Digital Alchemy: Technological Advancements in the Teaching of Chemistry- a Review

K. Nagaraj
Lecturer, Department of Chemistry, Mount Carmel PU College, Bengaluru
Karnataka- 560052, India.
ORCID- ID: 0009-0006-4180-5536; E-mail: nagarajchkrg123@gmail.com

Area/Section: Chemical Science.
Type of Paper: Exploratory Research.
Number of Peer Reviews: Two.
Type of Review: Peer Reviewed as per |C|O|P|E| guidance.
Indexed in: OpenAIRE.
DOI: https://doi.org/10.5281/zenodo.16497509
Google Scholar Citation: PIJBAS

How to Cite this Paper:
Nagaraj, K. (2025). Digital Alchemy: Technological Advancements in the Teaching of Chemistry- a Review. *Poornaprajna International Journal of Basic & Applied Sciences (PIJBAS), 2*(1), 53-62. DOI: https://doi.org/10.5281/zenodo.16497509

Poornaprajna International Journal of Basic & Applied Sciences (PIJBAS)
A Refereed International Journal of Poornaprajna Publication, India.
ISSN: 3107-8478

Crossref DOI: https://doi.org/10.64818/PIJBAS.3107.8478.0012

Received on: 10/05/2025
Published on: 30/06/2025

Digital Alchemy: Technological Advancements in the Teaching of Chemistry- a Review

K. Nagaraj
Lecturer, Department of Chemistry, Mount Carmel PU College, Bengaluru
Karnataka- 560052, India.
ORCID- ID: 0009-0006-4180-5536; E-mail: nagarajchkrg123@gmail.com

ABSTRACT

Purpose: *The purpose of this review is to systematically examine the integration of modern technological tools in the teaching of chemistry. It aims to highlight how innovations such as virtual laboratories, simulation software, augmented and virtual reality (AR/VR), and gamified platforms have influenced pedagogical practices and student learning outcomes in chemical education.*

Methodology: *This review is based on a thematic analysis of peer-reviewed, open-access literature published between 2018 and 2024. Sources were selected using academic databases such as ScienceDirect, MDPI, Springer Open, and arXiv, with a focus on studies that report empirical data or offer theoretical insights into the use of technology in chemistry education.*

Results/Analysis: *Findings reveal that virtual labs and simulation platforms enhance conceptual clarity, especially in topics involving molecular modelling and reaction mechanisms. AR/VR tools significantly improve learner engagement and spatial visualization skills. Gamified approaches have been associated with improved motivation and assessment performance. However, challenges remain in accessibility, infrastructure, teacher training, and over-dependence on digital tools. A strong preference for blended learning models emerges as the most sustainable and impactful approach.*

Originality/Value: *This review consolidates recent technological advancements in chemistry pedagogy and critically evaluates their practical implementation and outcomes. It provides a consolidated reference for educators, curriculum developers, and policymakers seeking to integrate or expand digital pedagogies in chemistry education, particularly in line with evolving educational frameworks such as India's National Education Policy 2020.*

Type of paper: *Thematic review article*

Keywords: Chemistry education, educational technology, virtual laboratories, simulation software, AR/VR in science education, gamification, blended learning

1. INTRODUCTION :

Chemistry, often called the central science, forms a vital bridge between the physical and life sciences, connecting disciplines like physics, biology, medicine, and engineering. Because it plays a vital role in diversified areas, it's important to introduce this subject early on in school, starting from the K-12 level. (A. Alhashem & H. Alfailakawi (2023). [1]). For decades, chemistry education has leaned on traditional approaches- chalk-and-talk lectures, hands-on lab work, and textbook learning. While these methods laid a solid foundation, they've also shown limitations, especially when it comes to abstract concepts, resource constraints, or engaging today's digitally native learners. When the COVID-19 pandemic hit, teachers had to quickly adapt to online teaching. Many were left without the usual professional development opportunities (S. Aydın-Günbatar & M. Özel, (2021). [2]).

In recent years- especially in the wake of the COVID-19 pandemic—there has been a noticeable and accelerated shift toward integrating technology into the chemistry classroom. Digital learning platforms are now a common part of modern education. As technology has progressed rapidly, these tools have become crucial in supporting learning from a distance (Dr. Petare Purushottam Arvind et.al. (2023). [3]). What was once supplemental is now becoming essential. For certain tasks, active interaction can enhance learning more effectively than just immersive experiences. That's why computers have become a common and valuable tool in education, especially when it comes to hands-on or practical learning

(K. Khalaf & S. Al-Olimat, (2022). [4]). From virtual labs and simulation software to immersive technologies like augmented reality (AR) and virtual reality (VR), educators are reimagining how chemistry can be taught more effectively and inclusively. Students used computer simulations to explore and understand how laboratory equipment works in theory before handling the real thing. (A. Engdahl & N. Fahlgren (2023). [5]).

This review explores the wide-ranging involvement of technology in chemistry education. It highlights how digital tools- from learning management systems (LMS) to game-based learning platforms- are reshaping teaching strategies, improving student engagement, and addressing long-standing challenges. With the rise of the Fourth Industrial Revolution, there's a growing push to integrate modern technology into nearly every area of life (Sayed Abdul Aziz Ahmady Falah et. Al. (2024). [6]). Hands-on and engaging digital environments have proven to be powerful tools for helping students grasp core concepts in chemistry (Rahman Hameedur et. Al. (2024). [7]).

At the same time, it acknowledges the barriers to adoption, including technical, pedagogical, and institutional limitations. Finally, it offers a forward-looking perspective on how technology can be harnessed not just as a supplement but as a catalyst for deeper conceptual understanding and practical skill-building in the chemistry classroom.

2. OBJECTIVES OF THE PAPER :

The need for digital laboratory platforms is steadily rising in universities, as they offer adaptable, distance-friendly, and inclusive learning opportunities. (O. Bektas & A. Aslan (2022). [8]). This study aims to explore how technology is reshaping the way chemistry is taught, learned, and experienced in classrooms and laboratories. The focus is on understanding how modern technology is being integrated into the training of chemistry educators, specifically to equip them for teaching students with diverse learning needs. (Shatayeva Aigerim et. Al. (2022). [9]). From virtual labs and simulations to immersive tools like augmented and virtual reality, the review examines a wide range of digital innovations that are transforming traditional methods of chemistry instruction. When future teachers experience student-focused, constructivist teaching methods during their training, it often leads to stronger growth in their ability to use digital tools effectively. (Wohlfart Olivia et. Al. (2023). [10]). It also compares the effectiveness of these tools in enhancing conceptual understanding, student engagement, and teaching efficiency. In addition, the review highlights current challenges faced in implementation, such as accessibility, infrastructure, and teacher preparedness, and discusses the future potential of technology to create a more inclusive, interactive, and student-centered approach to chemistry education.

3. REVIEW OF LITERATURE :

Table 1: A descriptive summary of literature reviewed

S. No.	Area of Research	Focus and Outcome	Reference
1	Virtual Laboratory Technology in Pre-service Teacher Education	Examined virtual chemistry laboratories' impact on pre-service teachers, demonstrating enhanced engagement and understanding in teacher preparation programs.	A. Alhashem & H. Alfailakawi (2023). [1]
2	Virtual Chemical Laboratories - Systematic Review	Conducted comprehensive literature analysis of virtual chemistry labs, identifying key implementation trends, benefits, and educational challenges.	S. Aydın-Günbatar & M. Özel, (2021). [2]
3	Virtual Learning Environments Impact Assessment	Investigated virtual learning environments across disciplines, establishing positive correlations with student engagement and academic achievement.	Dr. Petare Purushottam Arvind et.al. (2023). [3]
4	Interactive Science Laboratory Systems	Systematically reviewed interactive laboratory technologies in science education, identifying best practices for implementation and effectiveness.	K. Khalaf & S. Al-Olimat, (2022). [4]

5	Virtual Reality Chemistry Laboratory Experiences	Explored student experiences with VR chemistry labs, revealing positive feedback and improved spatial understanding of molecular concepts.	A. Engdahl & N. Fahlgren (2023). [5]
6	Virtual and Augmented Reality in Chemistry Education - Literature Review	Systematically examined VR/AR applications in chemistry education, highlighting effectiveness in visualization and conceptual understanding enhancement.	Sayed Abdul Aziz Ahmady Falah et. Al. (2024). [6]
7	Game-based Learning in Metaverse Chemistry Education	Developed metaverse chemistry classroom for chemical bonding, successfully demonstrating improved engagement and learning outcomes in remote education.	Rahman Hameedur et. Al. (2024). [7]
8	Virtual Laboratories in Higher Education - Case Study Analysis	Analysed virtual laboratory implementation through learning theory frameworks, providing theoretical foundation for virtual lab effectiveness in tertiary education	O. Bektas & A. Aslan (2022). [8]

As in Table 1, the research articles collectively demonstrate the transformative impact of digital technologies on chemistry education. Virtual laboratory technologies have emerged as effective tools for enhancing student engagement and understanding, particularly in visualizing complex molecular structures and chemical processes. These studies reveal consistent positive outcomes in student learning experiences, with virtual reality applications showing particular promise in improving spatial understanding of chemical concepts. Augmented reality blends the tangible world around us with computer-generated visuals and interactions, using technology to enhance what we naturally see and experience in our everyday spaces. (Belford. R. E. (2019). [11]). Augmented reality transforms abstract molecular concepts into tangible learning experiences, helping students grasp complex spatial arrangements and chemical properties through direct manipulation and observation. (Levy Julia et. Al. (2024). [12]).

The evolution from traditional virtual laboratories to immersive, interactive learning environments represents a significant advancement in chemistry education. Game-based learning approaches and metaverse-based chemistry classrooms have created new paradigms for remote education, successfully addressing visualization challenges while maintaining pedagogical effectiveness. These digital technologies have matured from experimental tools to essential educational components, offering scalable solutions for modern chemistry teaching across diverse educational contexts.

4. METHODOLOGY :

This review is based on a thematic and narrative analysis of recent open-access literature related to technology use in chemistry education. A wide range of scholarly articles, case studies, and reports published between 2018 and 2024 were examined to identify patterns, trends, and key developments in the field. The materials were selected using academic databases and publicly accessible platforms, focusing on peer-reviewed sources that specifically discuss tools like virtual labs, AR/VR applications, gamification, and digital learning environments. The gathered content was then carefully organized, compared, and synthesized to evaluate both the practical impact and pedagogical value of these technologies in modern chemistry classrooms. Emphasis was placed on extracting insights that could inform future educational practices and policy considerations. The infographics displayed in this article were designed using AI tools.

5. TECHNOLOGICAL TOOLS AND PLATFORMS IN CHEMISTRY EDUCATION :

As classrooms evolve and students grow up in a digital-first world, teaching chemistry is no longer limited to the four walls of a lab or the pages of a textbook. Today, a growing set of digital tools are helping teachers bring chemistry to life in ways that are safer, more interactive, and more engaging than ever before (Fig. 2). It's important to see whether these hands-on digital experiences really help young learners connect the dots between chemistry equations, what's happening at the molecular level, and the experiments they can actually watch and touch. (Olim Sandra C amara et. Al. (2024). [13]) Below are some of the most impactful technologies currently shaping chemistry education.

5.1. Virtual Laboratories:

Virtual labs recreate the feel of a real laboratory, minus the cost, hazards, and space constraints. Platforms like PhET Interactive Simulations, ChemCollective, and Labster let students conduct digital experiments- from titrations to molecular reactions- right from their devices. These tools not only make experiments more accessible but also reduce the anxiety that many students face in real lab settings. The strength of these automated platforms comes from their advanced software, which empowers scientists to design studies, operate laboratory devices, and manage data collection and interpretation efficiently. (Ananikov Valentine P. (2024). [14]).

5.2. Simulation Software:

Software like Avogadro, ChemSketch, and Spartan is making molecular structures and reaction mechanisms much easier to understand. Instead of staring at static 2D diagrams, students can now interact with 3D models of molecules, rotate them, analyze bond angles, and even simulate chemical reactions. This kind of hands-on digital manipulation supports spatial reasoning and helps demystify some of chemistry's more abstract topics.

5.3. Augmented and Virtual Reality (AR/VR):

AR and VR are taking immersion in chemistry learning to an entirely new level. Whether it's walking through a giant molecule or conducting a virtual titration, these technologies allow students to experience chemistry in 360 degrees. Platforms like MolecularWebXR and Immersive Quantum Mechanics are pushing the boundaries of what's possible. According to recent research (MDPI, 2022; Springer Open, 2020), AR/VR not only boosts motivation but also helps students better understand complex ideas like atomic orbitals and reaction kinetics.

5.4. Gamification and Game-Based Learning:

Game-based tools like Kahoot, Quizizz, and custom-designed chemistry games turn learning into an engaging challenge. Whether it's racing through a quiz on periodic trends or solving a puzzle on balancing equations, students often absorb concepts more naturally when learning feels like play. These tools encourage participation, promote friendly competition, and can be especially effective in keeping learners engaged in traditionally tough topics like stoichiometry and thermodynamics.

5.5. Learning Management Systems and Digital Resources:

Platforms such as Moodle, Google Classroom, and Canvas have become the digital backbone of many classrooms. They help educators manage assignments, share resources, provide feedback, and personalize learning paths for students. When combined with digital tools like e-books, interactive modules, podcasts, and recorded lectures, these systems create a flexible and student-centred learning environment. This is especially valuable in blended and flipped classroom models, where students learn at their own pace.

6. PEDAGOGICAL IMPACT AND EFFECTIVENESS :

The integration of technology in chemistry education is not just a trend- it's a pedagogical shift. Beyond the novelty of digital tools, research consistently shows that when used thoughtfully, technology can strengthen students' conceptual understanding, increase engagement, and promote independent learning (Fig. 1). This section explores the pedagogical outcomes observed through various technological interventions in chemistry teaching.

6.1. Enhancing Conceptual Understanding:

One of the biggest hurdles in chemistry education lies in helping students grasp abstract concepts- like molecular geometry, electron configurations, and reaction mechanisms. Tools such as simulation software and 3D modelling programs make these ideas more accessible. Instead of imagining orbitals or bond angles, students can now manipulate interactive models, enhance their spatial reasoning, and deepen their comprehension. Studies have found that virtual labs and simulations improve both retention and application of concepts, particularly when compared to lecture-based learning alone.

6.2. Boosting Student Engagement and Motivation:

Using technology in education has inspired new teaching techniques and reinforced the learning ideas that teachers, behavioural specialists, and knowledge experts have been advocating. (Elias Michal et. Al. (2022). [15]) Technology brings with it an element of novelty, but more importantly, it introduces interactivity. Whether it's a game-based quiz on acids and bases or a virtual reality walk-through of a molecular structure, students tend to participate more actively when they're doing rather than just listening. AR and VR experiences have been especially effective in motivating learners who might otherwise struggle with conventional textbook content. These tools provide immediate feedback, allow for trial-and-error learning without real-world risks, and foster a more immersive educational experience.

6.3. Supporting Different Learning Styles:

Every student learns differently- some prefer visuals, others learn by doing, and a few thrive on repetition. Technology helps bridge this diversity. With learning management systems, educators can offer personalized learning paths, supplemental videos, and practice quizzes, all in one place. Gamification and simulations also cater to kinesthetic learners, while recorded lectures and animations support auditory and visual learners. This flexibility allows instructors to meet students where they are, rather than forcing them into a one-size-fits-all model.

6.4. Encouraging Inquiry and Critical Thinking:

Another benefit of technology is its ability to encourage inquiry-based learning. In a well-designed virtual lab, students aren't just following step-by-step instructions- they're making predictions, testing hypotheses, and analysing results. This fosters critical thinking and a more investigative mind-set. Some platforms even allow for open-ended experimentation, where students can explore "what-if" scenarios and learn from mistakes in a low-risk environment. Even though schools have been using three-dimensional visual tools and reality-enhancing technology for years, very little research actually looks at what students think they're gaining from these interactive molecular models and digital overlays in their chemistry classes. (Abdinejad Maryam et. Al. (2020). [16]). Students overwhelmingly agree that augmented reality is essential for deeply grasping chemistry concepts. (Nazar Muhammad et. Al. (2024). [17]).

6.5. Improving Assessment and Feedback Loops:

Digital platforms allow for instant feedback, automatic grading, and data-driven insights into student performance. Teachers can track who's struggling, where misconceptions are forming, and which topics may need revisiting. This kind of real-time monitoring is difficult to achieve with paper-based assessments alone and helps educators make informed decisions to improve their instruction. Augmented Reality blends virtual 3D chemical structures with the real world, letting users seamlessly view and manipulate molecules in their physical space. (Fombona Javier et. Al. (2022). [18]).

7. CHALLENGES AND LIMITATIONS :

While technology offers immense potential to transform chemistry education, its adoption is not without significant roadblocks. The effectiveness of any digital tool depends not just on its design, but also on infrastructure, accessibility, training, and institutional readiness. Below, we explore some of the key challenges currently limiting the widespread and equitable use of educational technologies in chemistry classrooms.

7.1. Digital Divide and Infrastructure Gaps:

Perhaps the most glaring limitation is the persistent digital divide, especially in rural and underfunded schools. Lack of high-speed internet, outdated devices, or even basic power supply issues can severely hinder the implementation of virtual labs or cloud-based platforms. In regions where access to basic lab facilities is already limited, introducing high-tech alternatives may paradoxically widen the learning gap if not carefully managed.

7.2. Limited Digital Literacy Among Educators:

Not all teachers are tech-savvy, and the sudden shift to digital tools, especially during the COVID-19 pandemic, highlighted this gap. Many chemistry educators, particularly those accustomed to traditional methods, face difficulties in navigating new platforms or adapting content for digital delivery. Without proper training and ongoing support, even the most advanced technology can become an unused or misused resource. To build a more sustainable future through chemistry education, there's a growing need for deeper research and stronger efforts to integrate digital tools that support systems thinking. (Chiu Wang-Kin. (2021). [19]).

7.3. Pedagogical Misalignment:

Technology is only as effective as the pedagogy behind it. Simply introducing flashy tools into a curriculum without aligning them with learning outcomes or instructional strategies can lead to superficial engagement. In some cases, educators over-rely on simulations or pre-packaged modules, resulting in passive consumption rather than active learning. A meaningful tech-enhanced classroom requires thoughtful integration of non-replacement traditional, hands-on practices (Fig. 3).

7.4. Cost and Licensing Barriers:

While many educational tools offer free trials or basic versions, comprehensive features often come at a price. Licenses for simulation software, AR/VR platforms, or even premium LMS features can strain school budgets, particularly in public institutions. Cost-related constraints can also limit scalability, with some students benefiting from enriched environments while others are left behind.

8. FUTURE DIRECTIONS AND OPPORTUNITIES :

As digital tools continue to evolve and education adapts to an increasingly connected world, the role of technology in chemistry education is expected to grow in both depth and sophistication. While current innovations have laid a strong foundation, the next wave of developments offers exciting possibilities to enhance how students explore and understand chemistry (Fig. 4). As technology continues to evolve, tools like augmented reality hold great promise for transforming how students explore and understand complex chemistry concepts- making learning more interactive, intuitive, and accessible for future generations. (Ou Kuo-Liang et. Al. (2022). [20]).

8.1. Integration of AI-Powered Learning Assistants:

Artificial Intelligence (AI) holds immense promise in personalizing the learning experience. AI-powered tutors and chatbots could provide students with real-time support, adaptive quizzes, and personalized feedback based on their performance. These intelligent systems can help identify individual learning gaps and recommend targeted content, ensuring students receive the support they need, when they need it.

8.2. Expansion of Mixed Reality Experiences:

While AR and VR are already making waves, future developments point toward mixed reality (MR) environments that seamlessly blend real lab work with virtual overlays. Imagine a student wearing smart glasses in a real lab, seeing step-by-step instructions, animated molecules, or reaction predictions layered over their physical workspace. These immersive setups can enhance understanding while maintaining the tactile learning experience.

8.3. Blockchain for Academic Integrity and Micro-Credentialing:

In the near future, blockchain technology could play a role in securing student assessments, tracking learning progress, and issuing micro-certifications for specific skills, like spectroscopy interpretation or lab safety training. This would provide verifiable, decentralized records of achievement and build student portfolios that go beyond grades.

8.4. Open-Source and Locally Adapted Tools:

To bridge the accessibility gap, there's a growing need for open-source educational tools that can be adapted to regional languages, curricula, and technological limitations. This includes lightweight mobile apps, offline-friendly simulations, and culturally relevant content. Empowering local educators to customize tools could significantly increase adoption in resource-constrained settings.

8.5. Collaborative Virtual Learning Environments:

The future also holds the potential for highly social, multi-user virtual classrooms where students from different parts of the world can work together in real time. Group simulations, global chemistry challenges, and peer-led experiments can help foster a sense of community and cross-cultural collaboration, all while deepening scientific understanding.

Fig. 1

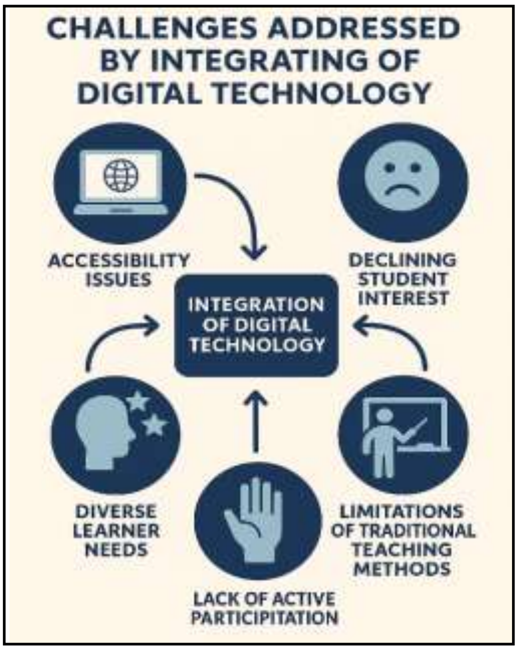

Fig. 2

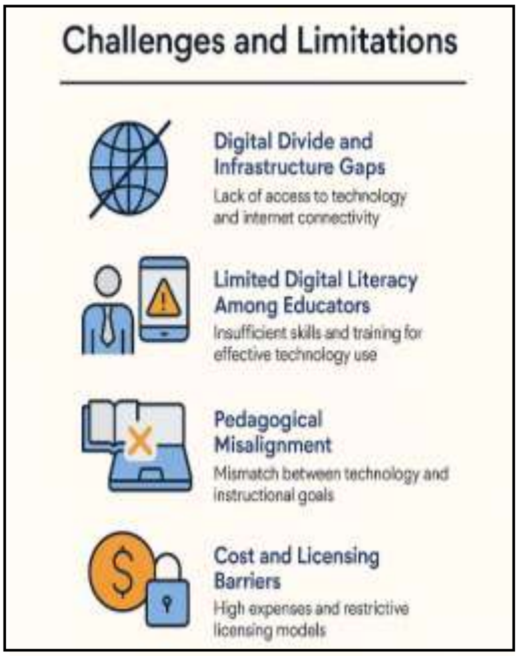

Fig. 3

Fig. 4

Fig. 1. Teaching Efficacy and Learning Advancement.

Fig. 2. Overcoming Instructional Challenges via Technological Innovation
Fig. 3. Barriers and Constraints
Fig. 4. Prospects and Emerging Pathways

9. CONCLUSION :

The evolution of chemistry education is increasingly shaped by technological innovation. From virtual laboratories and simulation software to immersive AR/VR platforms and gamified learning environments, these tools are redefining how students engage with complex scientific concepts. The evidence reviewed in this paper highlights the clear pedagogical benefits of such tools- enhanced conceptual understanding, increased motivation, personalized learning pathways, and improved student-teacher interaction.

However, the full potential of these innovations can only be realized by addressing persistent challenges, such as infrastructural inequalities, gaps in teacher preparedness, and the lack of integration between pedagogy and digital tools. Educational institutions must approach technology not as a replacement for traditional methods, but as a complementary force that enhances and deepens the learning experience.

Looking ahead, developments in AI, mixed reality, open-source tools, and blockchain-backed credentials offer exciting possibilities for building a more inclusive, flexible, and future-ready chemistry classroom. The key lies in creating scalable, equitable solutions and ensuring that both teachers and students are empowered to navigate this evolving digital landscape with confidence and competence.

In essence, technology is not the answer to all educational challenges, but when thoughtfully applied, it can be a powerful catalyst for meaningful and lasting transformation in chemistry education.

REFERENCES :

[1] Alhashem, A. & H. Alfailakawi (2023). Technology-enhanced learning through virtual laboratories in chemistry education: Effects on pre-service teachers' engagement and understanding. Contemporary Educational Technology, 2023, 15(4), ep474 https://www.researchgate.net/publication/374366931_Technology-enhanced_learning_through_virtual_laboratories_in_chemistry_education

[2] Aydın-Günbatar, S. & M. Özel, (2021). Virtual chemical laboratories: A systematic literature review. Computers & Education Open, 2, 100038. https://www.sciencedirect.com/science/article/pii/S2666557321000094?via%3Dihub

[3] Petare Purushottam Arvind et.al. (2023). Exploring The Impact of Virtual Learning Environments on Student Engagement and Academic Achievement. DOI:10.13140/RG.2.2.23223.91040. Journal of Survey in Fisheries Sciences 10(1S) 5912-5923

[4] Khalaf, K. & S. Al-Olimat, (2022). Interactive laboratories for science education: A systematic review. Education Sciences, 12(6), 421. https://www.mdpi.com/2414-4088/6/10/85

[5] Engdahl, A. & N. Fahlgren (2023). Students' experiences from virtual reality-based chemistry lab exercises. Education for Chemical Engineers, 44, 44–53. https://www.researchgate.net/publication/372004928_Student_experiences_from_virtual_reality-based_chemistry_laboratory_exercises

[6] Sayed Abdul Aziz Ahmady Falah et. Al. (2024). Effects of Virtual and Augmented Reality in Chemistry Education: Systematic Literature Review. International Journal of Arts and Social Science www.ijassjournal.com. ISSN: 2581-7922, Volume 7 Issue 1, January 2024

[7] Rahman Hameedur et. Al. (2024). Game-based learning in metaverse: Virtual chemistry classroom for chemical bonding for remote education. Education and Information Technologies 29:19595–19619. https://doi.org/10.1007/s10639-024-12575-5 https://link.springer.com/article/10.1007/s10639-024-12575-5

[8] Bektas, O. & A. Aslan (2022). Virtual Laboratories in Tertiary Education: Case Study Analysis. Educ. Sci. 2022, 12, 554. https://doi.org/10.3390/educsci12080554 https://www.academia.edu/108625440/Virtual_Laboratories_in_Tertiary_Education_Case_Study_Analysis_by_Learning_Theories

[9] Shatayeva Aigerim et. Al. (2022). Technologies used in teaching children with special educational needs by future chemistry teacher. World Journal on educational technology, current issues 14(4): 1152- 1162. DOI:10.18844/wjet. v14i4.7672

[10] Wohlfart Olivia et. Al. (2023). Digital tools in secondary chemistry education – added value or modern gimmicks? Front. Educ., 29 June 2023. Sec. Digital Education. Volume 8 - 2023 | https://doi.org/10.3389/feduc.2023.1197296

[11] Belford. R. E. (2019). Introduction: Technology integration in chemistry Education and Research. ACS Symposium Series; American Chemical Society: Washington, DC, 2019. DOI: 10.1021/bk-2019-1318.ch001

[12] Levy Julia et. Al. (2024). MoleculAR: An Augmented Reality application for understanding 3D geometry. Journal of chemical education Volume 101/Issue 6

[13] Olim Sandra C amara et. Al. (2024). Augmented reality interactive experiences for multi-level chemistry understanding. International journal of child-computer interaction December 2024, 100681

[14] Ananikov Valentine P. (2024). Top 20 influential AI-based technologies in chemistry. Artificial Intelligence chemistry. https://www.sciencedirect.com/science/article/pii/S2949747724000332

[15] Elias Michal et. Al. (2022). Development of digital and science, technology, engineering, and mathematics skills in chemistry teacher training. Frontiers in education. https://doi.org/10.3389/feduc.2022.932609

[16] Abdinejad Maryam et. Al. (2020). Student Perceptions Using Augmented Reality and 3D Visualization Technologies in Chemistry Education. Journal of Science Education and Technology. https://doi.org/10.1007/s10956-020-09880-2

[17] Nazar Muhammad et. Al. (2024). Development of augmented reality as a learning tool to improve student ability in comprehending chemical properties of the elements. Chemistry Teacher International 2024; 6(3): 241-257. https://www.degruyterbrill.com/document/doi/10.1515/cti-2023-0070/html

[18] Fombona Javier et. Al. (2022). Augmented Reality, a Review of a Way to Represent and Manipulate 3D Chemical Structures. J.Chem. Inf.Model.2022,62,1863−1872

[19] Chiu Wang-Kin. (2021). Pedagogy of Emerging Technologies in Chemical Education during the Era of Digitalization and Artificial Intelligence: A Systematic Review. Educ. Sci. 2021, 11, 709. https://doi.org/10.3390/ educsci11110709

[20] Ou Kuo-Liang et. Al. (2022). Application of Augmented Reality for Learning Material Structures and Chemical Equilibrium in High School Chemistry. Systems 2022, 10, 141. https://doi.org/ 10.3390/systems10050141

****