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Integration of 3D animation flipbook to enhance spatial visualization in molecular geometry learning

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Abstract. Students' limited spatial visualization skills pose challenges in understanding abstract chemical concepts such as molecular geometry. This study aimed to develop an interactive flipbook assisted by 3D animations to enhance students' spatial visualization and comprehension of molecular geometry. This research employed a Research and Development (R&D) approach using the ADDIE model and involved 32 purposively selected eleventh-grade students at SMA Negeri 7 Surabaya. Data were collected using validation sheets, student response questionnaires, pre-test and post-tests, and observation sheets, with instrument reliability confirmed by expert judgment and Cronbach's Alpha. Validation results showed that the flipbook was highly valid in both content and construct. Students' responses indicated a high level of practicality (92.9%). Effectiveness testing revealed significant improvement in learning outcomes, with an average N-Gain of 0.75 for competence and 0.80 for spatial ability, both categorized as high. These results suggest that the 3D-assisted flipbook enables students to visualize and manipulate molecular structures, thereby reducing reliance on imagination and strengthening conceptual understanding. Teachers are recommended to adopt 3D-assisted flipbooks as a low-cost and effective instructional medium to foster students' spatial reasoning and improve chemistry learning outcomes.

Introduction

Effective chemistry learning should foster students' spatial visualization skills, enabling them to transform two-dimensional representations into accurate three-dimensional molecular models. These skills are essential for explaining chemical phenomena, avoiding misconceptions, and strengthening conceptual understanding. Instructional media therefore, need to provide interactive and visual learning experiences that connect abstract concepts with real molecular structures (Tamami & Dwiningsih, 2020).

In practice, chemistry is often regarded as a challenging subject for senior high school students, particularly when it involves abstract or microscopic concepts. One of the most challenging topics is molecular geometry, which requires students to construct three-dimensional (3D) mental models from two-dimensional (2D) representations. Previous studies have shown that many students face difficulties in visualizing molecular structures, which leads to misconceptions and lower academic performance (Karonen et al., 2021; Rohmah & Hidayah, 2022). Spatial visualization ability has been identified as a key factor in students' success in chemistry learning. Students with higher spatial abilities are more likely to accurately interpret chemical representations and achieve better performance (Wu & Shah, 2004). However, recent studies confirm that a large proportion of students in Indonesia still rely on rote memorization, which hinders conceptual understanding of molecular geometry (Sunyono et al., 2017).

In line with these findings, the researcher also conducted a survey and diagnostic tests at SMA 7 Surabaya, which revealed similar challenges. A total of 63.89% of students reported experiencing difficulties in learning chemistry, primarily due to complex terminology (47.22%), abstract concepts (25%), and the emphasis on memorization (16.67%). Specifically, 63.9% of students admitted having poor mastery of molecular geometry; 41.67% were only able to recognize molecular structures in two dimensions, while 27.78% were unable to visualize them at all. The results of the visual-spatial ability test further indicated that most students struggled with rotation (57.14% incorrect), symmetry (61.43% incorrect), and interpreting molecular shapes (55.71% incorrect). These findings suggest that students' visual-spatial skills in understanding molecular geometry remain relatively low. Interviews with chemistry teachers also confirmed that classroom instruction still relies heavily on conventional tools such as blackboards, plastisin, and molymod, with minimal use of digital interactive media. Meanwhile, 94.4% of students expressed interest in 3D animation-based media as an alternative to traditional learning support. Previous studies have also emphasized that interactive multimedia has significant potential to improve visual-spatial ability (Tamami & Dwiningsih, 2020). yet research on interactive flipbooks as accessible learning media that can be independently used by students remains limited.

These findings clearly reveal a significant gap between the expected learning conditions and the actual classroom situation. Although students are ideally expected to acquire strong spatial visualization skills to master molecular geometry, the data indicate that many of them still struggle with fundamental aspects, such as rotation, symmetry, and interpreting molecular shapes. This discrepancy emphasizes the urgent need for practical and accessible learning media that can bridge the gap between abstract chemical concepts and students' current cognitive abilities.

Various technology-assisted learning media have been introduced in recent years, such as augmented reality (AR), interactive simulations, and digital modules. These innovations enhance students' comprehension of abstract concepts by providing dynamic and manipulable visualizations (Pohan et al., 2024; Maulida & Kamaludin, 2024; Syahri & Ekaputra, 2024). Augmented reality and 3D applications in chemistry have also been reported to improve students' spatial reasoning and achievement significantly (Sirakaya & Cakmak, 2018). Similarly, studies on interactive e-modules demonstrate their effectiveness in improving visual-spatial intelligence. (Zakiyah & Dwiningsih, 2021) and enhancing students' understanding of chemical bonding concepts (Simanjuntak & Purba, 2025). Furthermore, 3D visualization has been shown to foster critical thinking and positive scientific attitudes in chemistry classrooms (Rana et al., 2022). Meanwhile, digital flipbooks have gained attention as affordable and user-friendly tools that can support student engagement and independent learning (Rahmawati et al., 2021; Firdaus et al., 2024; Hamidah et al., 2025). Nevertheless, most of these advanced technologies require high-cost infrastructure, limiting their implementation in schools with constrained resources. Flipbooks, on the other hand, are more feasible to be applied widely due to their practicality and accessibility.

Recent research has strengthened this perspective by showing that digital flipbooks integrated with interactive features can significantly improve students' comprehension of abstract chemical concepts and support independent learning (Romadhon & Rahmawan, 2025). Moreover, the use of 3D visualization within digital media has been proven to enhance spatial reasoning and conceptual understanding, allowing students to better interpret molecular geometry (Alharbi, 2025). In addition, augmented reality–based applications in chemistry education have been reported to foster students' motivation, critical thinking, and problem-solving abilities, which are essential for mastering complex topics (Singh & Kaur, 2025). These findings indicate that combining the practicality of flipbooks with the cognitive benefits of 3D visualization offers a promising approach to addressing students' learning difficulties in molecular geometry.

In this study, the main variables are clearly defined to provide a strong theoretical foundation. A digital flipbook is an electronic learning medium designed in the form of an interactive book that can present text, images, and animations in a dynamic format, and it has been shown to support student engagement and independent learning (Rahmawati et al., 2021). The integration of 3D animation within the flipbook aims to provide dynamic molecular visualizations that allow students to manipulate and better interpret molecular structures, thereby reducing misconceptions (Alharbi, 2025). To evaluate the developed media, this research employs three aspects commonly used in educational product development: validity, referring to expert judgments on content and design feasibility; practicality, referring to the ease of use and accessibility of the media for both teachers and students; and effectiveness, referring to the impact of the media on improving students' learning outcomes and spatial visualization skills (Zakiyah & Dwiningsih, 2021). By incorporating these variables, the study seeks to provide a comprehensive analysis of how 3D-assisted flipbooks can serve as effective learning tools in chemistry education.

The novelty of this study lies in the integration of 3D animations into flipbook media. While digital flipbooks have been developed for chemistry learning (Rahmawati et al., 2021) and 3D visualization has been shown to improve students' understanding (Setiawan et al., 2020; Sirakaya & Cakmak, 2018; Adnyana, 2023), there is still limited research in Indonesia that combines both approaches in senior high school chemistry, particularly in teaching molecular geometry. This integration offers the potential to merge the practicality of flipbooks with the cognitive benefits of 3D visualization. Considering these gaps, this study develops and evaluates a 3D-assisted flipbook as an alternative medium for learning molecular geometry. The research aims to assess its validity, practicality, and effectiveness in improving students' spatial visualization skills and learning outcomes in chemistry.

Building on these considerations, the present study seeks to design, develop, and evaluate a 3D-assisted flipbook as an innovative alternative medium for learning molecular geometry. The integration of 3D animation into flipbook media is expected to provide dynamic visualizations that enable students to better interpret molecular structures, reduce misconceptions, and strengthen their conceptual understanding. In line with this aim, the research focuses on examining three key aspects: the validity of the product as assessed by experts, the practicality of its use as perceived by students, and the effectiveness of the media in improving learning outcomes. More specifically, the study investigates whether the use of 3D-assisted flipbooks can significantly enhance students' spatial visualization skills, which play a crucial role in mastering abstract chemical concepts. Accordingly, the central research question guiding this study is framed as a query on the extent to which the integration of 3D animation into flipbook media can improve students' spatial visualization ability and conceptual understanding of molecular geometry.

Based on the background and literature review, the problem of this study can be formulated as follows: how effective is the integration of 3D animation into flipbook media in enhancing students' spatial visualization ability and conceptual understanding of molecular geometry? Accordingly, the objectives of this research are (1) to determine the validity of the developed 3D-assisted flipbook, (2) to examine its practicality in classroom implementation, and (3) to evaluate its effectiveness in improving students' learning outcomes. The hypothesis proposed in this study is that the use of 3D-assisted flipbooks significantly enhances students' spatial visualization skills and supports better conceptual understanding in learning molecular geometry compared to conventional instructional media.

Method

Research Method and Design

This study employed a Research and Development (R&D) approach using the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation) (Branch, 2010). The ADDIE model was chosen because it provides a systematic framework to design, develop, and evaluate learning media, ensuring that the developed product is valid, practical, and effective for classroom use.

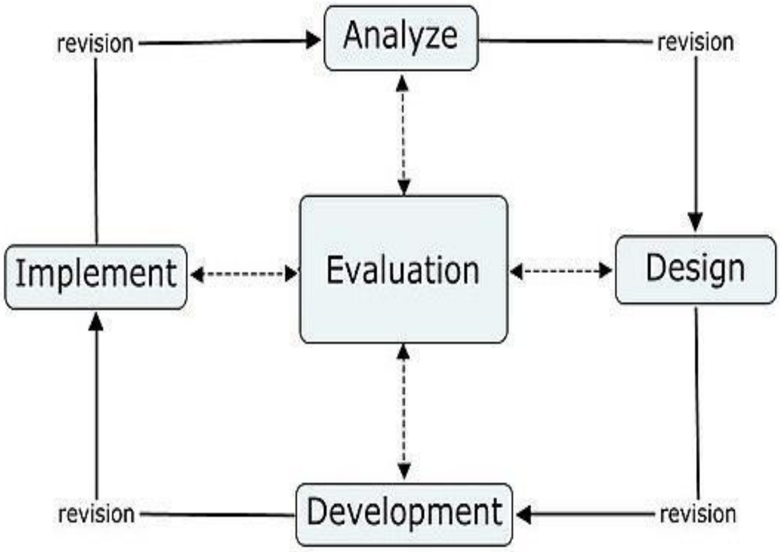

Image 1. Model ADDIE development

Participants and Sampling Technique

The subjects in this study were 32 students of class XI MIPA at SMA Negeri 7 Surabaya enrolled in the science program (class XI MIPA). The selection of participants was carried out purposively, considering that they had already received prior instruction on chemical bonding and molecular geometry, which made them suitable for testing the developed product. In addition to students, three experts were involved in validating the flipbook: a media expert, a chemistry education expert, and a practitioner teacher. The inclusion of validators was intended to guarantee the quality of the product in terms of content accuracy, design, and instructional feasibility.

In addition to students, three experts were involved in validating the flipbook: (1) a media expert, who evaluated the technical design and navigation of the flipbook; (2) a chemistry education expert, who assessed content accuracy and instructional feasibility; and (3) a practitioner teacher, who reviewed the practicality of the media in classroom settings. The inclusion of validators was intended to guarantee the quality of the product in terms of content accuracy, design, and instructional feasibility.

Research Setting and Timeline

This research was conducted at SMA Negeri 7 Surabaya on October 7, 2024, during the odd semester of the 2024/2025 academic year. The participants' role was to take part in the classroom implementation of the 3D-assisted flipbook, complete the pre-test and post-test, and provide responses through questionnaires.

The researcher's role was to design and develop the flipbook using the ADDIE model, facilitate classroom implementation, administer research instruments (validation sheets, questionnaires, observation sheets, pre-test, and post-test), and analyze the collected data to determine the validity, practicality, and effectiveness of the media.

Research Procedures

The implementation of the ADDIE stages began with the analysis stage, where student difficulties in understanding molecular geometry were identified through interviews and needs assessments. The design stage involved the preparation of a storyboard, the selection of appropriate three-dimensional (3D) molecular animations, and the planning of interactive navigation. During the development stage, the flipbook was created using digital design software and refined based on expert feedback. During implementation, the flipbook was tested directly in the classroom, where students were given a pre-test before using the flipbook and a post-test afterward. Student responses were also collected through questionnaires, and classroom activities were monitored using observation sheets. In the evaluation stage, data obtained from validators, students, and learning outcomes were analyzed to determine the validity, practicality, and effectiveness of the product, followed by necessary revisions (Branch, 2010).

Data Collection Techniques and Research Instruments

Several instruments were used in this study, including validation sheets, student response questionnaires, pre-tests and post-tests, and observation sheets. The validation sheets measured the content and construct validity of the flipbook, focusing on indicators such as clarity, relevance, and accuracy. The questionnaires assessed practicality by evaluating the attractiveness, usability, and usefulness of the media from the students' perspective. The tests were designed to measure both student competence and spatial visualization ability in molecular geometry, while observation sheets were used to document student engagement during the trial. The validity of the instruments was confirmed by expert judgment, and their reliability was analyzed using Cronbach's Alpha, with coefficients of 0.70 or higher considered reliable (Akpoghol et al., 2025).

Instrument Validity and Reliability Tests

The collected data were analyzed quantitatively and descriptively. The validity data were calculated as mean scores and categorized according to established criteria. Practicality was analyzed using the percentage of student responses, with a minimum of 61% required to be considered practical (Riduwan, 2016). Effectiveness was determined using normalized gain (N-Gain) to measure the improvement in student competence and spatial visualization ability (Hake, 1998). In addition, classical completeness was calculated to determine the proportion of students who achieved the minimum mastery criteria. This analytical procedure is consistent with recent studies that apply quantitative evaluation to assess the impact of 3D-assisted media in education (Sirakaya & Cakmak, 2018; Abdinejad et al., 2021). The instruments used in this study included validation sheets, student response questionnaires, pre-tests and post-tests, and observation sheets. A summary of the instruments is presented in Table 1.

Table 1. Research Instruments and Indicators

Instrument	Purpose	Indicators	Example Item	Scale
Validation sheet	To assess the content and construct validity of the flipbook	Clarity, relevance, accuracy	The visualization supports the concept of VSEPR	Likert 1–5

Instrument	Purpose	Indicators	Example Item	Scale
Student questionnaire	To measure practicality and student responses	Ease of use, attractiveness, usefulness	The flipbook helps me understand molecular shapes	Dichotomous (Yes/No)
Pre-test & Post-test	To measure competence and spatial ability	Molecular structure analysis, 3D–2D projection	Determine the molecular geometry of SO_2	Score 0–100
Observation sheet	To evaluate student activity and engagement	Attention, participation, interaction	Students actively rotate molecular models	Checklist (Yes/No)

The data analysis techniques used in this study were designed to ensure the validity, practicality, and effectiveness of the 3D-based flipbook media. The data were analyzed descriptively and quantitatively using three main approaches. First, students' learning improvement was calculated using the N-Gain formula to measure the effectiveness of the flipbook in enhancing conceptual understanding and spatial visualization ability. Second, the practicality of the media was evaluated through the percentage of students' responses to questionnaires, which included indicators of ease of use, learning motivation, and clarity of visual illustrations. Third, the consistency of validity assessments by validators was tested using the Cronbach's Alpha coefficient to ensure the reliability of the evaluation. These approaches were designed to provide a comprehensive overview of the success of the media implementation in chemistry learning.

Data Analysis Techniques and Criteria

Validation data were analyzed using the mode, with a minimum score of ≥3 considered valid. The validation results were further analyzed using a qualitative descriptive method with a Likert scale, as shown in the following table.

Table 2. Likert Scale

Score	Category
5	Very valid
4	Valid
3	Fairly valid
2	Less valid
1	Not valid

The percentage of student responses and observations was calculated, with ≥ 61% considered practical. The response questionnaire data were obtained from students who completed the instrument, which contained several criteria. Each criterion was assessed using a dichotomous scale, as shown in the following table.

Table 3. Response Scale

Dichotomy	Score
Yes	1
No	0

The improvement of student learning outcomes was analyzed using the N-Gain formula (Hake, 1998). Students' individual scores were declared complete at the classical level if at least 75% of the students achieved the Minimum Mastery Criterion (KKM). The percentage of students who met this criterion was calculated using the following formula:

$$\text{Classical completeness} = \frac{\text{number of students who completed}}{\text{total number of students}} \times 100\%$$

The pre-test and post-test results were also used to determine whether students' learning outcomes increased or decreased. The N-Gain (g) score was calculated using the following formula:

$$g = \frac{\text{Spost-Spre}}{\text{Smaks-Spre}} \times 100\%$$

(Hake, 1998)

keterangan:
g = N-Gain score
Spost = Post-test score
Spre = Pre-test score
Smax = Maximum score

The criteria for interpreting the N-Gain score are presented in the following table:

Table 4. Student Learning Improvement Based on N-Gain

Dichotomy	Score
$g > 0.7$	High
$0.3 \leq g \leq 0.7$	Medium
$g < 0.3$	Low

(Hake, 1998).

Through this approach, the study aimed to develop learning media that are valid, practical, and effective in enhancing students' spatial visualization abilities and improving their learning outcomes on molecular topics.

Product Specifications

The product developed in this study is a digital flipbook integrated with 3D animations. The flipbook was designed to support chemistry learning on the topic of molecular geometry for eleventh-grade senior high school students. Its content includes a concept map, learning objectives, theoretical explanations, two-dimensional illustrations, and interactive three-dimensional molecular animations that allow students to visualize and manipulate molecular structures. In addition, the flipbook features practice questions, formative tests in the form of interactive quizzes, and supporting sections, including a preface, user guide, and list of figures. The flipbook was developed using Flip PDF Corporate, ensuring simple navigation and a user-friendly interface. This product is intended to enhance students' spatial visualization skills and conceptual understanding by providing an engaging, low-cost, and accessible medium for classroom implementation.

Results and Discussion

This study is a Research and Development (R&D) project that follows systematic stages using the ADDIE instructional model. Through this process, information was gathered regarding the validity, practicality, and effectiveness of the developed flipbook, enabling its implementation in learning. The ADDIE model consists of five main stages: analysis, design, development, implementation, and evaluation. However, the scope of this article is focused on the stages of needs analysis, design, and initial product development of the 3D animation–assisted flipbook, supported by empirical evidence. Each stage was evaluated to determine how development activities positively contributed to the quality of the product. The following section describes the steps undertaken by the researchers in developing the 3D-assisted molecular geometry flipbook.

Analysis Phase

At this stage, the researchers focused on identifying the specific needs of the intended users, namely, students and teachers. The analysis included a review of students' difficulties in understanding the abstract concept of molecular geometry. The primary objective was to identify problems that arise during the learning process and to define the specifications of the product to be developed. Through interviews with chemistry teachers and a student needs assessment, it was found that students struggled to visualize molecular structures from 2D representations into 3D models, which in turn hindered their conceptual understanding. This information served as the foundation for designing a learning medium that is relevant and contextual.

Based on interviews with grade XI chemistry teachers at SMA Negeri 7 Surabaya, it was discovered that molecular geometry learning had thus far relied heavily on printed textbooks and verbal explanations. Students faced obstacles due to the limited use of interactive visual media, which made it challenging to connect theoretical knowledge with real molecular representations. Questionnaire results also revealed that students perceived molecular geometry as challenging, unappealing, and ineffective in linking concepts to everyday contexts. These findings highlighted the need for an alternative learning medium that can bridge such limitations. The needs analysis indicated that both teachers and students struggled mainly due to the lack of adequate resources for illustrating molecular structures. Molecular geometry is a key topic in the grade XI chemistry curriculum, which requires students to construct three-dimensional models and apply concepts in real-life contexts. For this reason, the 3D animation–assisted flipbook was designed to provide dynamic and interactive molecular representations, thereby supporting students' spatial visualization skills.

Design Phase

The planning process of the 3D-based flipbook involved several key steps, including the selection of learning materials, preparation of the flipbook content framework, determination of the 3D animations to be presented, and the choice of supporting software for the design process. Once the validation instruments were developed, they were reviewed and validated by experts, including media specialists and chemistry education experts. Feedback and recommendations from these validators were then incorporated to refine the instruments, ensuring they aligned with the study's objectives.

The content of the flipbook was adjusted to the expected learning outcomes and formulated into clear instructional objectives. In this study, a flipbook was developed to support chemistry learning for senior high school students in grade XI, specifically on the topic of molecular geometry. The material was presented by combining text, images, and interactive three-dimensional molecular animations, allowing students to visualize molecular structures more concretely. These variations in representation were designed to accommodate diverse student learning styles while enhancing the attractiveness of the flipbook as a learning medium. After determining the content, the researcher arranged the framework and designed the layout of the flipbook. This framework outlined the scope of material tailored to the 3D visualizations and spatial skills targeted in accordance with the learning objectives. At this stage, research instruments were also developed to assess the feasibility of the flipbook. These included validation questionnaires, spatial visualization ability tests, pre-test and post-test items, and student response questionnaires. The validation questionnaire was specifically designed to obtain expert evaluation of the flipbook's content, presentation, and clarity.

Development Phase

The stage following the design process is the development phase. The purpose of this phase is to transform the prepared design into a flipbook product ready for classroom use. The primary focus of this development was to create a 3D animation–assisted flipbook designed to enhance students' spatial visualization skills and conceptual understanding of molecular geometry. The resulting product was then declared feasible after undergoing evaluation by expert validators.

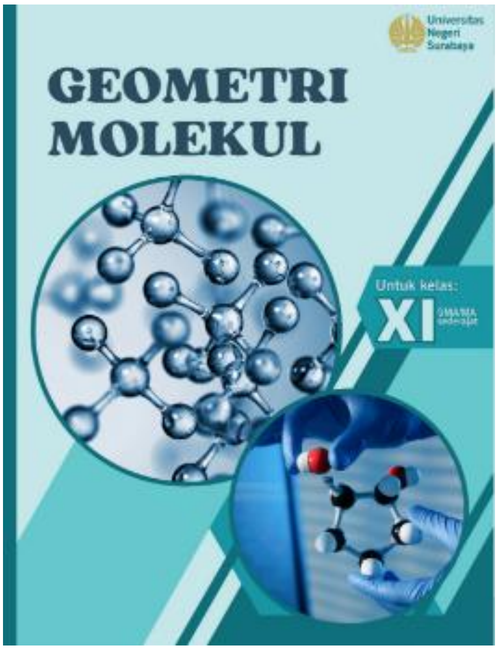

Image 2. Flipbook Cover Display

Image 3. Table of Contents in Flipbook

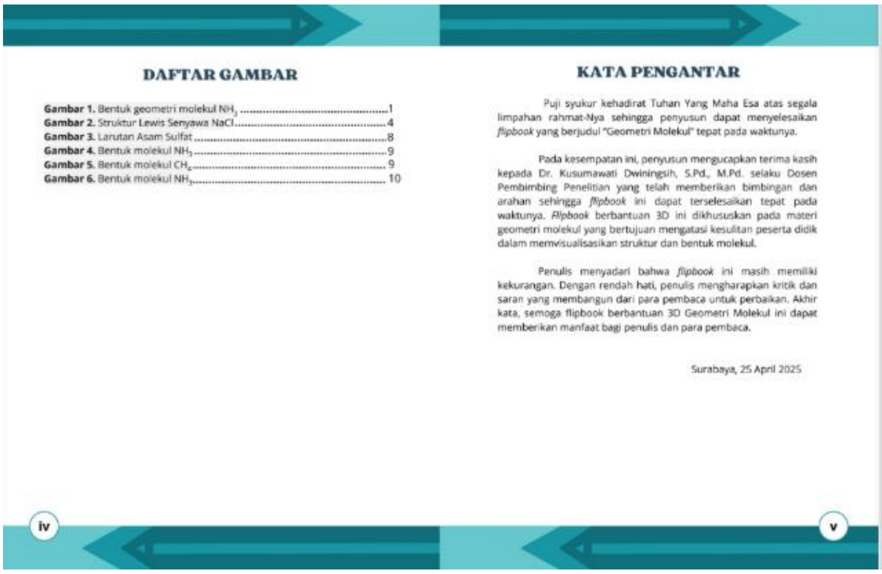

Image 4. Preface and List of Figure in Flipbook

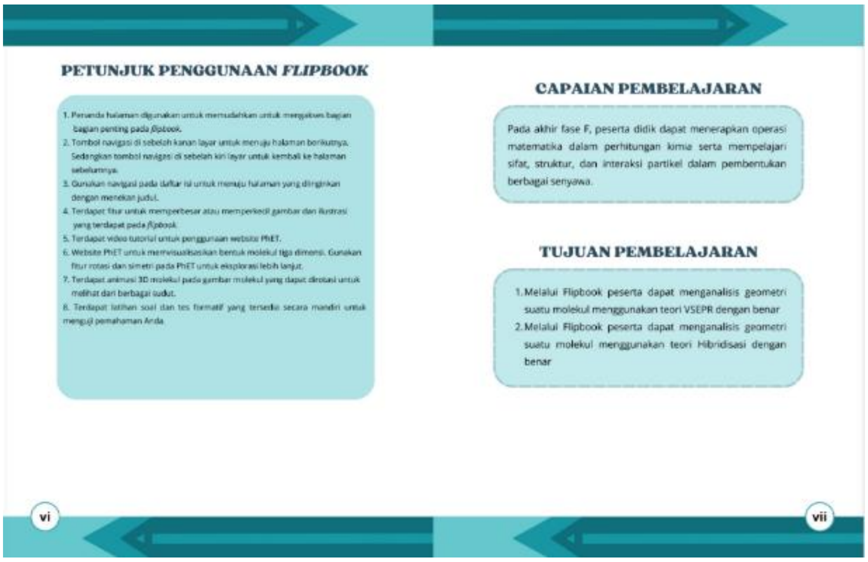

Image 5. User Guide and Learning Outcomes inf Flipbook

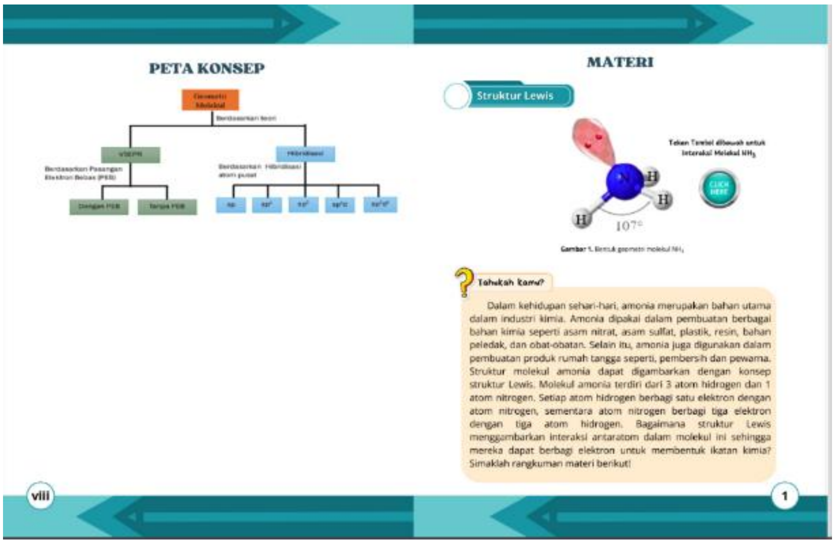

Image 6. Concept Map and Content in Flipbook

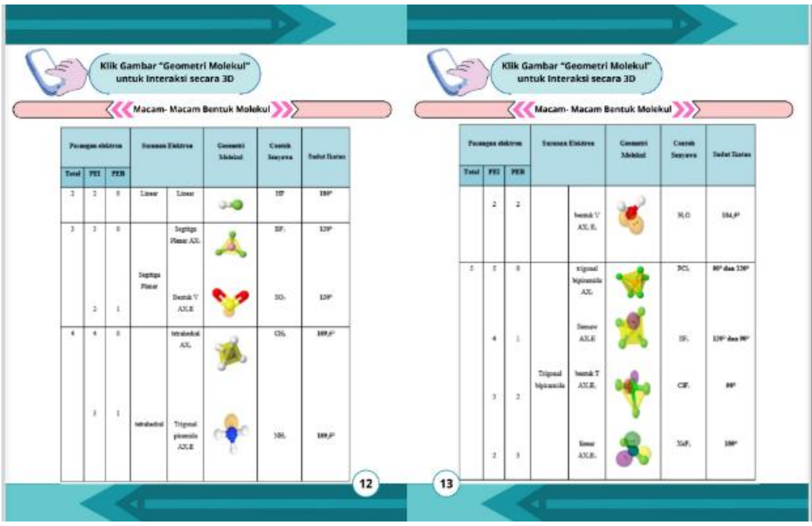

Image 7. 3D Molecular Geometry Animation

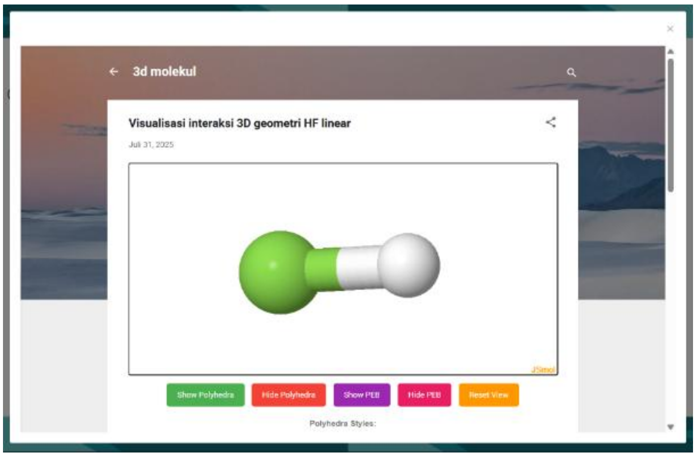

Image 8. 3D Molecular Geometry Animation in Interaction

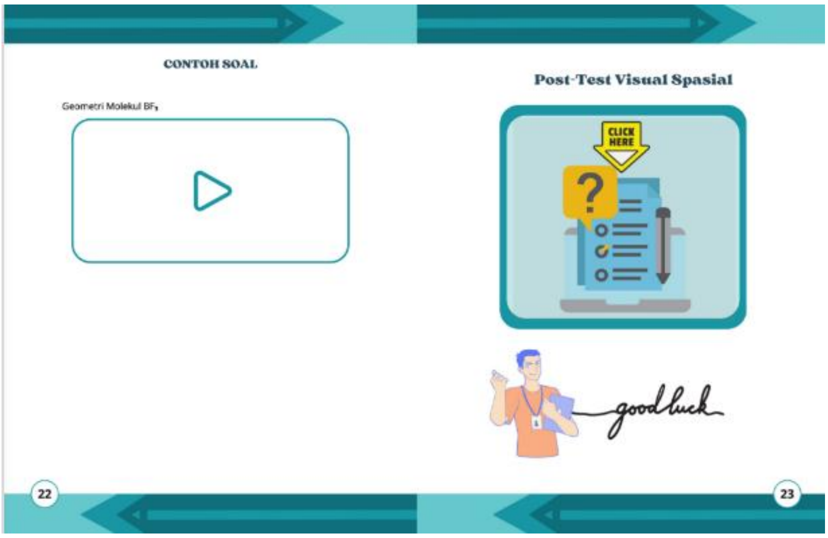

Image 9. Post-test in Flipbook

Once the product was developed, the next step involved validation by experts. This validation was conducted using assessment sheets completed by media experts, chemistry education specialists, and practicing teachers to evaluate the quality of content, design, and instructional feasibility. The validation results confirmed that the flipbook met the criteria of validity in terms of content clarity and the accuracy of 3D visualizations, making it appropriate for use in chemistry learning.

The research findings indicate that the 3D-assisted molecular geometry flipbook developed in this study possesses a high level of validity. The validity of the 3D flipbook was assessed by three validators, comprising two chemistry lecturers and one chemistry teacher, using a 5-point Likert scale. This scale covered three main criteria: (1) the alignment of content with learning objectives, (2) the appropriateness of 3D visualization for enhancing students' spatial abilities, and (3) the clarity of language and layout of the media. Validators assigned scores for each aspect based on a pre-established assessment rubric. The validation results showed that all aspects received a mode score of 5, which is categorized as "Highly Valid." Content validity ensured that the material presented was relevant to the targeted competencies. In contrast, construct validity confirmed that the media design could be effectively used to support the achievement of learning objectives.

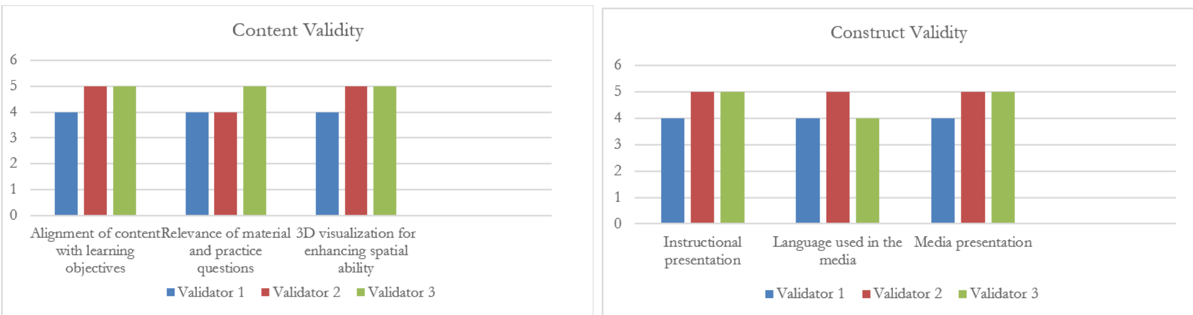

Image 10. Validity Diagram

The practicality of the flipbook media was also assessed through student response questionnaires and observation of their activities during the trial. Based on the questionnaire results, the flipbook received highly positive responses from students, with percentages of 84.3% or higher for indicators such as ease of use, clarity of illustrations, learning motivation, and material presentation, resulting in an overall average of 92.9%. These findings indicate that all aspects achieved ≥ 61%

for each criterion. According to Riduwan (2016), a flipbook is considered practical if it meets a percentage score of ≥ 61%. The following diagram presents the results of the student response questionnaire.

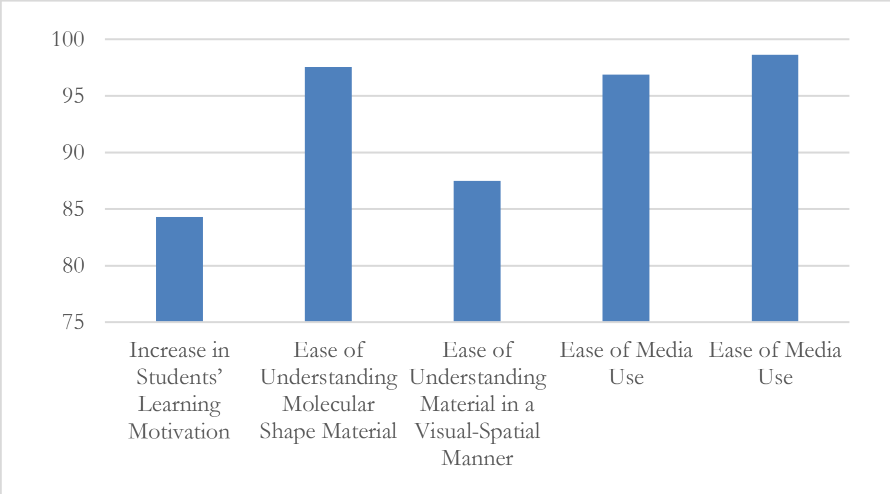

Image 11. Diagram of Student Response Questionnaire Results

Observation of student activities revealed that they were actively engaged in all stages of the learning process, from the pre-test to exploration using the flipbook and continuing through to the post-test. The following diagram presents the results of the student activity observations.

Student responses showed that the flipbook was highly practical, with an average score of 92.9%. Indicators such as ease of use, clarity of illustrations, and motivation to learn exceeded 84%, which met the minimum threshold of practicality (≥61%). This is consistent with Yamtinah et al. (2023), who found that digital flipbooks support student engagement and self-paced learning. The results of the student response questionnaire are presented in image 11.

Observation of student activities also confirmed these findings. During the implementation, students were actively engaged in all stages, including exploring molecular models, completing tasks, and discussing results. These qualitative observations support the questionnaire data and indicate that the flipbook provided a comfortable and motivating learning experience.

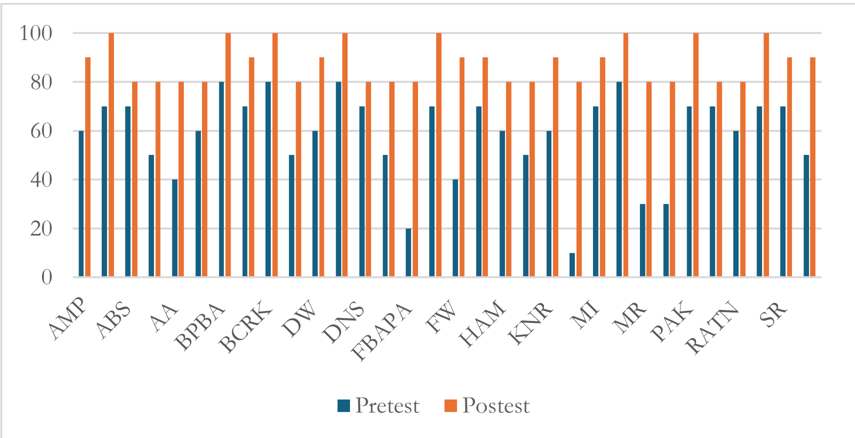

Image 12. Diagram of Pre-test and Post-test Score Comparison

The analysis of learning outcome improvement using the N-Gain formula showed an average score ranging from 0.63 to 1.00, which falls within the Moderate to High categories. Furthermore, in terms of spatial visualization ability, 26 out of 32 students achieved a High N-Gain category, indicating significant improvement in their ability to project 3D structures into 2D and vice versa, imagine molecular rotations, and identify symmetrical molecules.

The study revealed that the average N-Gain for competency was 0.75 (High category), while the average N-Gain for spatial visualization ability was 0.80 (High category). The percentage increase from pre-test to post-test in molecular structure analysis skills reached 90.6%, while the ability to visualize molecular shapes, transitioning from 3D to 2D, rose from 25.0% to 95.3%. These findings are consistent with previous studies demonstrating that the use of interactive visualization media can enhance students' spatial abilities and learning outcomes in understanding abstract chemical concepts. The following image presents the N-Gain data.

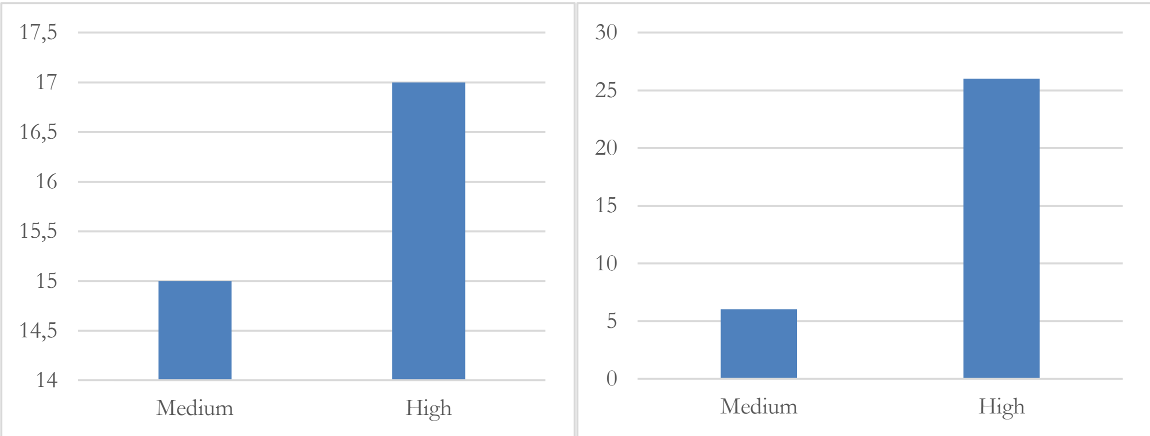

Image 13. Diagram of the Number of Students by N-Gain Category for Competency and Spatial Visualization

The most significant improvement in student learning outcomes occurred in the competency indicator related to molecular structure analysis, such as determining lone pairs of electrons and molecular geometry, which increased substantially from 50.0% in the pre-test to 90.6% in the post-test. In terms of spatial visualization, the most significant gain was observed in the ability to project molecular forms from 3D to 2D and vice versa, rising from 25.0% in the pre-test to 95.3% in the post-test. This finding demonstrates that the 3D-assisted flipbook not only facilitates a deeper understanding of the material but also enhances students' ability to visualize and manipulate molecular structures in three dimensions.

To clarify the analysis results, the pre-test, post-test, and N-Gain data are presented in tabular form. This presentation facilitates readers' understanding of the improvement in student learning outcomes after using the 3D-based flipbook. The table includes both competency and spatial visualization aspects, analyzed based on the average pre-test and post-test scores, as well as the N-Gain calculation to assess the effectiveness of the learning media.

Table 5. Analysis of Competency and Spatial Visualization Aspects

Aspect	Pre-test	Post-test	N-Gain
Competency	50.0%	90.6%	0.75
Spatial Visualization	25.0%	95.3%	0.80

The pre-test average for competence was 50.0%, and it increased to 90.6% in the post-test, with an N-Gain of 0.75 (classified as high category). Spatial visualization increased from 25.0% to 95.3%, with an N-Gain of 0.80 (classified as high). Student responses indicated high practicality, with an average score of 92.9%. From the table, it can be seen that the average N-Gain score for competency reached 0.75, which falls into the High category. The N-Gain score for spatial visualization ability was slightly higher at 0.80, also in the High category. This demonstrates that the use of 3D-based flipbooks is efficacious in improving students' understanding of molecular geometry.

The improvement in student learning outcomes, as indicated by these N-Gain values, shows that the developed flipbook had a strong effect on enhancing students' performance. The integration of 3D animations into a digital flipbook effectively reduced students' reliance on imagination when interpreting molecular structures. Instead of mentally constructing 3D models from 2D representations, students were able to manipulate molecular visualizations, which facilitated deeper conceptual understanding directly. This suggests that multimedia learning tools can reduce unnecessary mental effort, enabling students to focus on essential concepts. Furthermore, the high practicality score (92.9%) confirms that students not only benefited cognitively but also found the media easy to use and engaging, which likely contributed to their improved learning outcomes.

These findings correspond with earlier research in the field. For example, Dwiningsih et al. (2022) reported that the use of 3D-assisted learning media significantly enhanced students' spatial skills, particularly in visualizing molecular representations. Similarly, Yamtinah et al. (2023) showed that digital flipbooks are effective in supporting student engagement and self-paced learning, which aligns with the high practicality results obtained in this study. These results also align with (Alharbi, 2025), who demonstrated that 3D molecular visualization improves learners' spatial reasoning in chemistry, and Singh & Kaur (2025), who found that interactive visualization enhances students' understanding of molecular structures. However, compared to studies using more advanced technologies such as augmented reality (Sirakaya & Cakmak, 2018; Abdinejad et al., 2021), the present research demonstrates that comparable improvements in learning outcomes can be achieved with simpler and more accessible media (Adnyana, 2023). This suggests that 3D-assisted flipbooks provide a practical and cost-effective alternative that remains effective even in schools with limited technological infrastructure.

In addition to supporting these previous empirical studies, the results also confirm theoretical perspectives such as cognitive load theory and dual coding theory. According to these frameworks, combining verbal explanations with visual representations reduces unnecessary mental effort and enhances memory retention. The integration of interactive 3D molecular animations into a flipbook exemplifies the application of these theories in practice, showing that when students engage with multimodal content, their conceptual understanding and spatial visualization skills improve more effectively than through traditional methods.

In addition to aligning with previous research, the present study makes a distinctive contribution in terms of novelty. The novelty of this study lies in the integration of interactive 3D molecular animations into digital flipbooks, which has rarely been investigated in the context of Indonesian high school chemistry learning. While previous studies demonstrated the benefits of 3D visualization reality (Sirakaya & Cakmak, 2018; Dwiningsih et al., 2022), and the practicality of digital flipbooks Yamtinah et al., (2023), few have combined both approaches in a single learning medium. This combination provides a low-cost yet effective alternative to more sophisticated technologies such as augmented reality or virtual reality, making it highly relevant for schools with limited resources. Thus, the present research contributes not only by confirming the effectiveness of 3D visualization but also by demonstrating how it can be integrated into simple and accessible digital media. This novelty emphasizes that the study provides a unique contribution to the field by offering a feasible solution that bridges the gap between high-cost technologies and practical classroom applications.

The findings of this study have both theoretical and practical implications. Theoretically, the results reinforce cognitive load theory and dual coding theory by demonstrating that combining textual explanations with interactive 3D visualizations can reduce extraneous cognitive effort and enhance students' conceptual understanding. This study thus provides empirical evidence that supports the integration of multimedia principles into the teaching of chemistry. Practically, the developed 3D-assisted flipbook offers teachers a low-cost and accessible instructional medium that can be easily implemented in schools with limited technological infrastructure. The positive student responses and significant learning gains indicate that this medium is not only effective in improving spatial visualization skills but also feasible for large-scale classroom application. These impacts highlight the potential of 3D-assisted flipbooks as a scalable solution to bridge the gap between advanced learning technologies and the everyday realities of classroom teaching.

Despite these promising results, this study has several limitations that must be acknowledged. First, the trial was conducted in a single school with a relatively small sample size, which restricts the generalizability of the findings to broader student populations. Second, the learning media was applied only to one topic molecular geometry so its effectiveness in other areas of chemistry remains uncertain. Third, the study was carried out in a relatively short time frame, meaning that long-term impacts on students' conceptual retention and motivation could not be fully assessed. Future studies should therefore expand implementation to diverse schools, cover a wider range of chemistry topics, and include longitudinal measurements in order to examine the scalability, robustness, and sustainability of the learning outcomes.

Conclusion

This study concludes that the development of a 3D-assisted flipbook on molecular geometry has met the criteria of validity, practicality, and effectiveness as a learning medium. Expert validation indicated that the flipbook is categorized as very valid in terms of content, design, and clarity. Student responses further showed a very positive evaluation, with an overall practicality score exceeding 90%, demonstrating that the flipbook is easy to use, engaging, and supportive of independent learning. In terms of effectiveness, the use of the flipbook led to a significant improvement in students' learning outcomes, as evidenced by the increase in pre-test to post-test scores with an average N-Gain of 0.75 for competence and 0.80 for spatial ability, both in the high category. These results suggest that the flipbook not only facilitates students' mastery of molecular geometry concepts but also enhances their visual-spatial skills, which are essential in understanding abstract chemical structures. Based on these findings, the 3D-assisted flipbook can be considered an effective alternative to conventional teaching methods in chemistry learning. This study implies that integrating interactive and visual digital media in the classroom can reduce learning difficulties, increase student motivation, and optimize learning efficiency. Therefore, teachers are encouraged to adopt similar media in other chemistry topics or related subjects to foster deeper conceptual understanding and higher-order thinking skills. Future research should test this media across different schools and subjects to examine its scalability.

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