the period 2021-2026?*

Augmented Reality (AR) technology is projecting computer-generated virtual pictures onto an actual world, usually through an application that uses a phone's camera (Keller et al., 2021). Augmented Reality (AR) technology is projecting computer-generated virtual pictures onto an actual world, usually through an application that uses a phone's camera. Numerous studies have indicated that understanding molecular geometries in the setting of a chemistry classroom can

help learners. By utilizing visual cues and geographic data, augmented reality technology can help guide and steer the learner (Yang & Wang, 2023).

Early AR tools mostly focused on "stick and-ball" static models. Between 2024 and 2026, the trend has shifted toward dynamic simulation. Real-time Reaction Visualizing: Users can now trigger chemical reactions (e.g., nucleophilic substitutions) where the AR environment shows the movement of electrons and the breaking/forming of bonds in real-time. Haptic Integration: High-end systems now incorporate haptic feedback, allowing researchers to "feel" the electrostatic push and pull of molecules as they attempt to dock a ligand into a protein's active site.

The technology has moved away from the requirement of "Physical Markers" (QR codes or printed patterns). SLAM Technology: Modern applications use Simultaneous Localization and Mapping (SLAM), allowing molecular models to be "placed" on any flat surface, like a lab bench, without needing a paper printout. WebAR: A major trend in 2025–2026 is the rise of browser-based AR. Students no longer need to download heavy apps; they can visualize complex protein structures directly from a URL or a textbook's digital companion.

The capacity to combine engineering, design, and reality is known as augmented reality, and it can be crucial for fully comprehending chemical processes (Kum-Biocca et al., 2020). Several research have shown how important augmented reality is to teaching. AR-created interactive worlds pique students' interest, making classes more captivating and interesting. It has been proposed that the use of AR technology in the classroom helps pupils focus on important material, develop curiosity, and pay attention.

The system makes use of AR marker-based technology, which leverages the mobile device's camera to identify images or visual patterns. Each child can explore one, two, three, or all of the cubes because the content has been created without any dependencies. Attaining complete closure with every encounter. The system starts generating and transferring digital data onto the device screen after scanning these photographs. As a result, we created high contrast images for each cube face to make them easy to recognize, coupled with text and icons to help the user identify the kind of data they will collect.

However, markerless technology also referred to as location-based augmented reality uses motion tracking and light estimation. This technique tracks the movement of features, which are important points in the surroundings. This enables the installation of virtual items and any other kind of digital data by allowing the system to identify any flat surfaces, such floors or tables. AR markerless detects the user's location and orientation using a variety of sensors, including GPS, accelerometers, and gyroscopes. This enables the virtual data to be positioned and viewed in connection to the real environment.

Using position or picture recognition, augmented reality (AR) is an immersive technology that blends virtual objects and data with the actual environment. Combining the virtual and real worlds, real-time interaction, and operation in three-dimensional situations are the three main features of augmented reality. To improve engagement with and awareness of surrounding environments, it can be used to superimpose virtual items on the user's vision (Habig, 2020). In general, there are three types of augmented

reality: (1) classic AR, which uses markers or images for detection; (2) location-based AR, which uses GPS to identify the position; and (3) hybrid AR, which combines markers, images, and GPS data. Three features define an augmented reality system: (1) integrating the actual and virtual worlds; (2) real-time interaction; and (3) being registered in three dimensions (Azuma, 1997).

The two categories of augmented reality on molecular structure and chemical reactions that have been examined between 2021 and 2026 are marker and markerless. Table 3 displays the outcomes of classifying molecular structure and chemical reactions AR.

**Table 3.** Outcomes of Classifying Chemical Reactions and Molecular Structures that are Digital and Non-Digital AR

| Category   | N  | Percentage (%) |
|------------|----|----------------|
| Marker     | 7  | 43.75          |
| Markerless | 9  | 56.25          |
| Total      | 16 | 100            |

According to the article criteria listed in Table 1, it was discovered that 85.7% of AR of molecular structure and chemical reaction developed during the 2021–2026 era had markers, while 14.3% did not. Table 4 lists the various varieties of augmented reality that are available in both digital and non-digital formats.

**Table 4.** Molecular Structure and Chemical Reaction Augmented Reality Groupings

| Category   | AR Type           | N  | Percentage (%) |
|------------|-------------------|----|----------------|
| Marker     | Classic AR        | 5  | 31.25          |
|            | Location-based AR | 2  | 12.50          |
| Markerless | Hybrid AR         | 9  | 56.25          |
| Total      |                   | 16 | 100            |

Table 4 outlines the distribution of Augmented Reality (AR) groupings specifically used for visualizing molecular structures and chemical reactions. The data categorizes these technologies into two primary tracking methods: Marker and Markerless. Within the Marker category, Classic AR accounts for 31.25% of the cases (N=5), while Location-based AR represents 12.50% (N=2). However, the most prevalent method identified is Hybrid AR, which falls under the Markerless category and makes up the majority of the study at 56.25% (N=9). In total, the table aggregates 16 different instances or applications, illustrating a clear preference for hybrid, markerless systems in the field of chemical education and molecular visualization.

The dominance of Hybrid/Markerless AR aligns with the educational need to solve "Johnstone's Triangle." By moving away from fixed markers, these systems allow: Greater Flexibility: Students can place molecular structures on any lab surface, facilitating a

better connection between the macroscopic lab environment and submicroscopic models. Advanced Interaction: Hybrid systems often allow for more complex interactions, such as hand-tracking or multi-user collaboration, which are essential for visualizing dynamic chemical reactions. Classic AR Persistence: The significant presence of "Classic AR" (31.25%) indicates that image-triggered models remain a popular and cost-effective entry point for schools using textbooks or printed lab manuals.

*Q2. What hardware, software platforms, and types of AR (marker or markerless) are most effective for visualizing chemical interactions?*

In molecular structures and chemical reactions teaching, the use of software to generate 3D simulations helps students grasp difficult ideas (Hoai et al., 2023).

**Table 5.** Groupings of the Concepts of Molecular Structure and Chemistry Reactions in the Form of Augmented Reality

|                     | Chemistry Concepts                            |
|---------------------|-----------------------------------------------|
| Molecular geometry  | Elements and compounds                        |
|                     | Periodic table                                |
|                     | Conservation of mass                          |
|                     | Valence Shell Electron Pair Repulsion (VSEPR) |
|                     | Molecular symmetry and orbitals               |
|                     | Substance structure                           |
| Chemical bonding    | Chemical transformations                      |
|                     | Covalent bonds                                |
|                     | Ionic bonds                                   |
|                     | Hydrocarbon bonds                             |
| Material structure  | Resonance structure                           |
|                     | Atomic/Molecular Representation               |
|                     | Chemical equilibrium                          |
|                     | Elements and compounds                        |
| Electrolysis        | Chemical reaction                             |
|                     | Transfer electron                             |
|                     | Migration of ions                             |
| Organic chemistry   | Redox reaction                                |
|                     | Electrophilic aromatic substitution reaction  |
|                     | Stereochemistry                               |
|                     | Crystallography                               |
|                     | Isomerism                                     |
| Biochemistry        | DNA molecule                                  |
|                     | Macromolecules                                |
| Medicinal chemistry | Thrombin                                      |
|                     | Antithrombin                                  |
|                     | Carbonic anhydrase                            |
|                     | Sars-cov virus                                |

Table 5 illustrates the diverse pedagogical applications of Augmented Reality (AR) across various domains of chemistry, ranging from fundamental principles to complex molecular systems. In the study of

Molecular geometry, AR is employed to visualize elements, compounds, the periodic table, and advanced theories such as Valence Shell Electron Pair Repulsion (VSEPR), molecular symmetry, and substance structures. Similarly, the technology aids in understanding Chemical bonding by representing covalent, ionic, hydrocarbon, and resonance structures. For Material structure and Electrolysis, AR provides a platform to observe atomic representations, chemical equilibrium, ion migration, and redox reactions.

The "engine" behind the AR experience determines how scientifically accurate the chemical reactions are. Nanome (AR Edition): Currently the gold standard for drug design. It allows scientists to manipulate molecular structures in a shared 3D space with real-time energy calculations. Schrödinger Maestro (AR Plugin): Used by pharmaceutical companies to bridge professional-grade computational chemistry with AR visualization. Unity + Vuforia/ARFoundation: The primary platform for developers building custom chemistry apps. Most educational AR chemistry apps (like ARchemy or Futuclass) are built here. WebAR (e.g., 8th Wall): Extremely effective for education because it requires no app download. Students just scan a link to see a 3D reaction on their desk via a browser.

The choice between these two types depends on the stability required for the visualization. Marker-Based AR (Image Tracking) How it works: Uses a physical "trigger" like a printed card with a molecular formula or a QR code. Effectiveness: \* High for "Reaction Games" where you physically move two cards (Reactant A and Reactant B) together to trigger a digital explosion or bond formation. Low for flexibility, as you always need the printed paper.

Furthermore, the application of AR extends into specialized branches such as Organic chemistry, where it facilitates the study of electrophilic aromatic substitution, stereochemistry, and isomerism. In Biochemistry, it is used to model macromolecules and DNA molecules, while in Medicinal chemistry, the technology assists in the visualization of complex biological entities like Thrombin, Carbonic anhydrase, and the Sars-cov virus. This comprehensive grouping demonstrates that AR serves as a versatile tool for making abstract chemical concepts more tangible and observable for students.

The augmented reality in chemical reactions was examined between 2021 and 2025 using the standards listed in Table 1. After that, it is categorized based on the ideas that are evolved into the augmented reality of molecular structures and chemical reactions. Table 5 displays this grouping. According to Table 5, the most advanced molecular structures and chemical reactions throughout the 2021–2025 period was in the basic

concepts of complexes like elements into compounds into chemical processes.

The chemical compounds used to create augmented reality differ between marker and markerless versions. The possibility of creating augmented reality on molecular structures and chemical reactions, both in marker and markerless forms, is still extremely likely given the numerous concepts of complicated structure in chemistry.

*Q3. To what extent can the use of AR have a positive impact on students' understanding of chemistry concepts in molecular structure and chemical reaction materials?*

As mentioned by Mazzuco et al. (2022) displaying more complex digital overlays in the real world, such as visualizations of abstract concepts like atoms, molecules, and phenomena such as organic chemistry, augmented reality (AR) can aid children's learning in STEM subjects. Table 6. Shows the equilibrium between chemical reactions concepts and the goals to be achieved using the AR used.

One of the most profound impacts of AR is its ability to improve spatial reasoning. 3D Visualization: Unlike 2D diagrams, AR allows students to walk around a molecule, viewing it from the top, bottom, and "inside." This is crucial for understanding VSEPR theory (molecular geometry) and stereochemistry. Chirality and Isomerism: Concepts like "handedness" in molecules (chirality), which are notoriously difficult to grasp, become intuitive when a student can physically try to "superimpose" two AR models in the air. Submicroscopic Representation: Research (2024) indicates that students using AR show a 44% higher improvement in identifying molecular symmetry and hybrid orbitals compared to those using traditional 2D textbooks.

Traditionally, chemical reactions are taught as "Before" and "After" equations. AR introduces the "During." Visualizing Intermediates: AR can slow down a reaction, showing the high-energy "transition state" where bonds are partially broken and formed. Reaction Mechanisms: For organic chemistry, AR overlays "curly arrows" on 3D molecules to show electron flow. This has been shown to reduce misconceptions about how electrons move during nucleophilic attacks. Collision Theory: Students can manipulate AR molecules to collide at different angles and speeds, instantly seeing which collisions result in a successful reaction.

The implementation of Augmented Reality (AR) in chemistry education, as detailed in Table 6, aligns closely with the cultivation of 21st-century skills, particularly in the domains of cognitive development and digital literacy. By enhancing cognitive abilities and deepening the understanding of complex scientific concepts, AR facilitates the "Critical Thinking and

Problem Solving" required in modern scientific inquiry. Furthermore, the evidence that AR promotes active learning and self-efficacy directly supports the skill of "Self-Direction and Initiative," empowering students to take agency over their learning within immersive environments.

The data also emphasizes technology acceptance and virtual presence, which are foundational to "Information, Media, and Technology Skills". As AR provides opportunities for innovative teaching strategies and inclusivity, it fosters a "Global Awareness" and "Social and Cross-Cultural Skills" by making high-level chemistry accessible to a broader, more diverse student population. Collectively, these impacts suggest that AR is not merely a visual aid but a transformative tool that prepares students for a technology-driven workforce by boosting their motivation, academic achievement, and ability to navigate complex digital frameworks. AR technology improves student comprehension and engagement when teaching organic compound reactions in chemistry (Costa Coelho et al., 2022).

**Table 6.** The Purpose of Using Organic and Chemistry Reactions AR in the 2021-2025

| Impact                                             | Source                                                                                               |
|----------------------------------------------------|------------------------------------------------------------------------------------------------------|
| Enhances cognitive ability                         | Kenneally et al. (2024)<br>Hoai et al. (2024)                                                        |
| Positive attitudes on students                     | Zambri et al. (2024)<br>Elford et al. (2023)<br>Câmara Olim et al. (2024)<br>Syskowski et al. (2024) |
| Provide active learning                            | Smith et al. (2021)<br>Elford et al. (2022)                                                          |
| Self efficacy                                      | Ripsam et al. (2023)                                                                                 |
| Supports virtual presence and scalable to students | Elford et al. (2022)                                                                                 |
| Enhance academic achievement                       | Silva et al. (2023)                                                                                  |
| Fostering students motivation                      | Silva et al. (2023)<br>Elford et al. (2022)<br>Câmara Olim et al. (2024)                             |
| Technology acceptance                              | Silva et al. (2023)<br>Syskowski et al. (2024)                                                       |
| Fosters interesting in learning                    | Jeon et al. (2024)<br>Câmara Olim et al. (2024)<br>Syskowski et al. (2024)                           |
| Enhances understanding concepts                    | Tarng et al. (2022)<br>Elford et al. (2023)<br>Jeon et al. (2024)<br>Yang et al. (2023)              |
| Opportunities of teaching and learning strategies  | Fombona-Pascual et al. (2022)                                                                        |
| Immersive and inclusivity                          | Cortés Rodríguez et al. (2025)<br>Cortés Rodríguez et al. (2022)                                     |

## Conclusion

According to the systematic literature review, a variety of molecular structures and chemical reactions augmented reality games, both marker-based and markerless, have been developed between 2021-2025. AR has moved beyond being a "tech gimmick" to become a fundamental scientific instrument. It bridges the gap between theoretical symbols and microscopic reality, making the "invisible" world of chemistry visible, tangible, and far more understandable for both students and professionals. The development of augmented reality has been shown to have a beneficial effect on students' academic performance and the development of some 21st-century abilities.

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## Author Contributions

Conceptualization, methodology, resources, writing—review and editing, S.D.E., W.W., and T.W.; formal analysis, investigation, writing—original draft preparation, visualization and project administration, S.D.E.

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## Conflicts of Interest

The authors declare no conflict of interest.

## References

- Ardura, D., Zamora, Á., & Pérez-Bitrián, A. (2021). The role of motivation on secondary school students' causal attributions to choose or abandon chemistry. *Chemistry Education Research and Practice*, 22(1), 77–92. <https://doi.org/10.1039/d0rp00168f>
- Azuma, R. T. (1997). A Survey of Augmented Reality. *Presence: Teleoperators and Virtual Environments*, 6(4), 355–385. <https://doi.org/10.1162/pres.1997.6.4.355>
- Câmara Olim, S., Nisi, V., & Romão, T. (2024). Augmented reality interactive experiences for multi-level chemistry understanding. *International Journal of Child-Computer Interaction*, 42(July). <https://doi.org/10.1016/j.ijcci.2024.100681>
- Castro-Alonso, J. C., Ayres, P., & Sweller, J. (2019). Instructional Visualizations, Cognitive Load Theory, and Visuospatial Processing. In *Visuospatial Processing for Education in Health and Natural Sciences* (pp. 111–143). Springer International Publishing. [https://doi.org/10.1007/978-3-030-20969-8\\_5](https://doi.org/10.1007/978-3-030-20969-8_5)
- Chang, H. Y., Binali, T., Liang, J. C., Chiou, G. L., Cheng, K. H., Lee, S. W. Y., & Tsai, C. C. (2022). Ten years of augmented reality in education: A meta-analysis of (quasi-) experimental studies to investigate the impact. *Computers and Education*, 191(September), 104641. <https://doi.org/10.1016/j.compedu.2022.104641>
- Chen, S.-Y., & Liu, S.-Y. (2020). Using augmented reality to experiment with elements in a chemistry course. *Computers in Human Behavior*, 111, 106418. <https://doi.org/10.1016/j.chb.2020.106418>
- Coduto, J. R., Lazicki, A., & Leddy, J. (2024). Visualizing 3D Objects in Analytical Chemistry. *Journal of Chemical Education*, 101(1), 77–87. <https://doi.org/10.1021/acs.jchemed.3c00821>
- Cortés Rodríguez, F., Dal Peraro, M., & Abriata, L. A. (2022). Online tools to easily build virtual molecular models for display in augmented and virtual reality on the web. *Journal of Molecular Graphics and Modelling*, 114(December). <https://doi.org/10.1016/j.jmgm.2022.108164>
- Cortés Rodríguez, F. J., Frattini, G., Phloi-Montri, S., Pinto Meireles, F. T., Terrien, D. A., Cruz-León, S., Dal Peraro, M., Schier, E., Lindorff-Larsen, K., Limpanuparb, T., Moreno, D. M., & Abriata, L. A. (2025). MolecularWebXR: Multiuser discussions in chemistry and biology through immersive and inclusive augmented and virtual reality. *Journal of Molecular Graphics and Modelling*, 135(June). <https://doi.org/10.1016/j.jmgm.2024.108932>
- Costa Coelho, F. da, de Magalhães Netto, J., & Almeida, T. O. (2022). A Case Study Using Augmented Reality for Teaching Organic Compound Reactions. 2022 *IEEE Frontiers in Education Conference (FIE)*, 1–7. <https://doi.org/10.1109/FIE56618.2022.9962460>
- Elford, D., Lancaster, S. J., & Jones, G. A. (2022). Fostering Motivation toward Chemistry through Augmented Reality Educational Escape Activities. A Self-Determination Theory Approach. *Journal of Chemical Education*, 99(10), 3406–3417. <https://doi.org/10.1021/acs.jchemed.2c00428>
- Elford, D., Lancaster, S. J., & Jones, G. A. (2023). Augmented reality and worked examples: Targeting organic chemistry competence. *Computers and Education: X Reality*, 2(November), 100021. <https://doi.org/10.1016/j.cexr.2023.100021>
- Fatemah, A., Rasool, S., & Habib, U. (2020). Interactive 3D Visualization of Chemical Structure Diagrams Embedded in Text to Aid Spatial Learning Process of Students. *Journal of Chemical Education*, 97(4), 992–1000.

- <https://doi.org/10.1021/acs.jchemed.9b00690>
- Fombona-Pascual, A., Fombona, J., & Vicente, R. (2022). Augmented Reality, a Review of a Way to Represent and Manipulate 3D Chemical Structures. *Journal of Chemical Information and Modeling*, 62(8), 1863–1872. <https://doi.org/10.1021/acs.jcim.1c01255>
- Gomollón-Bel, F. (2022). Discover the innovations that will transform energy, health, and materials science, to tackle the most urgent societal challenges and catalyse sustainable development. *Chemistry International*, 44(4), 4–13. <https://doi.org/doi:10.1515/ci-2022-0402>
- Habig, S. (2020). Who can benefit from augmented reality in chemistry? Sex differences in solving stereochemistry problems using augmented reality. *British Journal of Educational Technology*, 51(3), 629–644. <https://doi.org/10.1111/bjet.12891>
- Hoai, V. T. T., Son, P. N., An, D. T. T., & Anh, N. V. (2024). An Investigation into whether Applying Augmented Reality (AR) in Teaching Chemistry Enhances Chemical Cognitive Ability. *International Journal of Learning, Teaching and Educational Research*, 23(4), 195–216. <https://doi.org/10.26803/ijlter.23.4.11>
- Hoai, V. T. T., Son, P. N., Em, V. V. D., & Duc, N. M. (2023). Using 3D molecular structure simulation to develop chemistry competence for Vietnamese students. *Eurasia Journal of Mathematics, Science and Technology Education*, 19(7). <https://doi.org/10.29333/ejmste/13345>
- Horikoshi, R., Shirotani, D., & Shioyama, H. (2023). Studying the nomenclature of dioxins using a structure model kit based on electronic components linked with plastic tubes. *Chemistry Teacher International*, 5(1), 83–89. <https://doi.org/10.1515/cti-2022-0051>
- Jeon, Y. E., Ji, J. Y., & Hong, H. G. (2024). Development and Evaluation of a Marker Arrangement-Based Mobile Augmented Reality Application for Learning Covalent and Ionic Bonding in the High School Curriculum. *Journal of Chemical Education*, 101(3), 1130–1138. <https://doi.org/10.1021/acs.jchemed.3c01316>
- Keller, S., Rumann, S., & Habig, S. (2021). Cognitive load implications for augmented reality supported chemistry learning. *Information (Switzerland)*, 12(3), 1–20. <https://doi.org/10.3390/info12030096>
- Kenneally, C. D., & Bentley, B. (2024). A Cognitive Load Approach to Molecular Geometries: Augmented Reality Technology and Visuospatial Abilities in Chemistry. *Education Sciences*, 14(9). <https://doi.org/10.3390/educsci14091036>
- Khan, K. S., Kunz, R., Kleijnen, J., & Antes, G. (2003). Five Steps to Conducting a Systematic Review. *Journal of the Royal Society of Medicine*, 96(3), 118–121. <https://doi.org/10.1177/014107680309600304>
- Kum-Biocca, H. H., Farinas, E. T., Mistry, N., & Wan, Y. (2020). Molecular Augmented Reality for Design and Engineering (MADE): Effectiveness of AR Models on Discovery, Learning, and Education. In *HCI International 2020 -- Late Breaking Posters* (pp. 173–180). Springer International Publishing.
- Laohapornchaiphan, J., & Chenprakhon, P. (2024). A Review of Research on Learning Activities Addressing the Submicroscopic Level in Chemistry. *Journal of Chemical Education*, 101(11), 4552–4565. <https://doi.org/10.1021/acs.jchemed.4c00156>
- Lund, B., Harald, & H. (2016). Nordina : Nordic studies in science education. *Nordic Studies in Science Education*, 12(2), 157–174. Retrieved from <https://www.journals.uio.no/index.php/nordina/article/view/2399/3336>
- Mazzuco, A., Krassmann, A. L., Reategui, E., & Gomes, R. S. (2022). A systematic review of augmented reality in chemistry education. *Review of Education*, 10(1), 1–26. <https://doi.org/10.1002/rev3.3325>
- Mellander, E., & Lind, P. (2021). Recruitment to STEM studies: The roles of curriculum reforms, flexibility of choice, and attitudes. *Review of Education*, 9(2), 357–398. <https://doi.org/10.1002/rev3.3262>
- Nechypurenko, P. P., Starova, T. V., Selivanova, T. V., Tomilina, A. O., & Uchitel, A. D. (2018). Use of augmented reality in chemistry education. *CEUR Workshop Proceedings*, 2257, 15–23. <https://doi.org/10.31812/pedag.v51i0.3650>
- Okoli, C., & Schabram, K. (2012). A Guide to Conducting a Systematic Literature Review of Information Systems Research. *SSRN Electronic Journal*. <https://doi.org/10.2139/ssrn.1954824>
- Ponticorvo, M., Di Fuccio, R., Ferrara, F., Rega, A., & Miglino, O. (2019). Multisensory Educational Materials: Five Senses to Learn. In *Methodologies and Intelligent Systems for Technology Enhanced Learning, 8th International Conference* (pp. 45–52). Springer International Publishing.
- Rau, M. A. (2017). Conditions for the Effectiveness of Multiple Visual Representations in Enhancing STEM Learning. *Educational Psychology Review*, 29(4), 717–761. <https://doi.org/10.1007/s10648-016-9365-3>
- Ripsam, M., & Nerdel, C. (2023). Teachers' attitudes and self-efficacy toward augmented reality in chemistry education. *Frontiers in Education*, 8(January), 1–11. <https://doi.org/10.3389/feduc.2023.1293571>
- Ripsam, M., & Nerdel, C. (2024). Augmented reality for chemistry education to promote the use of chemical terminology in teacher training. *Frontiers*

- in *Psychology*, 15(July), 1–23.  
<https://doi.org/10.3389/fpsyg.2024.1392529>
- Silva, M., Bermúdez, K., & Caro, K. (2023). Effect of an augmented reality app on academic achievement, motivation, and technology acceptance of university students of a chemistry course. *Computers and Education: X Reality*, 2(April), 1–9.  
<https://doi.org/10.1016/j.cexr.2023.100022>
- Smith, C., & Friel, C. J. (2021). Development and use of augmented reality models to teach medicinal chemistry. *Currents in Pharmacy Teaching and Learning*, 13(8), 1010–1017.  
<https://doi.org/10.1016/j.cptl.2021.06.008>
- Syskowski, S., Lathwesen, C., Kanbur, C., Siol, A., Eilks, I., & Huwer, J. (2024). Teaching with Augmented Reality Using Tablets, Both as a Tool and an Object of Learning. *Journal of Chemical Education*, 101(3), 892–902.  
<https://doi.org/10.1021/acs.jchemed.3c00607>
- Tarng, W., Tseng, Y., & Ou, K. (2022). Structures and Chemical Equilibrium in High School Chemistry. *System*, 10, 1–23.  
<https://doi.org/10.3390/systems10050141>
- Vilia, P., & Candeias, A. A. (2020). Attitude towards the discipline of physics-chemistry and school achievement: revisiting factor structure to assess gender differences in Portuguese high-school students. *International Journal of Science Education*, 42(1), 133–150.  
<https://doi.org/10.1080/09500693.2019.1706012>
- Xiao, Y., & Watson, M. (2019). Guidance on Conducting a Systematic Literature Review. *Journal of Planning Education and Research*, 39(1), 93–112.  
<https://doi.org/10.1177/0739456X17723971>
- Yang, F. Y., & Wang, H. Y. (2023). Tracking visual attention during learning of complex science concepts with augmented 3D visualizations. *Computers and Education*, 193(October), 104659.  
<https://doi.org/10.1016/j.compedu.2022.104659>
- Zambri, M. A., & De Backere, J. R. (2024). A Mobile Device Application for Visualizing Molecular Symmetry and Orbitals in Augmented Reality. *Journal of Chemical Education*, 101(2), 382–391.  
<https://doi.org/10.1021/acs.jchemed.3c00652>