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Visualization Technology in High School Chemistry: A Systematic Review on Representations and Pedagogical Strategies

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Abstract

The basic concept of chemistry which can't be seen or touched poses a major cognitive challenge at the secondary school level, making the integration of digital visualization technologies essential for facilitating students' understanding of chemical representations. This study aims to analyze emerging trends in digital visualization technologies and identify the pedagogical strategies most prominently employed to support the development of chemical representational competence. A Systematic Literature Review (SLR) was conducted following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) protocol, analyzing 27 articles retrieved from the Scopus, ERIC, and Springer databases published between 2015 and 2025. The findings indicate that interactive simulations and computer-based visualization tools represent the dominant digital visualization technology trend, primarily supporting an integrated representation pattern that connects the macroscopic, sub-microscopic, and symbolic levels. Analysis of learning strategies revealed six principal categories, with Inquiry & Discovery Learning as the most frequently integrated model (25.9%), followed by Computational & Multimedia Learning (18.5%) and Model-Based Learning (14.8%). These findings suggest that the effectiveness of digital visualization technologies in chemistry education is contingent upon its strategic integration within active pedagogical designs that position students as active participants in constructing conceptual understanding through scientific inquiry.

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1. INTRODUCTION

Chemistry at the secondary school level frequently presents a substantial cognitive challenge for students. This difficulty stems from the inherent nature of the discipline, which requires engagement with phenomena at the sub-microscopic level a realm not directly accessible to human perception. In the chemistry education literature, this challenge is conceptualized through Johnstone's Triangle, which posits that students must be capable of constructing three levels of representation: the macroscopic (observable phenomena), the sub-microscopic (particles), and the symbolic (formulas and equations) (Johnstone, 1993; Gkitzia, 2020). Consequently, students' inability to bridge these three levels is frequently identified as a primary barrier to conceptual understanding and a major contributor to persistent misconceptions (Sunyono & Meristin, 2018).

Digital visualization technologies has emerged as a promising solution for overcoming this abstraction barrier. Its role has evolved from that of a supplementary medium to that of a cognitive instrument that facilitates the construction of students' conceptual frameworks. Rahmawati et al. (2022) demonstrated that the use of interactive simulations such as PhET enables students to directly observe particle motion. A complementary finding was reported by Martinez et al. (2021), who showed that integrating simulations with structured guidance helps students maintain focus, thereby enabling more effective management of the cognitive load involved in

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understanding gas particle behavior. Furthermore, Jere and Mpeta (2024) emphasized that dynamic visualizations through computer simulations prevent the formation of scientifically inaccurate mental models.

Technological advances extend beyond simulation-based tools to encompass immersive technologies. Irwanto et al. (2025) reported that Virtual Reality (VR) offers significant potential for enhancing students' spatial reasoning through immersive three-dimensional molecular manipulation experiences. In a related vein, research has shown that Augmented Reality (AR) visualizations facilitate the transfer of complex chemical structure concepts into more tangible understanding (Chiu et al., 2019). Collectively, the integration of these technologies has proven effective in facilitating an *integrated representation* pattern that connects observable phenomena with abstract theoretical concepts (Kotsalidis et al., 2024; Muljana & Selco, 2023).

Despite these advances, the effectiveness of technology remains highly dependent on the pedagogical design within which it is embedded. As argued by Martinez et al. (2021), the deployment of technology without accompanying instructional strategy risks producing only passive student engagement. While many independent studies have explored various digital tools, previous reviews (e.g., Sunyono & Meristin, 2018; Martinez et al., 2021) have primarily focused on the general effectiveness of individual media or specific models rather than a holistic synthesis. Consequently, there remains a lack of systematic synthesis that maps how specific digital visualization technologies align with distinct chemical representation levels and pedagogical strategies simultaneously over the last decade.

Accordingly, pedagogical frameworks that position students as active agents of learning are essential. Against this background, the present study conducts a systematic review addressing three research questions: (1) What trends in digital visualization technologies have been dominant over the past decade in chemistry education research? (2) What patterns of chemical representation have been most commonly facilitated by these digital visualization technologies? (3) Which learning strategies are most synergistic in supporting secondary school students' mastery of chemical representations?

2. METHOD

2.1 Research Method

This study employs a Systematic Literature Review (SLR) methodology, guided by the internationally recognized *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) reporting standards. This approach was selected for its capacity to synthesize research findings in a systematic and transparent manner, to provide a more comprehensive mapping of the field's development, and to generate evidence-based recommendations for future research. The review process was conducted through a series of structured stages, including the formulation of research questions, specification of inclusion and exclusion criteria, and the extraction and synthesis of data to comprehensively address the research questions.

2.2 Unit of Analysis

The unit of analysis for this study consists of scholarly articles focused on: digital visualization technologies in high school chemistry instruction; chemical representation patterns (including single, integrated, and fragmented representations) facilitated by such technologies; and the learning models or strategies implemented to support students' representational competence. Following the PRISMA protocol, a total of 27 articles drawn from nationally and internationally reputable databases were identified as meeting the established inclusion criteria.

2.3 Data Sources

This study employs secondary data sourced from peer-reviewed journal articles available in online academic repositories. The systematic literature search was conducted through three primary academic databases: Scopus, the Education Resources Information Center (ERIC), and Springer. These databases were selected for their comprehensive coverage of science education, instructional technology innovation, and chemistry education research.

The literature search was conducted using the following combination of specific keywords to retrieve relevant articles: (*"technology-enhanced" OR "digital tool" OR "visualization"*) AND (*"multiple representations" OR "chemical representation" OR "submicroscopic"*) AND (*"chemistry learning" OR "chemistry education"*) AND (*"high school" OR "secondary school"*). To ensure the relevance and currency of the findings, the search was restricted to English-language articles published between

2015 and 2025, involving secondary school students, addressing chemistry topics at the high school level, and classified as original research articles.

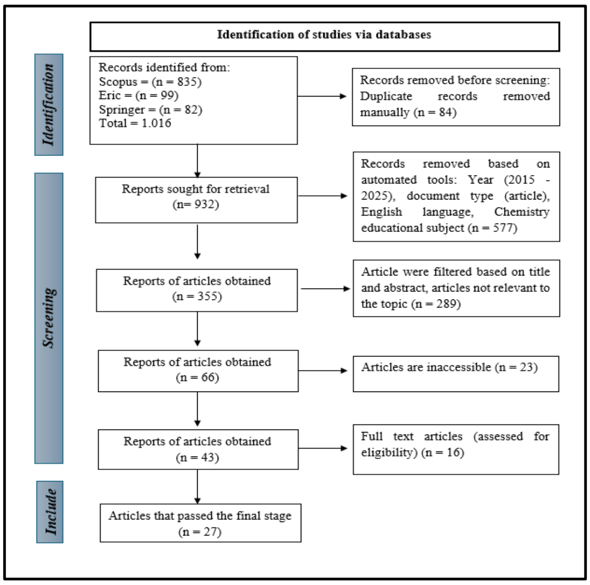

Figure 1. PRISMA flow diagram of the systematic literature review.

2.4 Data Collection

Data collection was conducted systematically in accordance with the *Preferred Reporting Items for Systematic Reviews and Meta-Analyses* (PRISMA) protocol. This process comprised three principal stages: (1) identification through database searches using the predefined keywords; (2) screening of titles and abstracts to eliminate duplicate and irrelevant articles; and (3) eligibility assessment through full-text review. The inclusion criteria were as follows: (1) articles describing a specific type of digital visualization technology used in high school chemistry instruction; (2) articles examining patterns of chemical representation; (3) articles describing an integrated learning model or strategy; (4) articles addressing high school chemistry topics; (5) articles published in peer-reviewed journals; and (6) articles published within the 2015 - 2025 timeframe. Following the screening process, the 27 selected articles spanned from 2018 to 2025. The exclusion of conference abstracts, editorials, book reviews, or articles lacking full-text availability was methodologically justified to ensure the robustness and reliability of the synthesis, as these document types typically lack the empirical data and rigorous peer-review process required for a comprehensive systematic review. Futhermore, during the full-text eligibility assessment, additional exclusion criteria were applied: articles were excluded if they did not specifically focus on secondary school chemistry education, or if the digital tools discussed did not serve a visualization purpose in chemical representation. This rigorous assessment ensured that the final 27 articles were strictly aligned with the review's conceptual focus on digital visualization technologies in a secondary school chemistry context

2.5 Data Analysis

Data analysis was conducted using a thematic content analysis approach, specifically designed to systematically map digital visualization technologies trends, representation patterns, and pedagogical strategies. The analytical process followed three iterative steps to ensure transparency and reproducibility:

1. Data Extraction: Information from the 27 selected articles was manually extracted into a synthesis matrix created in Microsoft Excel. This matrix acted as a structured database capturing essential study characteristics, including technology type, chemical representation patterns (macroscopic, sub-microscopic, symbolic), instructional models, and chemistry topics.
2. Manual Thematic Coding: A manual inductive coding process was employed to identify recurring patterns within the data. By systematically reviewing the synthesized information in Excel, descriptive labels (codes) were assigned to each study based on the specific focus of its implementation of digital visualization technologies.
3. Synthesis and Categorization: These manually identified codes were subsequently grouped into broader categories such as Inquiry & Discovery Learning or Integrated Representation Patterns to formulate key themes, allowing for a comparative analysis across the selected studies.

The final synthesis stage involved integrating these themes to identify patterns of media development and research gaps. This structured manual approach provides a clear audit trail from the raw article data to the final findings, thereby enhancing the credibility and reproducibility of this systematic literature review.

3. RESULT AND DISCUSSION

3.1. Result

Following the PRISMA protocol, 27 articles were identified as meeting all inclusion criteria for in-depth

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analysis. Although the initial literature search targeted the 2015 - 2025 timeframe, the final selection process yielded articles published predominantly within the 2018 - 2025 period. This narrowing reflects the fact that literature meaningfully addressing the integration of digital visualization technologies with chemical representation in the context of high school learning became concentrated and intensive from 2018 onward. Analysis of the 27 selected articles (2018 - 2025) reveals an accelerating digital transformation within high school chemistry education, with the peak of research productivity occurring in 2024 - 2025. This trend reflects a global pedagogical adaptation to address the challenges posed by the abstract nature of chemistry through digital visualization technologies. Table 1 presents a summary of the key characteristics and findings of the 27 articles analyzed in this review, encompassing information on authors, publication year, chemistry topic, technology type, representation pattern, learning strategy or model, and key findings. This synthesis matrix provides a comprehensive overview of the research landscape at the intersection of technology-integrated chemical representation and pedagogical strategy.

Table 1. Summary of key characteristics and findings of analyzed articles

No.	Author (Year)	Chemistry Topic	Technology (6 main categories) / detail	Representation Level (3 categories)	Learning Strategy / Model	Key Findings
1.	Kotsalidis et al. (2024)	Intermolecular forces	Computer Simulations / Interactive simulations & molecular dynamics	Integrated Representation	Problem-Based Learning	3D computational modeling is effective for teaching intermolecular forces.
2.	Fernández et al. (2023)	Stoichiometry	Learning Analytics / Student-generated multimedia & analytics	Integrated Representation	PjBL – Student-generated multimedia	Independently producing reaction videos promotes understanding of chemical equations.
3.	Lossjew & Bernholt (2024)	Reaction rates	Digital Instrumentation / Digital sensors & experimental hardware	Integrated Representation	Inquiry-Based Learning	Integration of Arduino pressure sensors and GeoGebra strengthens students' scientific literacy.
4.	Yamtinah et al. (2023)	Chemical equilibrium	Immersive Technology / Augmented Reality	Integrated Representation	Inquiry-Based Learning	AR media effectively improves learning outcomes.
5.	Irwanto et al. (2025)	Atomic structure	Mobile & Gamification / Mobile apps & gamification	Integrated Representation	Game-Based Learning	The 'Go-Chemist!' app significantly increases students' learning motivation scores.
6.	Kekeba (2025)	Acids and bases	Computer Simulations / Interactive simulations	Integrated Representation	Jigsaw Cooperative Learning	Integration of computer simulations and the Jigsaw strategy improves academic achievement.
7.	Praisri & Faikhamta (2020)	Chemical equilibrium	Digital Multimedia / Multimedia & dynamic animations (scaffolding)	Integrated Representation	Argumentation within Model-Based Learning	Combining particulate media with argumentation shifts students' tentative mental models toward scientifically valid ones.
8.	Berg et al. (2019)	Matter and its changes	Learning Analytics / Student-generated work & analytics	Integrated Representation	5R Teaching Approach	Creating animations improves students' representational understanding.
9.	Holmelin et al. (2025)	Intermolecular forces	Computer Simulations / Interactive simulations	Integrated Representation	Computer-Assisted Instruction (CAI)	Structured worksheets optimize simulation visualization outcomes.
10.	Magnone & Yezierski (2024)	Chemical bonding	Digital Multimedia / Multimedia & dynamic animations (scaffolding)	Integrated Representation	VisChem Approach	Chemistry instruction dominated by symbolic representations can be scaffolded toward deep particulate understanding.

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No.	Author (Year)	Chemistry Topic	Technology (6 main categories) / detail	Representation Level (3 categories)	Learning Strategy / Model	Key Findings
11.	Muljana & Selco (2023)	Chemical bonding	Computer Simulations / Interactive simulations	Integrated Representation	Computer-Assisted Instruction (CAI)	The 'Making Molecules' simulation builds concrete understanding of molecular bonding.
12.	Chiu et al. (2019)	Periodic table	Immersive Technology / Augmented Reality	Integrated Representation	Model-Based Learning	AR models facilitate complex cognitive transfer.
13.	Saputra et al. (2023)	Chemical equilibrium	Computer Simulations / Interactive simulations (Molecular Workbench)	Integrated Representation	Collaborative Discovery Learning	Molecular simulations in a collaborative environment improve critical thinking skills.
14.	Peperkorn et al. (2024)	Chemical equilibrium	Computer Simulations / Molecular dynamics simulations	Integrated Representation	Simulation-based mental modeling (SIMMS)	Drawing particles elicits stronger mental reflection than multiple-choice responses.
15.	Mubarak et al. (2025)	Acids and bases	Mobile & Gamification / Mobile apps & gamification	Fragmented Representation	Game-Based Learning	An RPG-style chemistry game demonstrably increases students' self-efficacy.
16.	Sunyono & Meristin (2018)	Chemical bonding	Digital Multimedia / Representational visualization media	Integrated Representation	Multiple Representation-Based Learning (MRL)	Students' conceptual understanding under MRL is significantly higher than under Problem-Based Learning.
17.	Wuttisela et al. (2024)	Chemical equilibrium	Digital Instrumentation / Smartphone-based colorimetric app	Integrated Representation	Inquiry-Based Learning	Smartphone-assisted experiments successfully improve conceptual understanding.
18.	Rahmawati et al. (2022)	Chemical equilibrium	Computer Simulations / PhET interactive simulations	Integrated Representation	Computer-Assisted Instruction (CAI)	PhET simulations help students connect all three levels of chemical representation.
19.	Chongo et al. (2021)	Electrolytic cells	Learning Analytics / Computational thinking chemistry modules	Integrated Representation	CT-Integrated Instruction	Plugged-in activities improve chemistry academic achievement.
20.	Lin & Wu (2021)	Electrochemistry	Digital Multimedia / Visualization software & tools	Integrated Representation	Model-Based Learning Approach	Animations and diagrams improve conceptual understanding of electrochemistry and enhance learning motivation.
21.	Saidin et al. (2024)	Chemical bonding	Immersive Technology / Mobile AR – CBOND	Single Representation	Immersive/AR-Based Learning	The 'CBOND' mobile AR application significantly improves students' visualization skills.
22.	Irwanto et al. (2025)	Reaction rates	Immersive Technology / VR vs. PhET simulations	Integrated Representation	Inquiry-Based Learning (5E model)	Immersive VR technology improves students' academic achievement.
23.	Jere & Mpeta (2024b)	Reaction rates	Computer Simulations / Computer simulations	Integrated Representation	Predict–Observe–Explain (POE)	Computer simulations combined with the POE strategy improve representational understanding.
24.	Martinez et al. (2021)	Gas laws	Digital Multimedia / Screencasts & eye-tracking	Integrated Representation	Simulation-Based Learning	The screencast group successfully bridged macroscopic explanations to the sub-microscopic level.
25.	R. Zohar & Levy (2019)	Chemical bonding	Computer Simulations / Interactive simulations – ELI-CHEM	Integrated Representation	Discovery Learning	The ELI-Chem simulation effectively helps students construct dynamic mental models.
26.	Yaseen (2018)	States of matter	Digital Multimedia / Animation software	Integrated Representation	Constructionist Approach	Creating animations helps students visualize

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No.	Author (Year)	Chemistry Topic	Technology (6 main categories) / detail	Representation Level (3 categories)	Learning Strategy / Model	Key Findings
						particulate concepts and correct misconceptions.
27.	Hunegnaw et al. (2025)	Reaction rates	Computer Simulations / Virtual experiments	Integrated Representation	Experiential Learning	Students tend to rely predominantly on the macroscopic level when representing their knowledge.

Note: Single representation: Use of a single representational level in isolation. *Integrated representation:* Full integration of all three levels (triplet): macroscopic, sub-microscopic, and symbolic. *Fragmented representation:* The three representational levels are presented separately, without explicit connections.

3.1.1 Technology Trends in Chemistry Education

Based on the analysis of the 27 articles, the technologies identified were classified into six principal categories, as illustrated in the figure below.

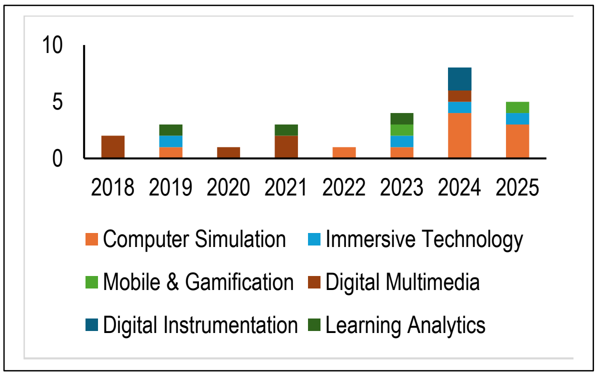

Figure 2. Distribution of technology categories across the 27 analyzed articles

Further analysis reveals that, of the six technology categories identified, *Computer Simulations* encompassing digital simulations, PhET, and molecular dynamics represent the most dominant category, accounting for 10 articles (37%). Over the 2018 - 2025 period, the use of computer simulations increased notably in 2024 - 2025, reaching 26%. This indicates that digital simulations such as PhET and molecular dynamics tools have become the primary standard for visualizing sub-microscopic phenomena that are not directly observable. *Digital Multimedia* ranks second, with 6 articles (22.2%), covering the use of animations, educational videos, and 3D modeling as visualization tools that transform static representations into dynamic ones. *Immersive Technology* - encompassing Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) - is establishing a significant presence, with 4 articles (14.8%), reflecting a shift toward spatially immersive, experience-based learning.

The remaining categories - *Learning Analytics* (3 articles; 11.1%), *Digital Instrumentation* (2 articles; 7.4%), and *Mobile & Gamification* (2 articles; 7.4%) - represent diverse innovations targeting personalized assessment, active engagement through real-time sensor data, and enhanced learning motivation through gamification, respectively. Collectively, this diversity of technology categories demonstrates that the design of digital chemistry learning is not monolithic; rather, it has diversified to address the varied cognitive and interactive needs of secondary school students.

Computer simulations occupy the dominant position as a cognitive instrument for bridging the limitations of human perception with respect to sub-microscopic phenomena. These tools function not merely as supplementary media, but as interactive instruments that enable students to manipulate variables and observe particle behavior in real time (Jere & Mpeta, 2024; Rahmawati et al., 2022).

3.1.2 Patterns of Chemical Representation in Digital Learning Environments

The analysis reveals a paradigm shift from conventional, fragmented methods toward the *Integrated Representation* pattern. Data indicate that 92.6% of the reviewed studies employed an integrated pattern, in which the macroscopic, sub-microscopic, and symbolic levels are presented simultaneously. The dominance of this integrated pattern represents a strategic response to the cognitive barriers students face when attempting to connect laboratory phenomena with molecular structure (Sunyono & Meristin, 2018).

3.1.3 Pedagogical Strategies in Digitally Integrated Chemistry Education

Analysis of the 27 selected articles demonstrates that the integration of technology in high school chemistry education is not homogeneous; rather,

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it is highly dependent on the pedagogical model employed. The identified learning strategies were synthesized into six principal categories based on their cognitive mechanisms and instructional objectives.

Inquiry & Discovery Learning holds the dominant position, accounting for 29.6% of the reviewed studies. This suggests that scientific inquiry continues to be a widely prioritized pedagogical approach in contemporary chemistry education. Within the context of technology integration, the inquiry model serves as a framework for exploration in which simulations (PhET and Molecular Workbench) are used not as passive information delivery tools, but as experimental instruments through which students test hypotheses and construct understanding independently (Saputra et al., 2023; Wuttisela et al., 2024).

Model-Based Learning (22.2%) and other approaches in the remaining category (22.2%) reflect a systematic effort to help students reconstruct scientifically valid mental models. Through model-based approaches, students are required to conceptualize abstract phenomena into coherent and valid mental structures. Meanwhile, the trend toward *Computational & Multimedia Learning* (18.5%) highlights the growing importance of advanced digital literacy. As demonstrated by Chongo et al. (2021), the integration of Computational Thinking (CT) through plugged-in activities effectively compels students to decompose complex chemistry problems, which ultimately sharpens their cognitive problem-solving skills in the context of chemical bonding.

3.2. Discussion

This study maps the landscape of technology integration in high school chemistry education with respect to chemical representation and pedagogical strategy. The findings indicate that technology integration represents not merely the addition of digital tools, but rather a complex pedagogical transformation. The analysis reveals a clear shift from the use of passive media (e.g., static images) toward dynamic cognitive instruments, including computer simulations (*Molecular Workbench*, PhET), Augmented Reality (AR), Virtual Reality (VR), and digital sensor instruments (*Arduino*). Furthermore, technologies in the *Immersive Technology* and *Digital Instrumentation* categories reflect a broader demand for more authentic experimental experiences. AR/VR addresses students' difficulties in comprehending stereochemistry and molecular geometry through spatial presence that enables independent manipulation of 3D structures (Irwanto et al., 2025; Yamtinah et al., 2023). Digital Instrumentation (e.g., Arduino sensors) complements virtual media with empirical data, which has been shown to enhance students' scientific literacy (Wuttisela et al., 2024).

From a theoretical standpoint, these technologies are effective in part because they align with Cognitive Load Theory (CLT). The abstract nature of chemistry involves sub-microscopic phenomena that are inherently invisible. Interactive simulations function as cognitive scaffolds that, as reported by Jere and Mpeta (2024) and Rahmawati et al. (2022), enable students to manipulate variables in real time, thereby facilitating the construction of dynamic mental models rather than rote memorization of facts - an approach that is inherently prone to the development of misconceptions.

Appropriate technology use can markedly improve students' representational understanding in chemistry. Based on findings from the 27 selected articles - organized according to three representational categories - the analysis reveals a paradigm shift from fragmented approaches toward the *Integrated Representation* pattern (92.6%). This pattern presents the macroscopic, sub-microscopic, and symbolic levels simultaneously. The integration of these representational levels is critical, as students' frequent failure to understand chemistry is often attributable to their inability to connect the three levels articulated in Johnstone's Triangle. When technology presents all three levels concurrently, cognitive load can be minimized. Research has shown that the *Integrated Macroscopic–Microscopic–Symbolic Approach* (IMMSA) significantly reduces cognitive load compared to fragmented instruction, which tends to generate misconceptions (Martinez et al., 2021). In the context of chemical bonding, this integrated approach helps students understand that the symbolic formula NaCl represents both an extended ionic crystal lattice in the macroscopic world and the electrostatic interactions between ions at the sub-microscopic level. Without such integration, students tend to become trapped in conceptual fragmentation (Sunyono & Meristin, 2018).

For technology to maximally support students' development of representational understanding, it must be paired with appropriate pedagogical strategies. The findings confirm that technology is most effective when integrated with active learning strategies such as Inquiry-Based Learning, Model-Based Learning, and constructionist approaches. These strategies are superior because they are inherently constructionist in nature: students assigned to create animations of states of matter, for instance, must actively construct their own knowledge of molecular motion in order to produce a scientifically accurate visualization (Peperkorn et al., 2024; Yaseen, 2018). From a constructivist perspective, meaningful understanding is achieved only when students actively construct knowledge. When students design visual representations, they cannot produce scientifically correct models without first understanding the underlying concepts. Technology here functions as a thinking tool that demands students develop more scientifically valid mental models.

The *Predict–Observe–Explain* (POE) learning model also demonstrates strong synergy when applied to chemical representation development. As argued by Jere and Mpeta (2024), the POE strategy can generate valid student knowledge through a structured three-stage process: the *Predict* stage requires students to activate prior knowledge; the *Observe* stage provides immediate feedback through simulation; and the *Explain* stage demands a process of scientific synthesis. This process is considerably more effective than didactic instruction because it encourages students to think as scientists, validating their hypotheses through digital means.

While these active learning strategies demonstrate significant potential when combined with digital visualization, a critical examination of the broader literature reveals that certain areas remain underexplored. Despite the clear evidence supporting the integration of digital visualization technologies in chemistry education, several research gaps warrant further investigation. First, there is a clear bias toward certain chemistry topics; while topics like Chemical Equilibrium, Reaction Rates, and Chemical Bonding are extensively covered (representing the majority of the reviewed studies), abstract or challenging topics-such as Thermochemistry or Green Chemistry, which are often delivered through text-heavy instructional approach-remain underrepresented in the literature. Second, the methodological approach across these studies often relies on short-term experimental designs, limiting our understanding of the long-term cognitive retention of students who use these technologies. Third, while the 'Integrated Representation' pattern (92.6%) is dominant, empirical evidence regarding the specific 'scaffolding' threshold-at what point does technology integration transition from supporting to overloading students' cognitive capacity-remains fragmented. Finally, although most studies report positive learning outcomes, there is a lack of focus on how these digital visualization technologies perform in low-resource school settings where technological infrastructure and teacher digital literacy may act as significant barriers. Given the conceptual complexity of these topics, there is a compelling need for future research to explore how digital visualization technologies can transform these typically passive learning materials into dynamic, interactive experiences.

4. CONCLUSION

Based on the systematic literature review conducted on 27 scholarly articles concerning technology in high school chemistry education, three principal conclusions can be drawn, each corresponding to the research objectives of the study.

First, the research trends reveal a significant increase in the use of *Computer Simulations* including digital simulations, PhET, and molecular dynamics tools during the 2024–2025 period reaching 26% of the analyzed literature.

Second, a paradigm shift toward *Integrated Representation* is evident, with 92.6% of studies employing this pattern. The success of digital chemistry learning is determined by technology's capacity to connect the macroscopic, sub-microscopic, and symbolic levels simultaneously, thereby preventing the formation of misconceptions.

Third, the learning strategies most commonly integrated with technology are active learning approaches specifically inquiry-based learning, POE, and constructionism. The key to effective digital chemistry instruction does not reside in the sophistication of the technology itself, but in the pedagogical design that requires students to function as knowledge constructors, actively reconstructing their own understanding.

While these insights provide a valuable overview, this study is constrained by specific methodological limits. Because the systematic search focused exclusively on peer-reviewed articles written in English and archived across Scopus, ERIC, and Springer between 2015 and 2025, relevant scholarship available in other languages or open repositories may not be represented. Consequently, there is a clear opportunity for future scholars to pursue longitudinal field experiments. Such efforts should examine how emerging artificial intelligence (AI) applications and virtual environments operate within STEM frameworks to demystify complex chemistry topics that have received limited attention.

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