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Development of an Augmented Reality Learning Module for Atomic Structure

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Abstract

Education in Indonesia is increasingly oriented toward 21st-century learning, which requires students to develop skills that enable them to face global challenges and compete in a rapidly changing world. This study aimed to develop and evaluate the feasibility of an augmented reality (AR)-integrated atomic structure module as an alternative learning resource in chemistry education. The research adopted a development design based on the 4D model—define, design, develop, and disseminate. Product feasibility was evaluated through expert validation involving material and media specialists, as well as assessments by chemistry teachers and students. The findings revealed that the AR-based atomic structure module is highly feasible and pedagogically appropriate as a learning resource. Validation results indicated average scores of 98% from material experts and 96% from media experts. Readability tests with students yielded a score of 93% (very good), while teachers rated the module's practicality at 97% (very feasible). These results suggest that the developed module not only provides accurate content and engaging visualizations but also enhances students' comprehension, motivation, and independent learning. Therefore, the AR-based module can serve as an innovative and effective tool for chemistry learning, particularly in understanding abstract concepts such as atomic models, electron configurations, and orbitals. Furthermore, this study contributes to the growing body of research on AR applications in science education by demonstrating its potential to improve learning outcomes and foster 21st-century skills.

Keywords: atomic structure, augmented reality, learning module

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1. Introduction

Learning in Indonesia has increasingly shifted toward a 21st-century orientation, requiring students to be well-prepared with competencies that enable them to confront life's challenges and compete in the global era. Education is a continuous and long-term process through which individuals strive to improve their quality of life. This process necessarily involves various key components, including the educational system applied within teaching and learning practices (Fahrurrozi et al., 2023).

Learning itself is a process directed at fostering the development of affective, cognitive, and psychomotor skills. Teaching and learning activities can be considered effective when they provide opportunities for students to achieve learning goals by engaging in meaningful activities that align with their capacities (Saputri et al., 2023).

The effectiveness of these activities is strongly influenced by the presence of learning media, which serve as integral components of the instructional system in schools. Learning media play a pivotal role in facilitating interactions between teachers and students during the teaching and learning process (Wulandari et al., 2023). Media use in learning can enhance students' understanding of subject matter and, when selected appropriately, can foster more effective comprehension (Dewi, 2022).

Maximizing learning outcomes requires the careful selection of media and instructional models, which must be adjusted to the characteristics of learners as well as the instructional objectives. Furthermore, appropriate planning, utilization, and evaluation of media are crucial in ensuring that intended learning outcomes are achieved (Hia et al., 2022).

In the context of 21st-century learning, technology-integrated media are essential in supporting the teaching process and in cultivating students' critical, creative, and innovative thinking skills (Hatimah & Khery, 2021). Students must also acquire the ability to use technology appropriately to support learning in their everyday lives. Properly designed media can promote effective communication skills, innovation, spirituality, and productivity (Rahayu et al., 2022).

Chemistry learning, in particular, requires effective tools and facilities to enhance the efficiency of the teaching and learning process. This is because chemistry involves three levels of representation: symbolic, submicroscopic, and macroscopic. A clear example is the topic of atomic structure, which is one of the foundational concepts in chemistry yet remains conceptually difficult for students. Learners must not only recall theories of atomic structure but also recognize atomic diagrams, elements, symbols, and electron configurations. Hence, explaining this concept often requires molecular visualization in three dimensions (Hurrahman et al., 2022).

Preliminary interviews conducted with chemistry teachers on November 1, 2023, indicated that students' interest, comprehension, and achievement in atomic structure were relatively low. Students appeared disengaged during instruction, as evidenced by their average performance scores on the topic. Informal interviews with several students revealed that classroom instruction relied heavily on PowerPoint presentations and lecture-based delivery, which students described as monotonous and unengaging. However, these findings are merely preliminary and anecdotal, highlighting the need for systematic and methodologically rigorous data collection to validate learning challenges in the atomic structure topic.

Several factors may underlie students' learning difficulties, including low achievement, weak motivation, limited interest in chemistry, underdeveloped learning skills, and misconceptions about the relevance of the subject. Additional external factors include peer influence, insufficient instructional time, ineffective pedagogical approaches, and limited teacher expertise in selecting appropriate learning models and media (Palangda & Laloan, 2023).

Among the most abstract topics in chemistry is atomic structure. As a fundamental concept, it demands not only theoretical understanding but also representational competence across macroscopic, submicroscopic, and symbolic dimensions. The inherent complexity of atomic structure renders it pedagogically urgent to design instructional media capable of bridging these three representational levels, thereby supporting meaningful connections between abstract theory and visual representation.

With the advancement of educational technology, augmented reality (AR) has emerged as a promising alternative learning medium capable of displaying three-dimensional objects to provide a more authentic representation of atomic structures. Although several studies have reported teacher training initiatives in the use of AR for learning (Chen & Liu, 2020), its adoption in chemistry instruction—particularly in teaching atomic structure—remains limited. Previous research on AR in chemistry has largely focused on molecular visualization of organic compounds or chemical bonding, while its integration into atomic structure pedagogy is still underexplored, thereby highlighting the novelty of this study.

AR-based learning has the potential to stimulate creativity by enabling students to visualize abstract concepts as tangible objects or processes (Rahmawati et al., 2023). Moreover, AR-integrated media can enhance analytical and critical thinking skills, offering interactive and immersive learning experiences that promote conceptual understanding (Ashari, 2023). In this study, AR is not conceived merely as a visualization tool; rather, it is pedagogically designed to support inquiry-based learning, strengthen representational competence, and improve student engagement with abstract concepts of atomic structure.

Based on this rationale, the present study seeks to develop an Atomic Structure Module Assisted by Augmented Reality. The urgency of this research lies not solely in the technological application of AR but in its pedagogical integration with atomic structure learning objectives, its novelty in addressing a fundamental chemistry concept, and its potential to provide empirically validated instructional solutions for overcoming students' persistent difficulties in understanding atomic structure.

2. Research Method

This study employed a developmental research approach 4D model, which consists of four stages: define, design, develop, and disseminate. Data were collected through interviews and questionnaires, and analyzed using expert validation instruments based on a Likert-scale format adapted from Sugiyono (2022).

In addition to expert validation, the research also incorporated an implementation phase in which the developed augmented reality-based module was applied in the classroom setting to examine its practicality and effectiveness. The implementation stage ensured that the developed media was not only theoretically valid but also pedagogically applicable in real learning environments.

The evaluated aspects comprised media validity (visual design and usability), material quality (content accuracy, presentation, and language), and instructional effectiveness (enhancement of learning outcomes and creative thinking skills in atomic structure learning). Evaluation was conducted systematically through expert appraisal, teacher feedback, and student responses.

The research process was carried out sequentially in alignment with the 4D model: (1) the definition stage involved identifying students' learning difficulties and instructional needs; (2) the design stage included planning the AR-based module and preparing supporting materials; (3) the development stage encompassed expert validation and product revision; and (4) the dissemination stage consisted of limited trials in the classroom to assess the feasibility of broader implementation. Eligibility categories can be seen based on Table 1.

$$P = \frac{\text{score of data testing results}}{\text{ideal score}} \, x \, 100\%$$

P : Percentage number
Ideal score : Highest score x number of respondents x number of items

Table 1. Feasibility Level Categories

Percentage score (%)	Category
< 20	Very less
21 - 40	Not enough
41 – 60	Enuogh
61 - 80	Worthy
> 81	Very worthy

3. Result and Discussion

The final product of this study was the Atomic Structure Module integrated with augmented reality (AR). The module was designed to be accessible via smartphones and other supporting devices, enabling students to interact with three-dimensional representations of atomic structures. Unlike traditional modules that primarily present static texts and images, the AR-assisted module provides dynamic visualizations that interconnect symbolic notations, submicroscopic models, and macroscopic representations. This integration is crucial because the ultimate instructional goal in atomic structure is not limited to recalling theories, but also involves interpreting, analyzing, and relating atomic models to observable chemical phenomena.

The module development followed the 4D model (define, design, develop, and disseminate). In the design stage, the selected learning outcomes from Phase E of the curriculum were analyzed and transformed into specific learning objectives. The central aim of the module is to guide students in analyzing the development of atomic theory, while strengthening representational competence across multiple levels of chemical representation.

A unique feature of the module is its explicit interconnection of sub-concepts in atomic theory. Dalton's model is introduced with textual explanations accompanied by AR-based 3D spheres representing indivisible atoms. Thomson's "plum pudding" model is then visualized with electrons embedded in a positively charged sphere, prompting students to compare and critically evaluate the evolution of atomic models. Through AR, these models are not presented as isolated facts but contextualized with experimental evidence such as cathode-ray experiments for Thomson and the gold-foil experiment for Rutherford thereby reinforcing the causal relationship between empirical data and theoretical development.

When students reach Bohr's model, AR features highlight quantized electron orbits, allowing them to visualize transitions that explain spectral lines. Finally, the quantum mechanical model is introduced with interactive orbital shapes (s, p, d, f) that depict electron probability distributions. This structured integration ensures that learners perceive the progression of atomic models as a continuous scientific narrative rather than fragmented theories.

The result of developing an atomic structure module using augmented reality is an atomic structure module and Android application. The atomic structure Android application begins with creating a 3D image in Blender. Blender is free and open-source 3D creation software. This software supports the entire workflow of 3D modeling, rigging, animation, simulation, rendering, compositing, and motion tracking, as well as video editing and game creation.

The atomic structure application is accessible on an Android smartphone. This product is a software application that can be used anytime and anywhere because it can be accessed on smartphones running the Android operating system. The developer used Unity to create the application. Unity is a free platform used to develop multi-platform applications. Unity is popular for its ability to create 2D and 3D applications.

The atomic structure application is accessible on an Android smartphone. The atomic structure application contains 3D images, audio, and brief text based on the displayed images. The atomic structure application features six 3D images depicting the development of atomic theory, including images of Dalton's, Thomson's, Rutherford's, Bohr's, and quantum mechanics theories. There are also two experimental images of Thomson's and Rutherford's atomic theories.

The module was designed specifically for Senior High School students in the field of Mathematics and Natural Sciences. The learning materials were compiled from authoritative sources including textbooks and peer-reviewed journals. The module components such as content organization, AR-based visualizations, interactive exercises, and reflective questions are intended to provide students with accessible, accurate, and meaningful representations of atomic structure. More importantly, the integration of AR transforms the module from a static collection of texts and images into an innovative pedagogical tool that bridges abstract concepts with tangible experiences. The augmented reality integrated atomic structure module which has been tested on material experts, media experts and chemistry teachers has obtained the following results:

3. 1. Material Expert

The augmented reality integrated atomic structure module was tested by material experts on the content aspects, presentation aspects and linguistic aspects contained in the module. The results of trials on material experts can be seen in Table 2.

Table 2. Validation Results by Material Expert

No	Aspect	Average Total Score
1	Contents	16
2	Presentation	20
3	Language	22.5
	Amount	58.5
	Presentation	98
	Category	Very Feasible

The validation results from the material experts demonstrated that the first validator assigned a score of 58, while the second validator provided a score of 59. Both scores are classified within the "very appropriate" category, indicating a high level of content relevance and alignment with learning objectives. The mean score from the two validators was 58.5, further confirming the material's high degree of appropriateness. As presented in Table 2, the analysis of the material appropriateness components revealed that the linguistic aspect achieved the highest average score (22.5), followed by the presentation aspect (20) and the content appropriateness aspect (16). Overall, the material validation process yielded a feasibility percentage of 98%, categorizing the developed module as highly feasible and suitable for implementation in chemistry learning contexts.

3. 2. Media Expert

The augmented reality integrated atomic structure module was tested by media experts through analysis of graphic aspects and usage aspects in the module to see the suitability of the media for the atomic structure module being developed. The results of trials with media experts can be seen in Table 3.

Table 3. Validation Results by Media Expert

No	Aspect	Average Total Score
1	Graphics	23.5
2	Application	15
Amount		38.5
Presentation		96
Category		Very Feasible

The validation results from the media experts indicated that the first validator assigned a score of 39, while the second validator provided a score of 38. Both scores fall within the "very appropriate" category, suggesting that the developed media meets the established quality standards. The average score obtained from both validators was 38.5, which also corresponds to the very appropriate category. As presented in Table 3, the analysis of media suitability aspects revealed that the graphic aspect achieved the highest average score (23.5), followed by the usability aspect (15). Overall, the validation process resulted in a media feasibility percentage of 96%, classifying the augmented reality–integrated atomic structure module as highly feasible and suitable for educational implementation.

3. 3. Learner Readability

The student readability questionnaire was designed to assess learners' readability and comprehension of the augmented reality–assisted atomic structure module. The questionnaire, consisting of 15 items, was administered to five students during a small-scale trial. The results of the learner readability assessment indicated an average score of 93.33, which falls within the "very good" category, demonstrating that the module is easily understood and engaging for students. The detailed results of the learner readability assessment in the small-scale trial are presented in Table 4.

Table 4. Learner Readability Results

Evaluator	Score	Presentation
Student 1	57	95
Student 2	57	95
Student 3	55	92
Student 4	55	92
Student 5	56	93
Amuont	280	467
Average	56	93.33
Category		Very Good

3. 4. Chemistry Teacher Responses

The chemistry teacher's response was carried out with the aim of finding out the practicality of the atomic structure module integrated with augmented reality as a learning resource for class X students. The teacher analyzed the content aspects, presentation aspects, linguistic aspects, graphic aspects and usage aspects contained in the module. The following results of the chemistry teacher's responses can be seen in table 5.

Table 5. Validation Results by Chemistry Teacher

No	Aspect	Average Total Score
1	Contents	16
2	Presentation	20
3	Language	22
4	Graphics	24
5	Application	15
Amount		97
Presentation		97
Category		Very Practical

Based on the data presented in Table 4, the practicality of the augmented reality integrated atomic structure module was evaluated through the administration of a practicality questionnaire to chemistry teachers. The results revealed an average score of 97, which is categorized as "very

practical", indicating a high level of usability and feasibility for classroom implementation.
Moreover, the validation results obtained from material experts, media experts, and teacher responses collectively support the practicality and effectiveness of the developed module. A comprehensive summary of these evaluations is illustrated in Figure 1.

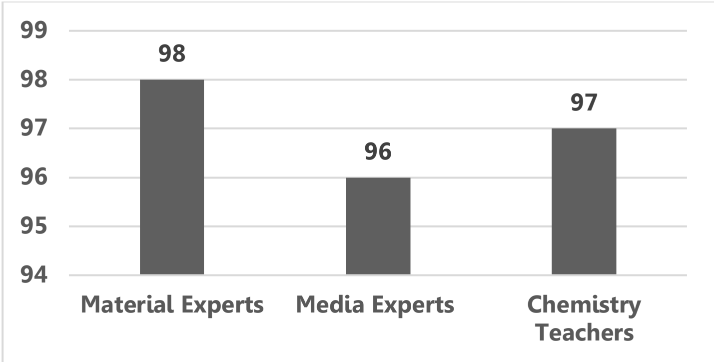

Figure 1. Graphic of Experts' and Teachers' Assessments

The validation results 98% from material experts, 96% from media experts, 93% from students, and 97% from teachers demonstrate that the module is highly feasible. Importantly, the significance of these findings lies not merely in the numerical values but in their pedagogical implications. Material experts confirmed that the sequence of atomic concepts was coherent with the curriculum and that the integration of AR preserved scientific accuracy. The exceptionally high score of 98% indicates that experts regarded AR not simply as an auxiliary feature, but as an essential tool for clarifying abstract content such as orbital visualization and electron configurations. Media experts emphasized the technical reliability, visual appeal, and user-friendliness of the AR features. The 96% rating reflects the success of the application in transforming abstract atomic models into interactive and engaging experiences that students can explore autonomously. Students' responses highlighted the motivational impact of the AR features, as well as their contribution to improved comprehension. In particular, several students noted that comparing Rutherford's and Bohr's models in AR helped them to overcome common misconceptions, such as the belief that electrons orbit the nucleus randomly without quantized energy levels. Teachers underscored that the module supported independent learning while simultaneously serving as a valuable discussion stimulus in classroom practice. They particularly appreciated its ability to foster inquiry-based learning, where students were encouraged to ask critical questions, such as why one atomic model was replaced by another, thereby cultivating higher-order thinking skills.

The feasibility of the augmented reality (AR)-integrated atomic structure module contributes to the diversification of technology-enhanced learning resources available to students. Previous studies have demonstrated the broad applicability of AR-based learning media. For example, Andriyani and Buliali (2021) developed Android-based AR media tailored for students with hearing impairments, while Aulawi (2019) explored interactive chemistry learning media using AR-based Android applications, showing their suitability for classroom implementation.

The development of AR-based learning modules provides an alternative approach to instructional resources, which are essential in managing the classroom environment, fostering student interest, and creating a positive learning atmosphere. This perspective is consistent with the findings of Harsono et al. (2019), Suryani et al. (2018), and Risnawati et al. (2018), who emphasized that the appropriate selection and application of learning media can significantly enhance student engagement and comprehension, as evidenced by improved academic performance.

Moreover, the AR-integrated atomic structure module does not only deliver content on atomic structure but also promotes autonomous learning and knowledge construction. This aligns with the findings of Arifin et al. (2020), which indicated that AR-based learning modules support independent learning and deepen students' conceptual understanding. Similarly, Ramadhani and Rosy (2023) confirmed that the integration of AR in learning modules is highly appropriate as supplementary teaching material in science education.

Specifically, the introduction of atomic structure concepts through AR can enhance classroom learning activities. As noted by Putra and Fajri (2022), AR-based chemistry applications can effectively visualize atomic elements, thereby enabling students to directly interact with abstract concepts in a more concrete manner. In addition, AR has been found to influence higher-order thinking skills. Purwanti et al. (2022) reported that the development of AR-based modules can foster students' critical and creative thinking abilities. This finding is further reinforced by Amalia et al. (2023), who demonstrated that providing students with direct, interactive learning experiences through AR not only improves learning outcomes but also increases motivation and interest in the subject matter. Taken together, these studies substantiate the potential of AR-based learning modules as innovative and pedagogically meaningful tools that go beyond visualization to support independent learning, enhance engagement, and foster critical and creative thinking.

Existing AR research in chemistry has largely concentrated on molecular visualization (e.g., organic compounds, bonding, or molecular shapes) (Aulawi, 2019; Hurrahman et al., 2022). The novelty of this study lies in its systematic integration of AR into the teaching of atomic structure a foundational concept that underpins subsequent topics in chemistry such as periodicity, bonding, and reactivity. By embedding AR within the pedagogical framework of representational competence, the module goes beyond visualization to actively engage students in reasoning about why models evolve, how experimental evidence supports them, and how they connect to observable phenomena.

From a pedagogical perspective, this AR-assisted module demonstrates that effective integration of technology is not limited to providing digital enhancements. The uniqueness of this module lies in its ability to bridge multiple levels of chemical representation: symbolic (atomic symbols, electron configurations), submicroscopic (electron orbits, orbitals), and macroscopic (spectral lines, periodic trends). The AR features serve as cognitive scaffolds, guiding students to connect abstract concepts with observable evidence.

Furthermore, the module supports inquiry-based learning by asking students reflective questions after each AR activity, such as: Why was Thomson's model replaced? How does Bohr's model explain spectral lines better than Rutherford's? These reflective prompts encourage critical thinking and move beyond rote memorization.

The contribution of this research lies in providing both a technological and pedagogical innovation. Technologically, the AR module demonstrates feasibility and accessibility on common student devices. Pedagogically, it introduces a framework where AR is deliberately designed to interconnect sub-concepts of atomic structure, align them with curriculum goals, and foster higher-order thinking skills. Unlike prior AR modules that primarily serve as add-ons, this study shows how AR can be embedded into the design of a structured learning module to enhance conceptual understanding, motivation, and inquiry in chemistry education.

4. Conclusion

This study concludes that the development of an Atomic Structure Module integrated with augmented reality (AR) is highly feasible and pedagogically valuable. Validation results from material experts (98%), media experts (96%), students (93%), and teachers (97%) collectively confirm that the module is scientifically accurate, technically reliable, user-friendly, and practically applicable in classroom contexts.

Beyond feasibility, the findings highlight the pedagogical significance of AR integration in chemistry learning. The module not only supports students in visualizing abstract atomic concepts such as orbitals and electron configurations but also strengthens their representational competence across symbolic, submicroscopic, and macroscopic levels. Furthermore, the AR-assisted module encourages inquiry-based learning by prompting students to critically evaluate the evolution of atomic models and the experimental evidence underpinning them.

Future research should extend the development of AR-assisted modules to other chemistry topics and conduct large-scale classroom implementations to further evaluate their long-term impact on student learning outcomes, motivation, and critical thinking abilities.

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