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THE INTEGRATION OF GREEN CHEMISTRY AND ETHNOCHEMISTRY IN THE DESIGN OF VIRTUAL REALITY LEARNING MEDIA ON CRYSTAL STRUCTURE MATERIAL USING A CONTEXTUAL APPROACH

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Abstract

This study aims to identify the needs and design a Virtual Reality (VR)-based learning medium for the topic of crystal structure using a contextual approach through the integration of green chemistry and ethnochemistry. The study is motivated by the challenges of teaching crystal structures, which are abstract in nature and require deep spatial visualization, as well as the importance of incorporating sustainability values and local culture into chemistry education. The method used is Research and Development (R&D) based on the Borg & Gall model, with the initial stage involving data collection through questionnaires administered to 80 chemistry students and interviews with three chemistry education experts. The analysis results show that the majority of students experience difficulties in understanding the spatial concepts of crystal structures and express the need for more interactive learning media. Respondents suggested ideal VR features such as 3D models, reaction simulations, audio-visual elements, and discussion forums. Additionally, the integration of green chemistry principles and ethnochemical practices, such as blacksmithing in Kotagede, was considered to enrich the learning experience. These findings affirm that VR media integrated with sustainability values and local wisdom can serve as an innovative solution to enhance engagement, conceptual understanding, and environmental awareness in chemistry learning.

Keywords: ethnochemistry, green chemistry, learning media, crystal structure, virtual reality

1 INTRODUCTION

The development of technology is required to move toward the collaboration of cyber technology and automation in the current era of the Industrial Revolution 4.0. Herman et al. (as cited in Purba et al., 2021) argue that in the Industrial Revolution 4.0, all existing elements collaborate and integrate in real-time by utilizing technology. The advancement of digital technology in the field of education has also undergone significant transformation in recent decades. Along with these changes, the demand for teachers' and lecturers' competencies in teaching has also increased. Teachers and lecturers in the digital era are also expected to be able to utilize technology in the learning process. The use of technology in learning can help

e-ISSN 2963-2870
Vol 6 2025

students grasp the material more deeply (Jufrida et al., 2020). This is supported by Baitiyah et al., (2024), who state that the use of technology in education plays an important role in improving the quality of the teaching and learning process. The wise use of technology can promote learning activities that are more inclusive, responsive, and relevant, providing long-term benefits for student development. Learning that involves the use of technology is expected to be an innovation, including in chemistry education (Tsuroyya et al., 2022).

One of the uses of technology in education is the innovation of learning media based on Virtual Reality, or more commonly known as VR. The use of Virtual Reality (VR) technology in higher education has shown a significant increase in student engagement. Studies have shown that VR can create an immersive learning environment, allowing students to experience a deeper and more realistic learning experience (Radianti et al., 2020). VR also provides students with the opportunity to interact directly with learning materials, which can enhance their interest and motivation to learn (Makransky & Lilleholt, 2018).

In her research, Sulistyowati explained that VR is still not commonly used in the field of education in Indonesia, as VR technology is predominantly used on smartphones for gaming applications. This technology is introduced as an innovative tool to solve complex problems, providing unique, realistic, and practical solutions for students (Sumardani et al., 2019). Similarly, Tsaaqib et al. (2022) showed that there is a difference in learning motivation between the experimental class using virtual reality learning media and the control class that did not use such media. This was evidenced by the fact that the average learning motivation score of the experimental class was higher than that of the control class. In addition, there was a difference in learning outcomes between the experimental class using VR learning media and the control class without the use of such media.

Based on the literature review, research on the use of VR in chemistry learning has been conducted, but its application to specific topics, such as crystal structures, remains very limited and scarce. VR, as a learning medium, presents a 3D reality of crystal structures that can be rotated 360°, thereby representing both the microscopic and symbolic levels, and has the potential to enhance visuospatial ability (Garg et al., 2024; Laohapornchaiphan & Chenprakhon, 2024). This study also supports the use of VR in improving students' spatial abilities in chemistry topics.

Student engagement and participation are key indicators of educational success. Students who are actively involved in the learning process tend to have a better understanding of the

e-ISSN 2963-2870
Vol 6 2025

material, achieve higher academic performance, and report greater satisfaction with their learning experience (Fredricks et al., 2004). By creating a more engaging and interactive learning environment, the use of VR can help enhance student engagement, which in turn can contribute to better learning outcomes (Merchant et al., 2014). The use of VR in higher education offers various positive implications for improving student learning outcomes. First, VR provides opportunities for students to engage in more interactive and contextualized learning, allowing for deeper understanding of the subject matter. For instance, medical students can practice surgical procedures in a safe virtual environment before performing them on real patients, thereby increasing their preparedness and confidence (Menhard, 2024). Second, VR can overcome geographical and resource limitations, enabling students from different locations to access equal and high-quality learning experiences (Freina & Ott, 2015). Third, integrating VR into the curriculum allows for more dynamic and real-time assessment, enabling instructors to provide immediate feedback during learning sessions, which accelerates the improvement process and mastery of the material by students (Makransky et al., 2017).

Understanding crystal structures as metallic solids is a fundamental aspect of material characterization, especially for materials with an ordered atomic structure. In learning about crystal structures, students often face difficulties in visualizing the shape, number of atoms, and their arrangement within a crystal. This hampers their comprehension of the subject matter and makes it challenging to determine the ionic percentage of a molecule or compound. Solid materials can be classified based on their level of atomic order, as atoms or ions are arranged in a regular pattern relative to one another (referred to as crystals), such as in diamond. A crystalline material is a condition in which atoms are positioned in a repeating arrangement over large atomic distances, resulting in a long-range order. When a crystal grows in a constant environment, its shape develops like identical blocks added continuously. Several types of crystal structures commonly studied include simple cubic, body-centered cubic, and face-centered cubic (Mudzakir et al., 2008).

The conventional approach that relies solely on static illustrations and theory is sometimes less effective in providing an intuitive understanding. Not all concepts can be explained merely through theory or by imagining the types of structures formed. Crystal structures fall under the submicroscopic level of representation because the submicroscopic refers to something real yet too small to be observed, thus requiring imagination to comprehend

(Gilbert & Treagust, 2009). With technological advancements, digital media can be developed to help students learn about crystal structures more independently and effectively (Sulaeman et al., 2024). In addition to the challenges of using digital media and learning materials that are abstract and submicroscopic in nature, a deeper understanding of crystal structures is also relevant to environmental issues, particularly in applications related to metal and mineral-based industries. When discussing crystal structures in metallic solids, this relates to metallic bonding, and it is known that one of the regions still processing metal traditionally is Yogyakarta. Although the blacksmithing industry in Kotagede holds high cultural and economic value, this activity also poses the risk of pollution due to industrial waste if proper waste management principles are not applied. In this context, the implementation of Green Chemistry can be a solution by adopting more environmentally friendly alternatives, efficiently managing waste, and utilizing technologies that reduce harmful emissions. Thus, integrating crystallography concepts within a sustainability-based approach not only contributes to education but also to reducing environmental impact and preserving ecosystems.

This innovative approach not only enhances interactivity in understanding the concept of crystal structure through VR, but also integrates the principles of Green Chemistry and Ethnochemistry, which have rarely been applied in the study of crystal structures. Through the application of Green Chemistry, this research contributes to more sustainable chemistry education by reducing the reliance on hazardous chemicals in laboratory practices. In addition, the integration of Ethnochemistry provides cultural context in learning crystal structure material, allowing scientific concepts to be connected with local wisdom and traditional practices based on natural materials. Thus, this study not only offers technological innovation in chemistry education, but also presents a holistic approach that connects science, sustainability, and culture in a unified VR-based learning experience.

Ethnochemistry can be defined as the study of traditional chemical knowledge possessed by specific ethnic or cultural groups and how this knowledge is applied in daily practices. Ethnochemistry is important because it helps document and preserve traditional chemical knowledge that may be lost over time. In addition, ethnochemistry can be used as an educational tool to raise awareness and understanding of the importance of local culture (Munandar et al., 2024). Ethnochemistry is the study of chemical practices by particular cultural groups that are used in activities aligned with the community's ideology. Integrating

e-ISSN 2963-2870
Vol 6 2025

ethnochemistry into culturally responsive chemistry teaching offers a way to connect chemical concepts with the cultural backgrounds of students.

One way to anticipate the loss of national culture and traditions as an impact of globalization is by implementing ethnopedagogical learning in the chemistry classroom. This is also supported by Rahmawati et al. (2020), who stated that the chemistry learning process must be integrated with culture and tradition, as the meaning of a nation's identity is built through culture as a fundamental element. The development of this learning approach was also carried out by Gunstone (2014), who discussed concepts and principles in science material and then related them to everyday life phenomena. Michell (as cited in Sarwanto et al., 2010) found that a science learning curriculum developed within a local cultural context enhances the sense of nationalism. The advantage of this approach is that it can serve as a means for students to create meaningful learning experiences. This is because students can connect chemistry concepts with local culture and traditions, which can increase their interest in the subject. Moreover, students can better understand chemistry concepts when they are linked to real-life situations (Taber, 2002). The cultural background of students has a greater effect on the educational process if it is incorporated into classroom learning (Sumarni, 2016). This is because students have spent most of their time in environments shaped or influenced by community culture rather than by formal educational theories.

Green chemistry is a comprehensive approach that designs chemicals to be safe, both in terms of the products and the processes involved. Also known as sustainable chemistry, green chemistry is used to design chemical products and procedures with the goal of reducing the formation of hazardous substances. According to Al-Idrus et al. (2020), green chemistry education provides an opportunity to integrate concepts and apply the 12 principles of green chemistry into the curriculum and teaching, with the aim of increasing students' environmental awareness. The central role of chemistry education in this context is to support sustainable development. Although green chemistry is closely related to environmental issues, green chemistry-based learning also impacts students' learning outcomes and process skills, while fostering a perspective of chemistry as safe, engaging, enjoyable, and offering many other benefits (Hadi, 2019).

The integration of green chemistry and the SDGs into chemistry education not only provides students with the opportunity to connect theory with practice, but also broadens their learning experience in a holistic and interdisciplinary manner, allowing them to see the connections

e-ISSN 2963-2870
Vol 6 2025

between green chemistry concepts and the SDGs (Sánchez Morales et al., 2024). Literature reviews show that various chemistry concepts can be linked to the principles of green chemistry and the SDGs, and discuss effective teaching methods to achieve these goals. Moreover, the potential challenges in implementing green chemistry and the SDGs in educational contexts can help teachers, lecturers, and educators design better and more effective strategies in educating future generations.

This study aims to develop an interactive Virtual Reality (VR)-based learning medium to enhance the understanding of crystal structure concepts. The development is grounded in the integration of Green Chemistry and Ethnochemistry principles, which are expected to provide a contextual approach to chemistry learning. Specifically, the research seeks to answer how VR media can help improve the understanding of crystal structures, how the principles of Green Chemistry and Ethnochemistry can be applied in the development of this media, and what benefits a contextual VR-based approach offers in the chemistry learning process. Thus, this study focuses not only on technological innovation in education but also on the effectiveness of sustainability-based and local wisdom-based approaches in improving the quality of chemistry learning. It is expected that the study will contribute to innovations in chemistry education by developing more interactive and effective VR media for visualizing crystal structures. In addition, it aims to enhance students' learning experiences through deeper and more contextual exploration, connecting crystal structure material with the principles of Green Chemistry and Ethnochemistry.

2 METHODOLOGY

This study is development research. The research method used in the development of virtual reality-based mobile learning for crystal structure material is Research and Development (R&D), utilizing questionnaires and semi-structured interviews. According to Sugiyono (2017), research and development is a research method used to produce a product and test the effectiveness of that product. The mobile learning development follows the research and development stages proposed by Borg & Gall (2003), which consist of ten stages: (1) research and information gathering, (2) planning, (3) developing a preliminary product, (4) preliminary field testing, (5) revising the main product, (6) main field testing, (7) revising the product based on field test results, (8) operational field testing, (9) final product revision, and (10) dissemination. These ten stages are summarized into three main parts: design, development, and evaluation.

e-ISSN 2963-2870
Vol 6 2025

This study focuses on the needs analysis stage, which represents the implementation of steps 1 and 2 in the Borg & Gall model—namely, research and data collection as well as planning. The main objective of the study is to identify user needs regarding the use of Virtual Reality (VR)-based learning media in understanding crystal structures through an ethnochemistry and green chemistry approach. The needs analysis process was conducted by distributing questionnaires to students and educators, as well as interviewing educational experts and chemistry specialists to gain insights into the challenges of teaching crystal structure. The results of this analysis will serve as the foundation for the development of the learning media in the subsequent research phase. Therefore, this study does not include the implementation or validation of the product, but is limited to identifying needs and developing an initial conceptual design. In addition, a literature review was conducted at this initial stage to identify theoretical concepts and determine appropriate steps in the product development process (Sukmadinata, 2006).

3 FINDINGS AND DISCUSSION

This section presents the results of data analysis and interpretation based on interviews with experts and student responses to the administered instruments. The aim is to identify the learning needs related to crystal structure and green chemistry materials, as well as the use of Virtual Reality (VR)-based learning media with an ethnopedagogical approach. The analysis covers pedagogical, cultural, and technological dimensions as the foundation for developing innovative and contextual learning media. The following discussion will address the needs analysis from the perspectives of both experts and students' experiences and perceptions.

3.1 Expert Needs Analysis

The needs analysis in this section was conducted by three experts with backgrounds in chemistry education and instructional technology. Data collection was carried out through semi-structured interviews, allowing the experts to provide in-depth opinions and reflections based on their experience and insights. Once the data were collected, the analysis was performed using thematic analysis. Thus, the analysis conducted by the experts served as the foundation for the development of the learning media and for formulating the key findings that will be discussed in the following section.

3.1.1 Learning Dynamics of Crystal Structure and Green Chemistry Material

The analysis results indicate that the learning process of crystal structure and green chemistry materials is complex and requires a more contextual approach. Respondents described how

e-ISSN 2963-2870
Vol 6 2025

these materials become more engaging and applicable when integrated with technology and approaches relevant to everyday life. This is particularly important, considering that learning about crystal structure and green chemistry demands high spatial visualization abilities and an understanding of sustainability principles, which are increasingly emphasized globally.

"Very interesting and applicable when connected to real-life situations, using technology integration, as well as contextual and interactive approaches" [Expert 1].

This statement emphasizes that chemistry learning must be linked to real-world practices, local cultural values, and technological advancements to become more meaningful. This aligns with the view of Merchant et al. (2014), who highlight the importance of media integration and contextual approaches in enhancing cognitive engagement. Respondents stressed the need to master cognitive skills such as analysis and spatial understanding, which are essential for visualizing often-abstract crystal structures. Affective aspects were also emphasized, such as environmental awareness, collaboration, and communication, which support collaborative and problem-based learning.

"Cognitive skills (spatial, analytical, basic math and chemistry), affective (environmental concern, collaboration, and communication), as well as psychomotor skills (experiments and 3D model-making)" [Expert 1].

These findings support the theory by Radianti et al. (2020), which demonstrates that interactive visual media such as VR can strengthen spatial skills and enhance students' understanding. This also underscores the importance of developing learning media that support cross-skill interaction, collaboration, and more concrete practical competencies. The learning dynamics of crystal structure and green chemistry require media innovation that not only conveys concepts but also connects them to real-life contexts and cultural values, while providing space for students' holistic development of interdisciplinary skills.

3.1.2 Limitations of Conventional Media and Visualization Challenges

One of the main challenges identified in the learning of crystal structure and green chemistry materials is the limitation of conventional media used in classrooms. Traditional media such as whiteboards, two-dimensional images, and static illustrations often fail to adequately visualize how atoms are arranged in three-dimensional space — which is the essence of crystal structure. This makes it difficult for students to grasp sub-microscopic and abstract concepts, such as crystal lattice arrangements and structural types (BCC, FCC, HCP), as well as the complex processes involved in green chemistry.

"Lack of visualization in crystal structure material and green chemistry processes" [Expert 3].

These media limitations become a major obstacle in understanding the inherently sub-microscopic and complex nature of crystal structures, which require deep spatial comprehension. As explained by Gilbert and Treagust (2009), crystal structures demand visual representations that help learners imagine how atoms are arranged and interact in three-dimensional space. Conventional media still fail to provide a complete and adequate learning experience. As a result, students' understanding of crystal structures often remains at a conceptual level, without fully grasping the sub-microscopic dimension through its spatial arrangement.

In this context, Virtual Reality (VR) technology emerges as a promising alternative. Makransky and Lilleholt (2018) demonstrate that VR can offer an immersive and realistic learning experience, enabling students to explore crystal structures in three-dimensional form and observe chemical processes in a more tangible way. Thus, the limitations of conventional media present an opportunity to develop VR-based digital learning media that can bridge the gap between abstract theory and deep visual-spatial understanding, while also enhancing students' active engagement in chemistry learning.

3.1.3 Enthusiasm Toward VR-Based Media Innovation

Enthusiasm for the innovation of Virtual Reality (VR)-based media in the learning of crystal structure and green chemistry is evident from the responses of the majority of participants. Experts expressed strong support for the integration of VR technology as a more interactive and engaging learning medium. VR has the potential to actively involve students and enhance their visual abilities.

"I fully support the use of Virtual Reality because it helps with visualization and student engagement" [Expert 2].

This statement indicates that VR is not merely seen as a new technology, but as a powerful tool to help visualize complex spatial concepts more effectively than conventional methods. Respondents acknowledged that chemistry materials, especially crystal structure, require strong spatial visualization skills for thorough comprehension. This aligns with Merchant et al. (2014), who demonstrated that VR usage can enhance learning motivation and student engagement by offering immersive and realistic learning experiences. The positive responses also reflect a growing openness among students and educators to adopt digital technology in

e-ISSN 2963-2870
Vol 6 2025

education, supporting the development of a learning ecosystem that is responsive, adaptive, and aligned with the demands of the modern era. Therefore, VR-based media innovation becomes a crucial key in addressing the increasingly complex and contextual dynamics of chemistry education.

3.1.4 Integration of Green Chemistry and Ethnochemistry Approaches

The integration of green chemistry and ethnochemistry approaches emerges as a significant innovation in the novelty of this research. Respondents viewed the collaboration between green chemistry principles and local cultural contexts as making chemistry content more relevant while enriching the learning experience in a more contextual and sustainable manner. Learning that connects local cultural practices with modern chemical concepts can help students understand the material more deeply and meaningfully.

"Linking crystal structure and green chemistry with the ethnochemistry of blacksmithing practices in Kotagede is an authentic, culturally-scientific approach that is highly relevant to local wisdom." (Expert 1)

This statement illustrates how learning that connects local traditions with modern chemical principles can help students gain a more profound understanding of the subject matter. The ethnochemistry approach, which bridges science and local traditions, can also foster cultural pride and support contextual learning principles (Munandar et al., 2024; Sánchez Morales et al., 2024). The principles of green chemistry, which emphasize sustainability, material efficiency, and environmental safety, were acknowledged by respondents as essential. They believed that green chemistry learning should not remain theoretical but must instill applicable values of sustainability that are relevant to current environmental challenges.

This aligns with the concept by Al-Idrus et al. (2020), which states that green chemistry education functions not only as a pedagogical approach but also as a means to build students' critical awareness of environmental and sustainability issues. Thus, the integration of green chemistry and ethnochemistry becomes a learning strategy that teaches cultural values, cross-disciplinary collaboration, and the importance of responsible chemical practices for environmental preservation.

3.1.5 The Need for Media Development and Ideal VR Features

The need for media development and the ideal features to be designed in Virtual Reality (VR)-based learning media is one of the key focuses of this needs analysis. During the identification process, respondents specifically mentioned a variety of features they expected

e-ISSN 2963-2870
Vol 6 2025

to be included in VR media to optimally support understanding of crystal structure and green chemistry materials. Respondents emphasized the importance of features such as interactive 3D models, solid crystal structure content, structure transformation simulations, and clear audiovisual elements to facilitate conceptual understanding.

"Interactive 3D models of various types of crystal structures, content in the form of in-text explanations, images, and videos related to solid-state crystal structures, simulations of crystal structure changes, visualization of green chemistry processes — such as energy-efficient or low-waste reactions — audio and text explanations for each part of the simulation, and quiz or direct evaluation features within VR." [Expert 1]

These features suggest that students not only require richer visual representations, but also dynamic and contextual learning experiences. This supports the importance of conducting a systematic needs analysis as the initial stage in learning media development, as proposed by Borg & Gall (2003). The demand for interactive 3D models and simulations highlights the urgency of media that can accommodate spatial skills and experimental practices, which are major challenges in chemistry education. Meanwhile, the desire for clear audiovisual features underscores the importance of multimodality in VR media to cater to different student learning styles. This also serves as evidence that VR media functions not only as a visualization aid but also as a tool that can respond to interdisciplinary and contextual learning needs. Therefore, the development of ideal VR media must consider relevant interactive and contextual features to bridge the gap between theoretical concepts and practical experience, while also enhancing student motivation and engagement in the learning process.

3.1.6 The Role of VR Media in Enhancing Student Engagement and Understanding of Learning Content

In general, the findings confirm that VR technology is not merely a digital innovation but also serves as a means of pedagogical transformation. The use of VR helps present more intuitive 3D representations, facilitates understanding of microscopic concepts, and creates more meaningful learning experiences (Garg et al., 2024). Moreover, the integration of ethnochemistry and green chemistry into the development of VR media supports a holistic learning approach that emphasizes a balance between science, culture, and sustainability. This aligns with the concept of Deep Learning, which emphasizes the importance of contextual, collaborative, and fully engaged learning experiences (Fullan et al., 2018). In this context, VR integration can support a holistic learning process by combining students' cognitive, affective, and psychomotor aspects. For example, the study by Merchant et al. (2014) confirmed that VR not only increases learning motivation but also promotes deeper cognitive engagement in understanding complex chemistry topics.

The Deep Learning concept, as proposed by the Ministry of Primary and Secondary Education (2025), highlights the importance of connecting learning to students' identity and the real world, while encouraging critical reflection to contextualize and apply knowledge meaningfully. This approach strongly aligns with the effort to integrate green chemistry and ethnochemistry principles into VR media — not only linking scientific content with local culture but also instilling awareness of sustainability and cross-disciplinary collaboration (Munandar et al., 2024; Sánchez Morales et al., 2024). Therefore, developing VR media based on these principles is expected not only to improve students' cognitive achievement but also to strengthen critical awareness, creativity, and local values — forming a foundation for relevant and transformative chemistry learning.

3.2 Student Needs Analysis

This study involved 80 chemistry students who participated in filling out the needs analysis instrument. All respondents came from the same geographic region, providing a relatively homogeneous perspective in terms of location. However, the data revealed variations in their learning experiences and readiness to adopt innovative learning media such as Virtual Reality (VR) and ethnopedagogical approaches. This forms an important basis for understanding students' needs, preferences, and potential acceptance of more interactive and contextual learning media (Makransky & Lilleholt, 2018).

The learning media commonly used by students for the topic of crystal structure include textbooks (35%), PowerPoint presentations (94%), and related instructional videos (15%). Although PowerPoint is the most widely used medium, a significant portion of students (40%) still reported difficulties in understanding the material. The challenges faced were diverse: 37% of students felt the material was too extensive, 82% struggled to visualize the spatial forms of crystal structures, and 18% found the learning media unengaging or insufficient in supporting comprehensive visual understanding. This indicates that traditional media have not been fully effective in addressing the challenges of spatial representation in chemistry learning (Gilbert & Treagust, 2009).

e-ISSN 2963-2870
Vol 6 2025

As an alternative, 81% of respondents suggested the use of alternative media as a learning resource, and around 69% proposed the creation of virtual representations of crystal structures. Meanwhile, 48% of respondents also agreed that practice exercises and instructional videos could be effective solutions to enhance understanding. The majority of students (88%) reported using the internet as their primary learning source. Their teaching experiences reflected creativity in utilizing available media, such as PowerPoint animations and YouTube videos.

"I try to understand basic concepts like atomic arrangement in crystal lattices, unit cells, and types of crystal structures (SC, BCC, FCC) using PowerPoint animations and YouTube videos, then relate them to students' daily lives." (Respondent 16)

This supports the findings of Merchant et al. (2014), who emphasized the importance of multimedia integration to facilitate cognitive engagement. The use of multimedia—such as videos, animations, and simulations—allows students to gain a more comprehensive learning experience, particularly when dealing with abstract concepts that are difficult to visualize in chemistry learning. This becomes especially relevant in the context of learning about crystal structures, where spatial representation and visualization of chemical processes pose significant challenges.

A total of 81% of students stated that they had a good understanding of green chemistry material. However, 25% of respondents admitted that they had not yet fully grasped the principles of green chemistry. This indicates that while conceptual understanding has begun to form, a more holistic comprehension is still needed—especially in terms of the material's relevance to everyday practice (Radianti et al., 2020). As many as 87% of respondents reported using digital learning media to study green chemistry, indicating a strong level of technological adaptation. The main challenges identified were the amount of material (68%) and the lack of alternative media (44%). As a solution, 75% of respondents recommended the use of alternative learning media.

Respondents' experiences in teaching green chemistry also reflected a strong integration with environmental contexts. One respondent shared that their teaching emphasized the 12 principles of green chemistry and the application of environmentally friendly chemistry, linking it to global issues and real-world examples such as the use of eco-friendly solvents. This approach shows that green chemistry is not merely theoretical, but also highly relevant to everyday life and the current challenges of environmental sustainability. These findings

e-ISSN 2963-2870
Vol 6 2025

support those of Al-Idrus et al. (2020), who affirmed that teaching green chemistry in connection with global issues and real-life practices can enhance students' learning motivation and awareness of the importance of sustainability.

Regarding the use of VR, all respondents (100%) were already familiar with the technology, although nearly 50% had never used it in a learning context. Interestingly, 94% of respondents agreed that VR should be used for learning crystal structure and green chemistry materials, and they also expressed interest in utilizing VR for educational purposes. Respondents' experiences highlighted the need for interactive features such as practice exercises, instructional videos, discussion forums, and digital notes. This indicates that students are not only seeking access to learning materials but also active engagement in the learning process (Croxton, 2014).

The majority of respondents (88%) had previously engaged in learning processes using an ethnopedagogical approach, although 40% of them were not yet familiar in detail with cultural products such as the blacksmithing center in Kotagede. However, nearly all respondents (94%) supported the integration of ethnopedagogy into VR for teaching crystal structure and green chemistry. This support reinforces the finding that the collaboration between ethnopedagogy and VR technology is relevant for delivering contextual and in-depth chemistry learning (Munandar et al., 2024). Additionally, all respondents stated that using VR would greatly assist them in understanding abstract and complex concepts. This supports the idea that VR not only facilitates visualization but also enhances both cognitive and affective engagement (Makransky & Lilleholt, 2018; Merchant et al., 2014). The finding that students are aware of the blacksmithing artisans in Kotagede also opens opportunities to connect crystal structure material with local cultural practices, such as metallurgy in metalworking. The integration of green chemistry and ethnopedagogy can enrich learning by embedding values of sustainability and cultural preservation (Sánchez Morales et al., 2024).

4 CONCLUSION

This study illustrates that the teaching of crystal structure and green chemistry materials faces challenges related to spatial visualization and the connection between theory and practice—challenges that have not been fully addressed through current media use. The limitations of conventional media present a major obstacle in understanding abstract and sub-microscopic concepts, thereby highlighting the need for more interactive and contextual learning media innovations. The analysis results show that both students and educators express strong enthusiasm for the use of Virtual Reality (VR), which can provide more intuitive 3D representations, facilitate immersive learning experiences, and enhance active student engagement. The features expected in VR media—such as interactive 3D models, reaction simulations, rich audiovisual content, and discussion forums—highlight the importance of media that not only supports cognitive understanding but also fosters collaboration and the development of interdisciplinary skills within a Deep Learning framework. This study also finds that the integration of green chemistry principles and ethnochemistry represents a key innovation in promoting more contextual, relevant, and sustainable learning. The ethnochemistry approach, which connects chemical concepts with local cultural practices such as the blacksmithing tradition in Kotagede, has proven effective in enriching students' learning experiences and increasing the relevance of the material to their everyday lives. The principles of green chemistry, emphasizing sustainability and environmental safety, are also recognized as essential for building students' critical awareness of global issues. Thus, the integration of VR, green chemistry, and ethnochemistry emerges as a strategic response to the research problems and provides a strong foundation for developing more responsive, adaptive, and transformative learning media for teaching crystal structure.

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