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Immersive Chemistry Learning with Augmented Reality: Exploring Students' Needs on Visualizing Chemical Bonding

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ABSTRACT

The digital transformation of education has opened broad opportunities for innovation, yet the use of advanced technologies such as Augmented Reality (AR) in chemistry learning remains limited, particularly in Indonesia. The present research examines high school students' needs for AR-based instructional media on the abstract topic of chemical bonding. A descriptive quantitative approach was employed within the Analysis phase of the ADDIE instructional design model. Data were collected using a validated questionnaire administered to 51 eleventh-grade students from a senior high school in Surakarta, Indonesia. The results show that more than 84% of students experience difficulties in learning chemistry, with chemical bonding identified as the most challenging topic (88.2%), mainly due to limited visualization and the abstract nature of the content. Students also perceived the instructional media currently used in class as insufficiently engaging and not yet effective in helping them understand chemical bonding. Although 90.2% of students had never used AR in chemistry lessons, nearly 59% expressed strong interest in its implementation. This study offers an empirical mapping of students' cognitive, media-related, and technological needs as a foundation for designing AR-based chemistry learning on chemical bonding. As far as we are aware, it is one of the first studies in the Indonesian context to conduct a structured needs analysis for AR integration specifically on chemical bonding within the ADDIE framework. At a practical level, the findings provide guidance for instructional designers and chemistry teachers regarding the urgency of developing immersive AR tools that bridge abstract chemical representations with spatial visualization while also enhancing student engagement in the digital era.

Keywords: *Augmented Reality, Chemical Bonding, Interactive Media, Chemistry Education, Student Needs*

INTRODUCTION

The rapid advancement of digital technology has brought substantial changes to teaching and learning practices worldwide. In several Asian countries such as South Korea, Japan, and Singapore, schools have widely adopted digital devices and interactive applications to support classroom instruction (Chen, 2024; G. Fang et al., 2024; Yuen & Hew, 2018). These innovations have been associated with increased student engagement and improved learning outcomes across disciplines (Carlile & George, 2025; Li et al., 2025; Zhong et al., 2022; Zolfaghari et al., 2025). Within this broader transformation, the selection and design of appropriate instructional media play a central role in shaping learning environments that are not only effective, but also engaging and meaningful (Nurdyansyah, 2019).

In the Indonesian context, however, the integration of innovative media in science classrooms remains limited. Observations in a senior high school in Semarang show that 98.3% of students frequently use PowerPoint as the main medium in chemistry lessons, 86.2% rely on textbooks, and only 6.8% access alternative resources such as websites, articles, or journals (Setiawan & Harahap, 2024). This strong dependence on conventional media presents challenges for chemistry teaching, which often involves concepts that cannot be easily represented through static text and images (Paristiowati et al., 2024; Widarti et al., 2024). As a result, there is a mismatch between the complexity of the content and the media used to support students' understanding.

Chemistry is well known as a subject rich in abstract and multi-level representations, linking macroscopic phenomena, submicroscopic particles, and symbolic notation. One of the topics that exemplifies this complexity is chemical bonding. Students are expected to understand how atoms interact, why bonds form, and how different types of bonds (ionic, covalent, and metallic) relate to molecular structure and properties. Numerous studies report that many students struggle with this topic, finding it difficult to visualize bonding processes and to connect symbolic formulas with underlying particulate-level interactions (Al-Atawna & Langbeheim, 2025; Cotiangco et al., 2024; Danckwardt-Lillieström et al., 2020; Nurillah et al., 2023). These difficulties are often exacerbated in classrooms where teaching relies heavily on teacher explanations and static media, with limited use of tools that support spatial and dynamic visualization (Habiburrochman & Purwanto, 2025; Lin & Wu, 2021; Martín-Sómer et al., 2024).

To address such challenges, many researchers have recommended the use of interactive visual media, including simulations and animations, to help students reason about particles, electron distribution, and molecular structures (Avargil & Piorko, 2022; Kuit & Osman, 2021; Laricheva & Ilikchyan, 2023; Santyadiputra et al., 2024). One technology that has attracted growing attention is Augmented Reality (AR). AR enables students to interact with three-dimensional molecular models in real time, offering intuitive visualizations of atomic interactions and chemical structures that cannot be easily conveyed through traditional media (Sukmawati, Suparmi, et al., 2024; Zhang et al., 2022). Previous studies have shown that AR can enhance motivation, support conceptual understanding, and increase engagement in science learning (Cai et al., 2023; Midak et al., 2021; Sari & Dwiningsih, 2025; Solikhin et al., 2022; Whatoni & Sutrisno, 2022).

Although the potential of AR in chemistry education is promising, existing research has predominantly focused on evaluating the effectiveness of specific AR products or interventions after they are developed, for example by comparing learning outcomes between experimental and control classes or by measuring changes in motivation. Far fewer studies have conducted a systematic needs analysis before development, particularly with regard to students' perceptions of their own learning difficulties, their experiences with existing media, and their readiness to adopt AR in specific chemistry topics. In the Indonesian context, empirical evidence on students' needs for AR-based media in chemical bonding remains scarce, and studies that situate this needs analysis within a structured instructional design framework such as ADDIE are still limited. This gap suggests that many AR applications may be designed without a detailed understanding of the characteristics and needs of the intended learners.

The present study seeks to address this gap by focusing on the Analysis phase of the ADDIE instructional design model in the context of chemical bonding instruction. Rather than evaluating an existing AR product, this research examines high school students' learning difficulties, perceptions of instructional media, and attitudes towards technology as an empirical basis for designing AR-based learning tools. Specifically, the study aims to: (1) examine students' perceptions of their learning difficulties in chemistry, particularly with respect to chemical bonding; (2) analyze how students view the instructional media currently used by teachers in chemistry classes; (3) assess students' self-reported understanding of chemical bonding concepts; (4) investigate students' perspectives on the use of technology and innovative media in chemistry learning; and (5) determine students' perceived need for the development of AR-based instructional media to support their understanding of chemical bonding.

By systematically mapping these aspects, the present study contributes to the field of AR-based chemistry education by providing a grounded description of learners' needs that can guide subsequent design, development, and implementation decisions. The findings are expected to inform instructional designers and chemistry teachers who intend to integrate AR into lessons on chemical bonding in ways that align with students' cognitive profiles, media experiences, and technological readiness.

METHODS

Research Design

The present research represents the initial phase of an educational research and development (R&D) project. The research adopted a quantitative descriptive approach within the framework of the ADDIE instructional design model (Analysis, Design, Development, Implementation, and Evaluation) (Molenda, 2003). In the broader project, the ADDIE model is used to guide the development of AR-based instructional media for teaching chemical bonding. The present article reports exclusively on the **Analysis** phase, which aims to identify students' learning difficulties, experiences with instructional media, and technology-related needs as the empirical basis for designing the AR prototype (M. J. Fang et al., 2011; Molenda, 2003).

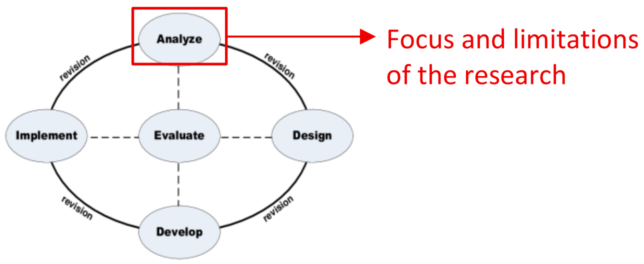

Figure 1. Steps of development using the ADDIE model

The research is part of the preliminary phase within a broader research and development framework, generally consisting of three stages: Phase I (Preliminary Study), Phase II (Development), and Phase III (Product Testing) (M. J. Fang et al., 2011). However, the current article focuses solely on the preliminary stage, particularly the needs analysis of students.

Participants

The participants were 51 Grade XI students from a public senior high school in Surakarta, Indonesia, who were enrolled in chemistry during the semester of data collection. A purposive sampling technique was applied to ensure that the respondents had direct learning experience with the topic of chemical bonding. This non-probability sampling strategy allowed the study to target students who were pedagogically relevant to the planned media development. However, because the sample was drawn from a single school and not randomly selected, the findings are not intended to be statistically generalized to all Indonesian high-school students; rather, they provide a focused picture of needs in a comparable instructional context.

Data Collection

Data were collected using a student needs-assessment questionnaire administered during regular chemistry lessons. The questionnaire was distributed in paper-based or digital form under the supervision of the teacher and researcher. Students were informed that their responses would be used for research purposes only and would not affect their grades. Sufficient time was provided for them to complete the instrument independently. All completed questionnaires were checked for completeness and then coded for analysis.

Instrument

A summary of the indicators and representative items is presented in **Table 1**.

Table 1. Student Needs Analysis Instrument

No.	Indicator	Question / Statement
1	Perception of Chemistry Learning Difficulties	"I find it difficult to learn chemistry compared with other school subjects." "Chemical bonding is one of the most difficult topics for me to understand."
2	Instructional Media Used	"The media used by my chemistry teacher (e.g., PowerPoint, textbooks) attract my attention and help me stay focused." "The media used by my teacher help me understand chemical bonding."
3	Learning Outcomes on Chemical Bonding	"I understand why ionic, covalent, and metallic bonds can form in compounds." "The most difficult part of the chemical bonding topic for me is … (e.g., explaining why bonds form, identifying bond types, drawing Lewis structures)."
4	Use of Technology in Learning	"My chemistry teacher often uses technology (videos, virtual simulations, applications, AR, etc.) in teaching." "I use my smartphone to access chemistry learning materials (videos, online modules, learning apps, etc.)."
5	Need for AR-Based Instructional Media	"I have used Augmented Reality (AR) media in chemistry learning." "I am interested in using AR media to help me understand chemical bonding."

These indicators were adopted and adapted from prior validated instruments (Setiawan & Harahap, 2024) and were reviewed by subject-matter experts in instructional media and technology (Hanif et al., 2018; Patel & Patel, 2019) for content validity and linguistic clarity. The student questionnaire was developed to capture five main indicators: (1) perception of chemistry learning difficulties; (2) instructional media used by teachers; (3) learning outcomes related to chemical bonding; (4) use of technology in learning; and (5) need for AR-based instructional media. The final instrument consisted of 13 items in dichotomous (yes/no), multiple-choice, and 3-4 point rating formats. Example items include: "I find it difficult to learn chemistry compared with other school subjects," "I understand why ionic, covalent, and metallic bonds can form," and "I am interested in using Augmented Reality (AR) media to help me understand chemical bonding." A summary of the indicators and representative items is presented in Table 1.

The initial pool of items was adapted from a previously validated questionnaire on media use in chemistry learning (Setiawan & Harahap, 2024) and then modified to focus specifically on the abstract topic of chemical bonding and the potential integration of AR. Draft items were reviewed by two university lecturers with expertise in chemistry education and instructional media. Both experts rated each item on a 4-point scale for relevance to the intended indicator (1 = not relevant to 4 = highly relevant) and clarity of wording for high-school students. All 13 items received ratings of 3 or 4 from both experts. On this basis, the item-level content validity index (I-CVI) was 1.00 for every item, and the average scale-level CVI (S-CVI/Ave) was also 1.00, indicating excellent content validity. Minor wording revisions were made according to the experts' comments before the questionnaire was administered to students.

An exploratory internal consistency check was carried out using coded responses from 31 students as a subset of the sample. Cronbach's alpha calculated across all 13 items yielded a negative coefficient (α = −0.36), which reflects negative average covariance among items. This pattern is consistent with the multidimensional design of the instrument: the items were not constructed to measure a single latent trait, but to map heterogeneous aspects such as perceived difficulty, media exposure, technology use, and interest in AR. Consequently, the questionnaire was not treated as a unidimensional psychometric scale, no composite score was computed, and Cronbach's alpha is not interpreted as a central quality indicator. Instead, the instrument functions as a descriptive needs-analysis tool at the item and indicator level.

Data Analysis

Student responses were coded numerically according to the response categories for each item (e.g., yes = 1, no = 0; 1-4 for frequency or level of understanding). Descriptive statistics in the form of frequency distributions and percentages were computed for each item and indicator. These results are reported as summary frequency tables and bar charts to clarify patterns in students' needs across the five dimensions and to identify priority areas for the subsequent development of AR-based instructional media.

RESULTS

The findings of this research represent the Analysis phase of the ADDIE model. The results describe students perceived difficulties in chemistry, their experiences with instructional media, their understanding of chemical bonding, and their use of and interest in technology and AR-based learning.

Difficulties in Chemistry and Chemical Bonding

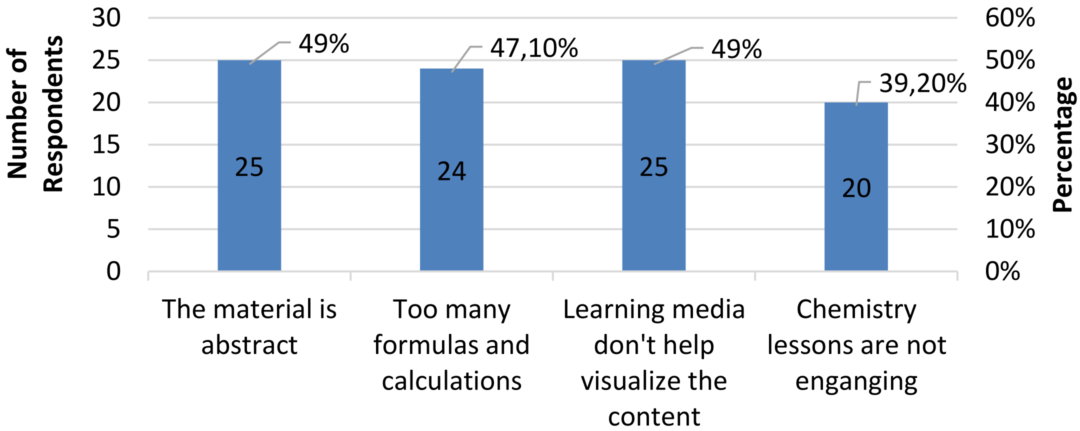

Figure 2. Overview of General Problems in Chemistry Learning

Figure 2 shows that 84.3% of students reported frequently experiencing difficulties in learning chemistry. The two most frequently mentioned reasons were the abstract nature of the content (49%) and the complexity of formulas and calculations (47.1%). In addition, 49% of respondents stated that the media used in class did not help them visualise chemical phenomena, and 39.2% felt that lessons were monotonous and did not sustain their attention.

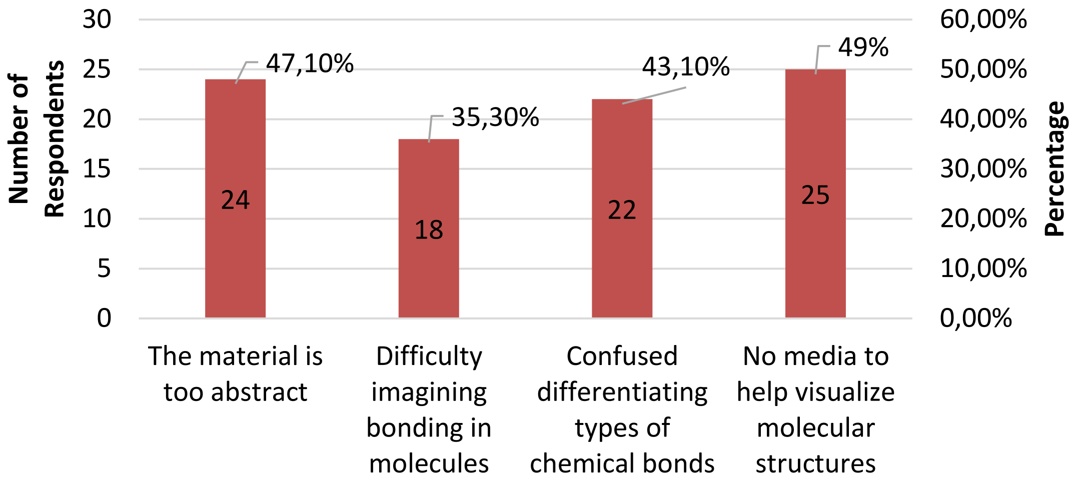

Figure 3. Specific Difficulties in Understanding Chemical Bonding

Chemical bonding emerged as one of the most problematic topics. As shown in **Figure 3**, 88.2% of students considered chemical bonding to be difficult. Students most often attributed this to the absence of media that can visualise molecules (49%), difficulty imagining molecular shapes and bonding processes (35.3%), and confusion in distinguishing between ionic, covalent, and metallic bonds (43.1%).

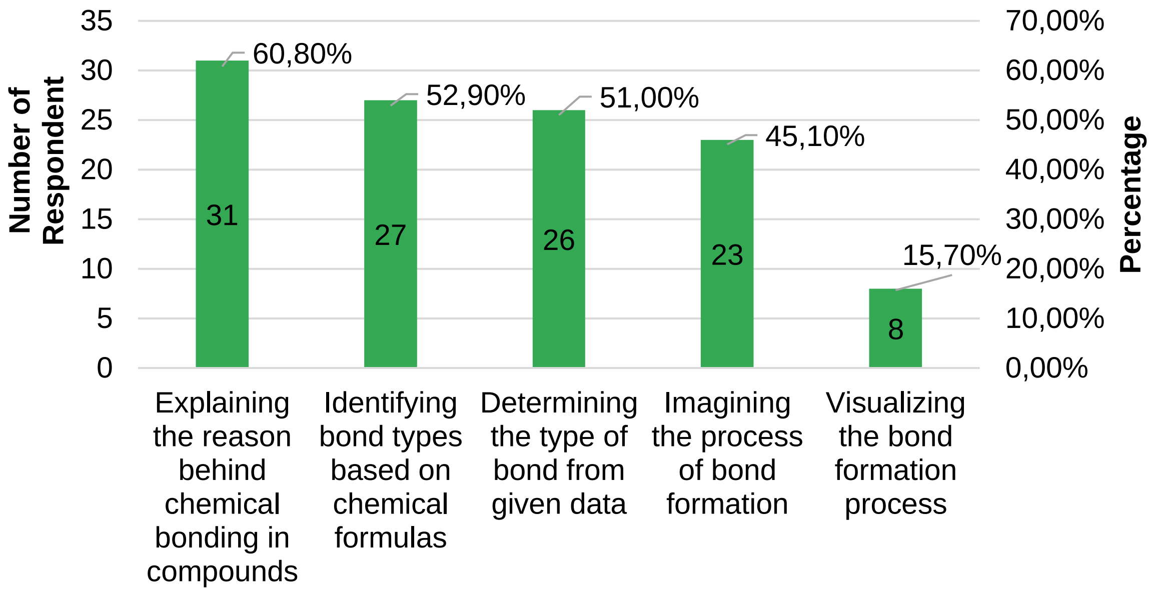

Figure 4. Most Difficult Aspects of Chemical Bonding

A more detailed picture is presented in **Figure 4**. A total of 60.8% of students reported difficulty explaining why bonds occur in compounds, 52.9% had difficulty analysing different types of chemical bonds, 51% struggled to identify bond types from chemical formulas, and 45.1% found drawing Lewis structures difficult. Only 15.7% selected "imagining the bonding process" as their main difficulty.

Instructional Media and Student Engagement

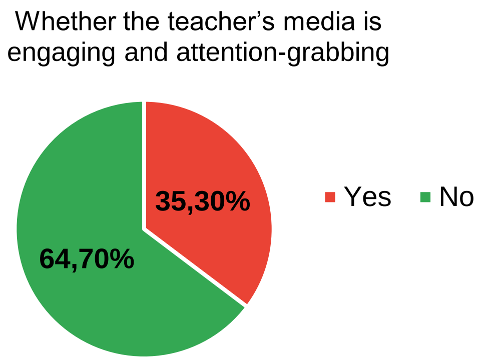

Figure 5. Instructional Media and Student Engagement

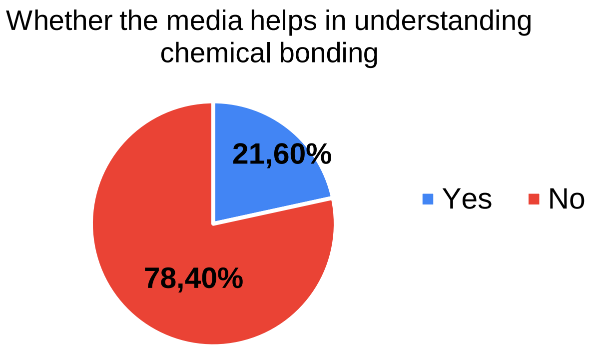

Figure 6. Learning Media and Understanding of Difficult Topics

Students' responses indicate that the instructional media currently used in chemistry lessons are limited in both variety and impact. As shown in **Figure 5**, 64.7% of students felt that the media used by their teachers did not attract their attention or help them remain focused during lessons. Consistently, **Figure 6** shows that 78.4% of respondents believed that the media used had not helped them understand difficult topics, particularly chemical bonding.

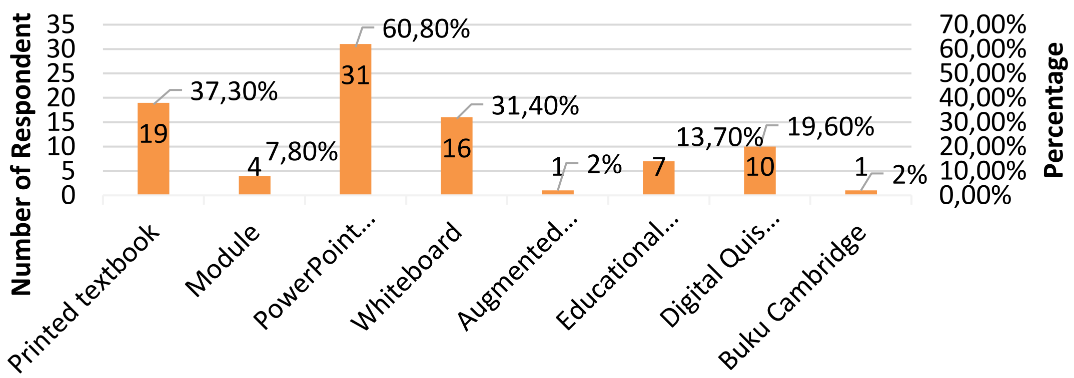

Figure 7. Most Commonly Used Instructional Media

Figure 7 summarises the types of media most commonly used. PowerPoint slides dominated (60.8%), followed by textbooks (37.3%) and whiteboards (31.4%). Only 3.9% of students reported ever using AR-based media, and 19.6% mentioned the use of digital quiz platforms such as Kahoot or Quizizz. These results suggest that chemistry teaching in the observed context is still dominated by conventional, teacher-centred media.

Self-Reported Understanding of Chemical Bonding

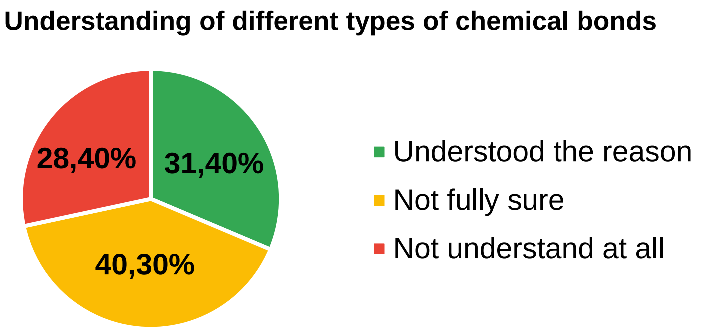

Figure 8. Student Understanding of Types of Chemical Bonds

Figure 8 presents students' self-perceived understanding of why ionic, covalent, and metallic bonds form. Only 31.4% of students stated that they understood these reasons. Meanwhile, 40.3% were unsure, and 28.4% reported that they did not understand them. Thus, more than two-thirds of respondents expressed uncertainty or a lack of understanding regarding basic bonding concepts, which are foundational for later topics such as molecular structure and chemical reactivity.

Use of Technology and AR in Chemistry Learning

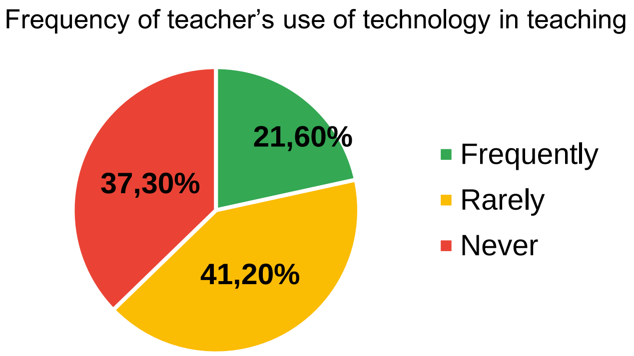

Figure 4. Teachers' Frequency in Using Technology or Innovative Media

Students' experiences with technology in chemistry learning were also limited. **Figure 9** shows that only 21.6% of respondents reported that their teachers frequently used technology or innovative media (such as videos, virtual simulations, or AR). In contrast, 41.2% stated that teachers rarely used such media, and 37.3% stated that they never did.

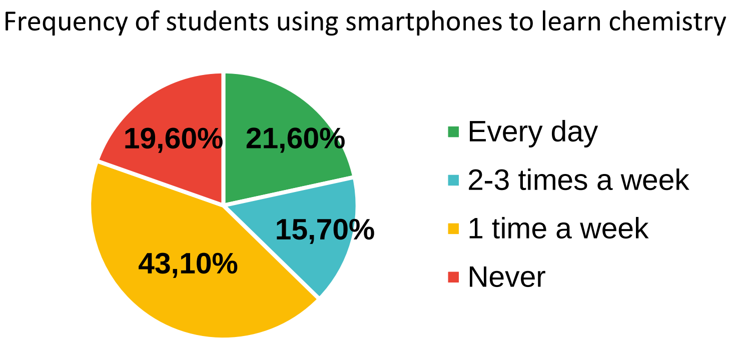

Figure 5. Frequency of Students Using Smartphones for Learning Chemistry

Students' own use of smartphones for learning chemistry is presented in **Figure 10**. A total of 21.6% reported using smartphones every day to study chemistry, 43.1% used them once a week, and 19.6% never used them for chemistry-related purposes.

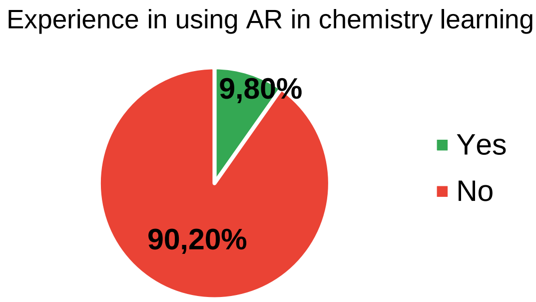

Figure 6. Use of AR in Chemistry Learning

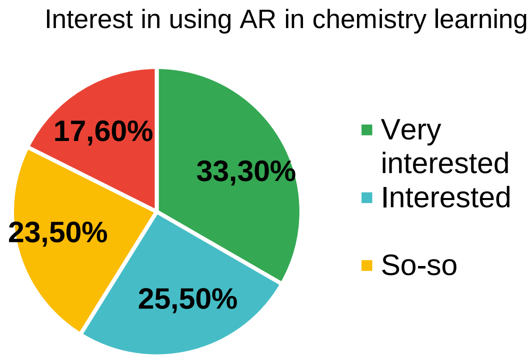

Figure 7. Student Interest in Using AR in Chemistry Learning

With regard to AR specifically, **Figure 11** indicates that 90.2% of students had never used AR media in chemistry learning, while only 9.8% had any prior experience. However, **Figure 12** shows that their interest in AR is relatively high: 33.3% of students reported being very interested and 25.5% interested in using AR to learn chemistry, so that nearly 59% expressed clear interest. Only 17.6% stated that they were not interested.

Overall, the results indicate that students face substantial difficulties in learning chemical bonding, are predominantly exposed to conventional media with limited visual and interactive support, and have very little experience with AR in chemistry lessons despite showing strong interest in its use.

DISCUSSION

The aim of this this present research was to map high-school students' needs regarding the use of AR-based media for learning chemical bonding. The findings point to three main issues: persistent difficulties with bonding concepts, the dominance of conventional instructional media that offer limited visual support, and an untapped opportunity for AR integration in chemistry learning.

First, the data confirm that chemical bonding is a critical area of difficulty for high-school students. A large majority of respondents reported that bonding is difficult, and many struggled with tasks such as explaining why bonds form, distinguishing bond types, and drawing Lewis structures. These findings are consistent with earlier work showing that students often have trouble coordinating macroscopic, microscopic, and symbolic levels of chemical representation and tend to develop fragmented mental models of bonding and structure (Hogan & Maglienti, 2001; Johnstone, 2000; Talanquer, 2006). When basic ideas such as electrostatic attraction, electron sharing, and energy changes in bonding are not well understood, subsequent learning about molecular structure and chemical reactivity is also hindered (Cooper et al., 2012). From an instructional design perspective, this situates chemical bonding as a high-priority topic for targeted media development.

Second, the study reveals a clear mismatch between students' learning needs and the instructional media used in their classrooms. Most students reported that the media used by their teachers did not engage them or help them with difficult topics. The dominance of PowerPoint, textbooks, and whiteboards indicates that abstract content is still presented largely through static, text-based materials. Previous research has shown that such materials are often not sufficient to support the visual spatial reasoning required to understand bonding processes, molecular geometry, and electron distributions, whereas technology-based visualisations and simulations can help make invisible phenomena more accessible (Michaluk et al., 2018; Wu & Shah, 2004). Studies on AR and other interactive media in chemistry have also reported that 3D models and dynamic visualisations can reduce misconceptions and improve students' ability to connect symbolic representations with underlying structures (Fitriyah et al., 2021; Rosanna, 2024; Setiawan & Harahap, 2024). The present findings therefore support the need for a more systematic integration of visual and interactive media when teaching chemical bonding.

Third, the results highlight both a gap and an opportunity in the use of AR for chemistry learning. Almost all students in this reserach had never used AR in their chemistry classes, yet more than half expressed interest in using it. This pattern is similar to reports from other contexts, where AR has been shown to enhance motivation, attention, and learning outcomes in science education, but its classroom use remains limited because of constraints in teacher training, infrastructure, and instructional design (Gutiérrez-Jara et al., 2025; Risqiyono & Setyasto, 2025; Uderbayeva et al., 2025). In addition, although smartphones are widely available, students in this study reported relatively low use of these devices for chemistry learning, echoing studies that note how mobile devices are often used more for entertainment than for structured academic purposes unless supported by clear pedagogical frameworks and engaging content (Brooks & Lawal, 2025; Pambudi et al., 2024; Tong, 2025). These parallels suggest that the challenge is not only technological but also pedagogical: teachers and schools need support to position AR and mobile technologies as integral parts of learning, rather than occasional add-ons.

Taken together, these findings provide concrete guidance for the next stages of the ADDIE process. In the **Design** and **Development** phases, AR-based media for chemical bonding should be aligned with the specific difficulties identified in this reserach. In practical terms, this means designing AR experiences that help students (1) explain why bonds form in terms of electron configurations and stability, (2) classify and distinguish ionic, covalent, and metallic bonds, and (3) relate 3D molecular models to symbolic representations such as formulas and Lewis structures. Prior work on AR flashcards and interactive modules in chemistry shows that such media can achieve high levels of expert validation and contribute to improvements in students' conceptual understanding when carefully integrated into lessons (Nurillah et al., 2022; Patel & Patel, 2019). At the same time, the media need to be feasible for use in typical Indonesian classrooms and accompanied by teacher guidelines so that AR is used to support, rather than distract from, core learning objectives.

This research has several limitations that need to be acknowledged. The data were collected from a single public high school in Surakarta using purposive sampling, so the findings are context-specific and not intended to represent all Indonesian high-school students. In addition, the questionnaire was designed as a multidimensional needs-analysis instrument rather than a unidimensional psychometric scale. As described in the Methods section, internal consistency indices such as Cronbach's alpha therefore play a limited role in evaluating the instrument, and the results are interpreted descriptively at the item and indicator level. Future research could extend this work by involving schools from different regions and by developing more focused subscales, for example, on AR readiness or technology acceptance, that can be examined with more conventional psychometric approaches (Patel & Patel, 2019).

Despite these limitations, the study makes a useful contribution to instructional design and AR-based chemistry education. Instead of starting from an existing AR product and then testing its impact, this research emphasises the importance of a structured needs analysis prior to media development. By documenting students' difficulties, experiences with instructional media, technology use, and interest in AR on the specific topic of chemical bonding, the study offers a data-driven starting point for designing AR tools that respond to actual classroom needs rather than to technology trends alone. This approach is in line with recommendations that educational technology should be developed based on clear problem diagnosis and user needs, rather than on the mere availability of new tools (Mashuri et al., 2025; Mushimiyimana et al., 2025).

CONCLUSION

The research was conducted to identify high-school students' needs related to AR-based media for learning chemical bonding as the Analysis phase in an ADDIE oriented development project. The findings show that many students still experience substantial difficulties in chemistry, with chemical bonding standing out as one of the most challenging topics. Learners struggle to explain why bonds form, to distinguish between ionic, covalent, and metallic bonds, and to represent bonding using Lewis structures, while classroom instruction remains dominated by conventional media such as PowerPoint, textbooks, and whiteboards. At the same time, almost all respondents have never used AR in chemistry lessons, yet more than half express clear interest in using AR to help them understand chemical bonding.

From a theoretical perspective, the work contributes to instructional design and AR-based chemistry education by demonstrating the usefulness of a structured, multidimensional needs analysis before any learning media are developed. Rather than starting from a finished AR product and then testing its impact, the analysis documents students' conceptual difficulties, everyday media experiences, technology use, and interest in AR on a single, well-defined topic "chemical bonding" within the ADDIE framework. On the practical side, the results point to several design directions for future AR-based media: tools should help students reason about bond formation in terms of electron configurations and stability, classify and distinguish different bond types, and move flexibly between 3D molecular models and symbolic representations, while still being realistic to implement in typical Indonesian high-school classrooms.

There are, however, some important limitations. Data were collected from a single public high school in Surakarta using purposive sampling, so the patterns described here are context-bound and not meant to represent all Indonesian students. The questionnaire was developed as a multidimensional needs-analysis instrument, and the data are self-reported, so the analysis focuses on descriptive patterns at the level of items and indicators rather than composite scores. Future work could involve schools from different regions and school types, develop more focused subscales, for example on AR readiness or technology acceptance and examine them with more conventional psychometric procedures. In the next phases of the ADDIE model, AR prototypes for chemical bonding that are explicitly aligned with the needs identified here can be designed, implemented, and evaluated through classroom trials or quasi-experimental studies, while parallel research explores how teacher preparation, school infrastructure, and lesson design can support the sustainable integration of AR into chemistry instruction.

CONFLICT OF INTEREST

The authors declare no financial, institutional, commercial, or personal conflicts of interest in the execution, authorship, or publication of this article. All research activities were conducted independently and in accordance with academic integrity.

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