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AR-MO Model: Augmented Reality–Based Learning to Enhance Students' Understanding and Skills in Molecular Geometry

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ABSTRACT

This study addresses the persistent difficulty Indonesian secondary students face in grasping abstract molecular geometry concepts, exacerbated by the limited adoption of immersive technologies in local curricula. We developed the AR-MO (Augmented Reality-Based Molecular) instructional model using a six-stage Design Science Research (DSR) approach, spanning from problem identification to the communication of results. The model's effectiveness was evaluated among 349 students across 15 public high schools in Tangerang using a pre-test/post-test design, with data analyzed through descriptive statistics and category-shift mapping. Results indicate a significant enhancement in cognitive understanding, attitudes, and practical skills, with nine schools completely eliminating "Fair" performance categories in favor of "Good" and "Very Good". User satisfaction and usability scores exceeded 90%, confirming the model's acceptance. The novelty of AR-MO lies in its structured integration of 3D visualization within a constructivist framework tailored for the Indonesian secondary education context.

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1. INTRODUCTION

The rapid advancement of digital technology has fundamentally reshaped educational paradigms, yet chemistry education often struggles to visualize abstract spatial structures. In Indonesia, despite the potential of immersive tools, the adoption of Augmented Reality (AR) remains sporadic and lacks integration into formal secondary school systems [3], [15]. A preliminary survey of 872 students in Tangerang revealed that 90.8% find molecular shapes difficult to comprehend, while 98% expressed a desire for AR-based interventions. Current literature indicates that AR can boost motivation, but a significant research gap exists regarding structured instructional frameworks that bridge the "technological-pedagogical" divide in Indonesian high schools [3], [4]. Most existing studies focus on primary or higher education, leaving a void in secondary-level chemistry frameworks. This research addresses this gap by proposing the AR-MO model, a constructivist-driven framework in which students interact with 3D virtual molecules superimposed on physical markers, thereby facilitating learning by doing. The theoretical foundation of this study is rooted in constructivism and experiential learning, which posit that knowledge is best constructed through active, immersive interaction with the subject matter [12]. The AR-MO model enables students to manipulate 3D molecular models in real time, transforming abstract formulas into concrete spatial experiences [8], [15].

This study aims to: (1) identify the key components in implementing AR in chemistry learning; (2) develop an AR-based learning model and prototype; and (3) evaluate the effectiveness of the developed AR-MO model on students' conceptual understanding, attitudes, and skills. We anticipate that this model will not only improve student outcomes but also provide a scalable blueprint for technology-enhanced learning in Indonesia, despite potential infrastructure and teacher-training limitations.

2. METHOD

Type of Research

This study employs the Design Science Research (DSR) approach in accordance with the model proposed by Alan R. Hevner and further operationalized by Ken Peffers et al [7], [10], which involves six stages: problem identification, definition of solution objectives, design and development, demonstration, evaluation, and communication of results.

Subjects and Sampling Technique

The research population consists of eleventh-grade students from public senior high schools in Tangerang. A sample of 349 students was selected from 15 senior high schools using disproportionate stratified random sampling.

Data Collection Techniques

Primary data were obtained through: (1) questionnaires using a 6-point Likert scale; (2) interviews and focus group discussions (FGDs) with chemistry teachers, educational technology experts, and AR developers; and (3) Student improvements were measured across three domains: cognitive (via pre-post written and oral tests), affective (via self-assessment, peer-assessment, and daily journals), and psychomotor (via project-based portfolios and practical products). Data were analyzed using descriptive statistics to map the distribution of student performance across four categories (Poor, Fair, Good, Very Good). Effectiveness was determined by the percentage shift in these categories from the pre-implementation to the post-implementation phases [4].

Secondary data were collected from scientific journals and official educational documents, including the National Curriculum and reports from Kementerian Pendidikan dan Kebudayaan.

Model and Prototype Development

The model was developed based on the results of a Systematic Literature Review (SLR) and expert validation. The AR application prototype was created using Unity, Blender, and Vuforia, featuring learning content on molecular geometry. Validation was conducted by 10 experts and teachers, and reliability was assessed using Cronbach's α.

3. RESULTS AND DISCUSSION

Descriptive Analysis of Students' Knowledge in Learning Molecular Geometry Using the AR-MO Model

The trial results indicate that implementing the AR-MO model consistently improved students' learning outcomes in molecular geometry. Across all 15 senior high schools studied, there was a significant shift from the "Fair" category to "Good" and "Very Good." A total of nine schools (including SMA 2, 3, 4, and 5) successfully eliminated the "Fair" category entirely in the post-test.

The most notable change occurred at SMA 7, where the proportion of students in the "Fair" category decreased from 65.71% to 85.71% in the "Good" category and 11.43% in the "Very Good" category. Additionally, SMA 10 and 12 experienced sharp increases in the "Very Good" category, which had previously been absent.

These findings indicate that AR-MO effectively enhances students' understanding through interactive 3D visualization. Support from constructivist theory and similar results from previous studies confirm that AR facilitates more concrete and meaningful learning. In practice, AR-MO can serve as an effective alternative to conventional methods, particularly for abstract and complex chemistry topics [4], [5].

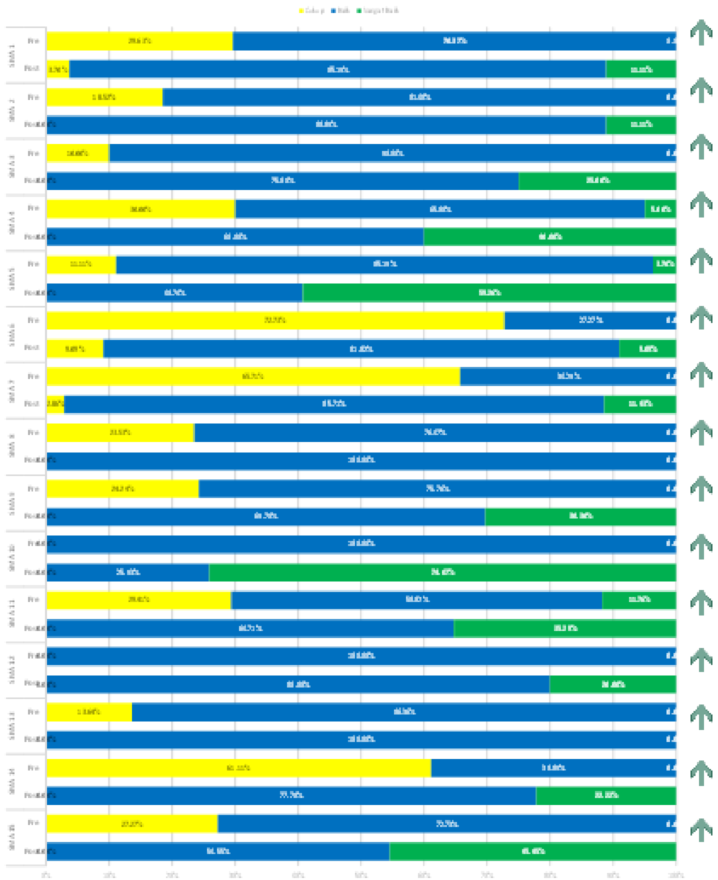

Figure 1. Percentage Chart of Pre- and Post- Implementation Assessments of AR-MO on the Knowledge Variable
Source: Processed by the researcher (2024)

Descriptive Analysis of Students' Knowledge Based on Written Indicators in Learning Molecular Geometry Using the AR-MO Model

The post-test results graph shows that the AR-MO model significantly improved students' performance on written tests in nearly all participating schools. A major shift occurred from the "Poor" category to "Good" and "Very Good," indicating improved conceptual understanding after using the AR application. Nine schools (SMA 3, 4, 5, 7, 8, 9, 10, 13, and 15) completely eliminated the "Poor" category. SMA 11 demonstrated the most dramatic improvement, with a 58.82% reduction in students in this category. SMA 9 recorded 81.82% of students in the "Good" category and 3.03% in the "Very Good" category.

Several schools, such as SMA 4 and 5, experienced sharp increases in the "Very Good" category (for example, from 11.11% to 44.44% at SMA 5). SMA 10 and SMA 12 showed consistent improvement; although there was a slight decline in the "Good" category, it was offset by an increase in the "Very Good" category. Despite some remaining room for improvement, particularly at SMA 6 and 8, which still had relatively high proportions in the "Fair" category, most schools demonstrated positive trends. This suggests that AR-MO can be applied broadly and flexibly, even among students with differing initial abilities.

This success supports the principle that interactive technologies such as Augmented Reality help students grasp abstract concepts through visualization and direct interaction. The findings are consistent with previous research showing that AR enhances information absorption and retention [4][5][6].

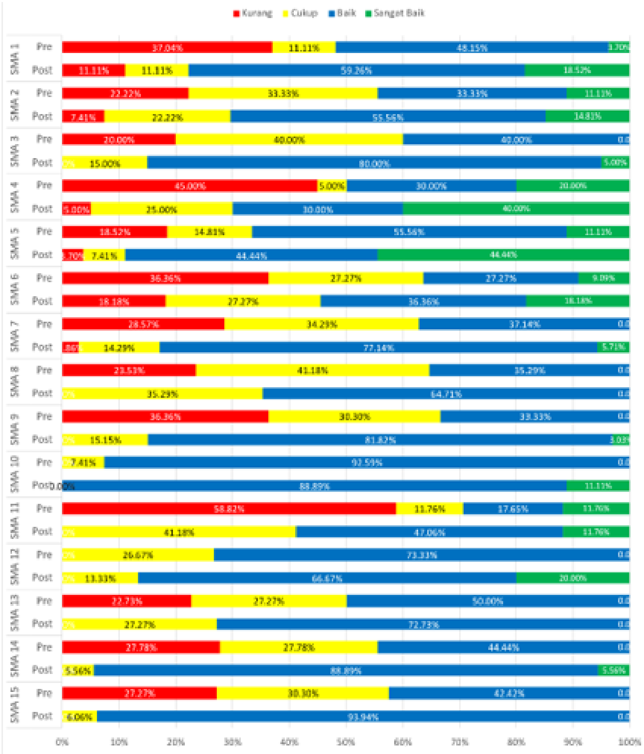

Figure 2. Percentage Chart of Pre- and Post-Implementation Assessments of AR-MO on Written Indicators
Source: Processed by the researcher (2024)

Descriptive Analysis of Students' Knowledge Based on Oral Indicators in Learning Molecular Geometry Using the AR-MO Model

The AR-MO model also proved effective in significantly improving students' oral test results. Three schools (SMA 6, 7, and 14) successfully eliminated the "Fair" category entirely in the post-test. Sharp improvements occurred at SMA 3, 5, and 9, where more than 60% of students achieved the "Very Good" category. Several other schools (SMA 1, 7, and 14) also showed substantial increases in this category from a previous baseline of 0%.

SMA 10 and 15 experienced declines in the "Good" category but substantial increases in the "Very Good" category, indicating qualitative improvement. Only SMA 13 showed no change, suggesting the need for alternative instructional approaches. Overall, AR-MO effectively enhanced students' oral abilities through interactive visualization, facilitating clearer understanding and verbal explanations of chemistry concepts. These findings are consistent with prior studies highlighting the benefits of AR in strengthening students' scientific communication skills.

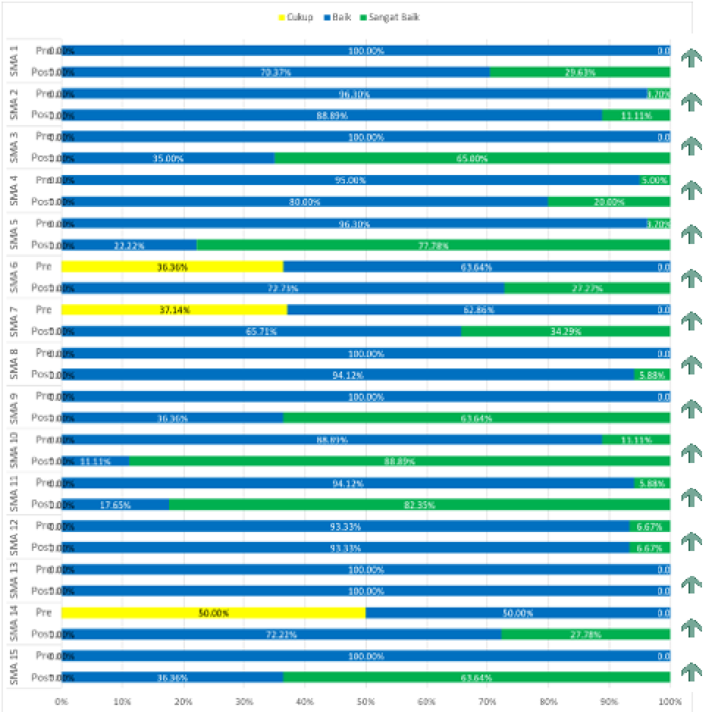

Figure 3. Percentage Chart of Pre- and Post-Implementation Assessments of AR-MO on Oral Indicators
Source: Processed by the researcher (2024)

Descriptive Analysis of Students' Knowledge Based on Assignment Indicators in Learning Molecular Geometry Using the AR-MO Model

The AR-MO model demonstrated significant effectiveness in improving students' performance on task-based assignments. Nearly all participating senior high schools experienced improvements from the "Fair" category to "Good" and "Very Good," with SMA 6 and 14 successfully eliminating the "Fair" category entirely in the post-test. The most notable increases occurred at SMA 3, 5, and 9, which shifted from 100% "Good" to more than 45%–74% "Very Good." Other schools, such as SMA 1, 7, and 14, also showed the emergence of the "Very Good" category, which had previously been absent.

substantial increases in the "Very Good" category, indicating a qualitative improvement. Only a few schools showed minimal change, while SMA 12 and 13 maintained 100% "Good." Overall, AR-MO not only raised learning standards but also deepened conceptual understanding through performance-based tasks. Students' interaction with 3D molecular visualizations strengthened meaningful, concrete learning. These results align with previous findings confirming that AR is effective in improving students' knowledge [4], [5], [6]. Dynamic visualization enabled students to complete assignments more effectively, as reflected in the significant improvement in task scores.

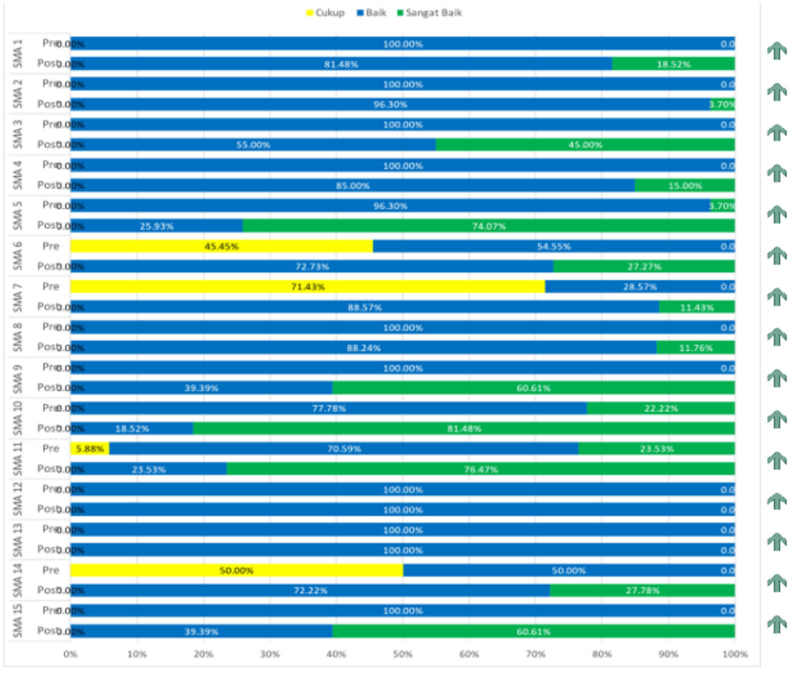

Figure 4. Pre- and Post-Implementation Graph of AR-MO on Assignment Indicators
Source: Processed by the researcher (2024)

Descriptive Analysis of Students' Attitudes in Learning Molecular Geometry Using the AR-MO Model

The AR-MO model showed varied effects on students' attitudes across the 15 senior high schools. In general, there was an improvement from the "Fair" category to "Good" and "Very Good," although the gains were not uniform across all schools. SMA 11 recorded the highest increase (from a score of 2.851 to 3.281), followed by SMA 10 (2.920 → 3.078). SMA 1 and SMA 11 also experienced significant shifts in category distribution, with increases in "Good" and "Very Good" and decreases in "Fair."

Conversely, SMA 6 and SMA 12 experienced slight declines in attitude scores, indicating the need to consider local contextual factors. Several schools, such as SMA 4 and 5, maintained stable "Good" ratings, while the "Very Good" category emerged in more schools after implementation.

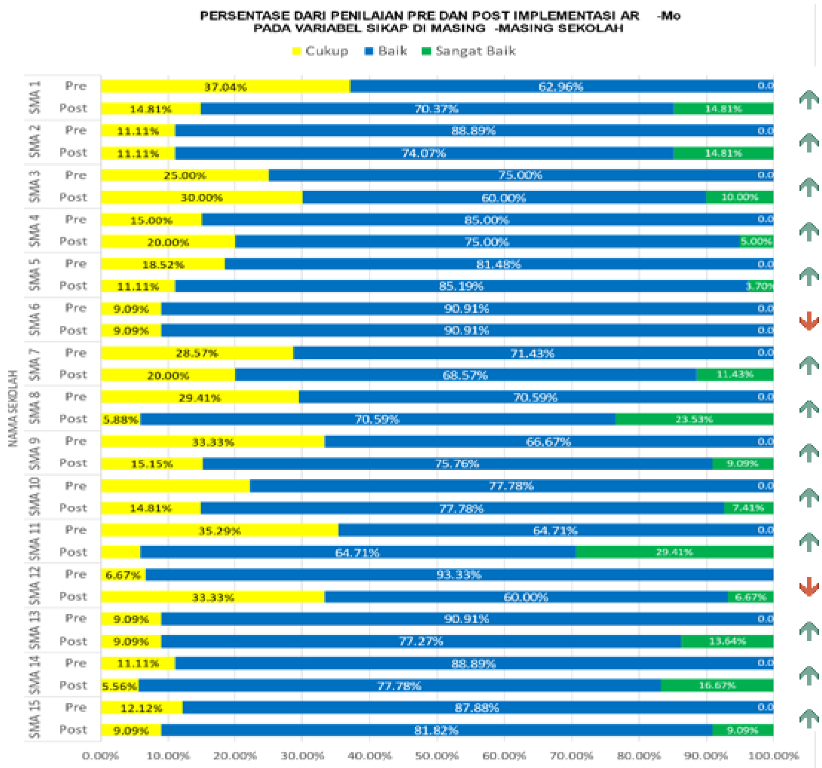

Figure 5. Pre- and Post-Implementation Assessment Graph of AR-MO on the Attitude Variable
Source: Processed by the researcher (2024)

These results indicate that AR-MO can improve students' learning attitudes; however, its effectiveness depends on each school's context. Theoretically, the findings support the concept of personalized learning, in which student engagement is influenced by readiness, teacher support, and the learning environment. This study is consistent with prior research indicating that AR can enhance learning attitudes and motivation [7], [8], [9]. In practice, structured, context-sensitive implementation strategies are required—including teacher training and infrastructure readiness—to ensure the optimal application of AR technologies such as AR-MO.

Descriptive Analysis of Students' Attitudes Based on Observation Indicators in Learning Molecular Geometry Using the AR-MO Model

The AR-MO model proved effective in improving students' attitudes, as evidenced by observational results. Average student scores increased across all schools, with no declines recorded. SMA 1, 6, and 15 successfully eliminated the "Fair" category entirely, with all students categorized as "Good" or "Very Good." SMA 6 showed the most dramatic improvement, shifting from 36.36% in the "Fair" category to 100% in the "Good" category. At SMA 1, the "Very Good" category emerged (7.41%) after previously being absent.

SMA 2 and SMA 10 recorded consistent increases in average scores, from 2.84 to 3.32 and from 2.83 to 3.42, respectively. Despite variations in initial distributions, all schools demonstrated improvement, confirming that AR-MO successfully enhanced students' attitudes and engagement in learning. These findings support constructivist theory and the importance of active student engagement. Interactive AR visualization helps students build a more concrete understanding, thereby strengthening positive attitudes toward chemistry learning. The results are consistent with previous studies showing that AR improves learning attitudes and motivation [7], [8], [9].

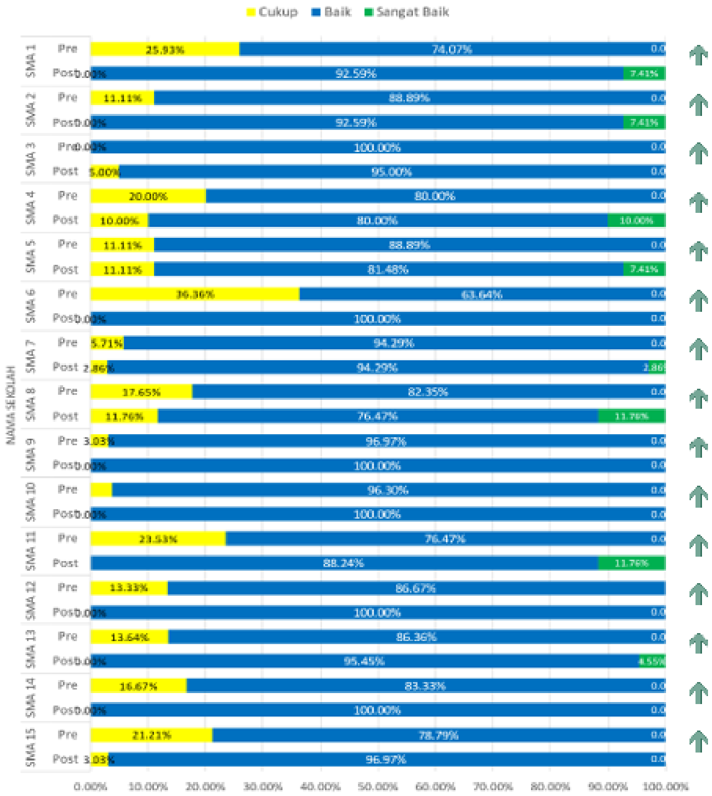

Figure 6. Pre- and Post-Implementation Assessment Graph of AR-MO on Observation Indicators
Source: Processed by the researcher (2024)

Descriptive Analysis of Students' Attitudes Based on the Daily Journal Indicator in Molecular Shape Learning Using the AR-MO Model

The AR-MO model demonstrates an overall improvement in students' attitudes across all schools, with no decline in average scores. Eight schools successfully eliminated the "Fair" category entirely in the post-test, indicating a positive shift toward the "Good" and "Very Good" categories. SMA 6 recorded the largest increase, from 2.82 to 3.30, followed by SMA 3 (2.73 → 3.28) and SMA 7 (2.63 → 3.27). The "Very Good" category also emerged significantly in SMA 7 (0% → 40%) and SMA 12 (0% → 26.67%). Most other schools showed a consistent upward trend, with a dominant shift toward the "Good" and "Very Good" categories. These results confirm that AR-MO effectively enhances students' engagement and attitudes toward chemistry learning, regardless of differences in initial backgrounds. The findings support theories of active engagement and conceptual learning, in which interactive AR visualization strengthens concrete, meaningful understanding of abstract concepts. These results are consistent with previous studies indicating that AR can significantly improve students' attitudes and learning experiences [7], [8], [9]. Practically, AR-MO creates a more engaging and interactive learning environment that fosters students' motivation and overall academic achievement.

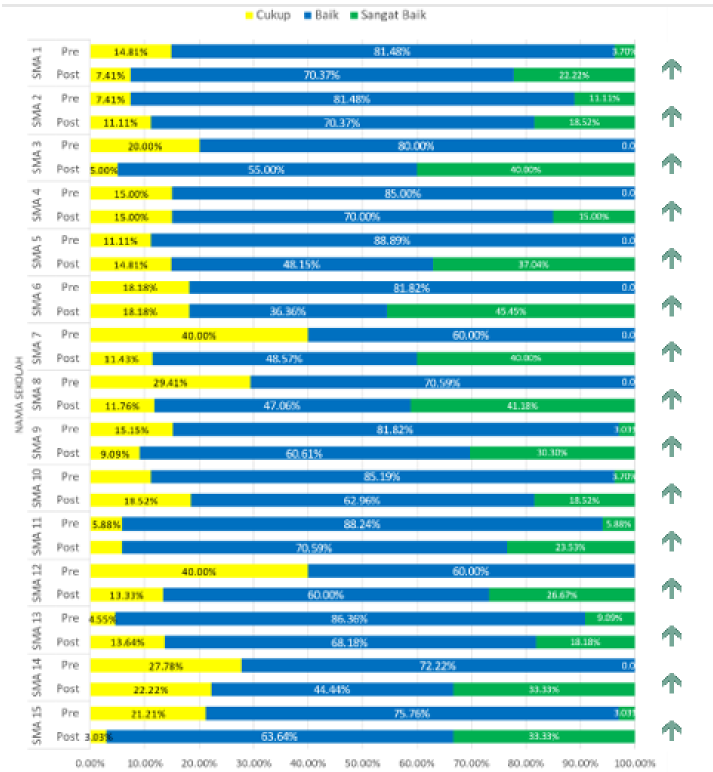

Figure 7. Pre- and Post-Implementation Assessment Graph of AR-MO on the Daily Journal Indicator
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' Attitudes Based on the Self-Assessment Indicator in Molecular Shape Learning Using the AR-MO Model

The AR-MO model shows a consistent improvement in students' self-assessment across all schools, with no decrease in average scores. SMA 14 and SMA 11 successfully eliminated the "Fair" category entirely, with all students shifting to the "Good" category. SMA 14 recorded the most significant improvement, with 27.78% of students moving from "Fair" to "Good," reaching 100% in that category. SMA 7 and SMA 11 achieved the highest scores (3.39), indicating substantial improvement in students' self-confidence. These results confirm that AR-MO is effective in enhancing students' self-awareness and self-evaluation. This supports social and cognitive learning theories, where active engagement through AR visualization encourages self-reflection and confidence in personal competence.

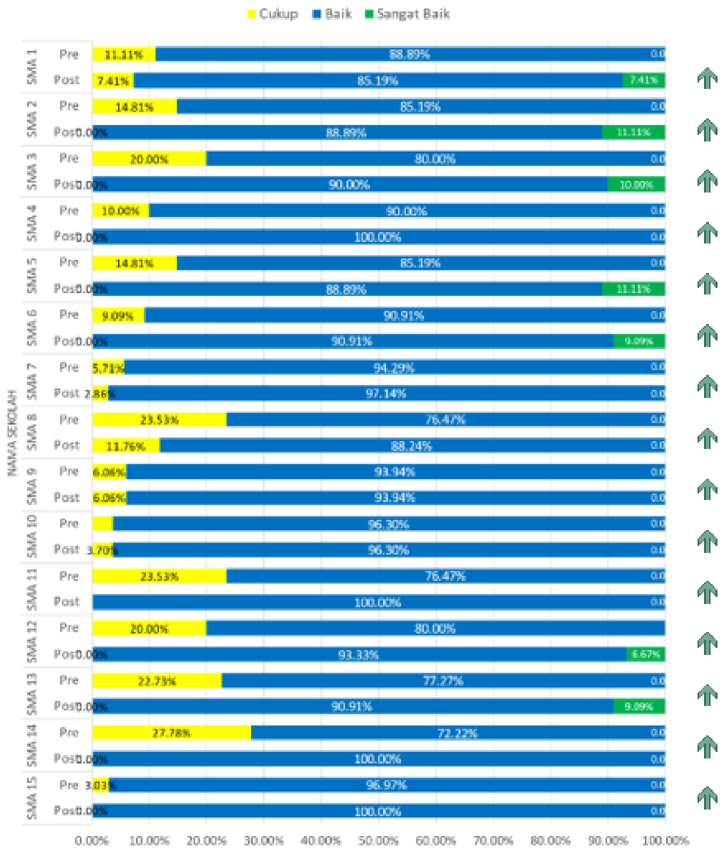

Figure 8. Pre- and Post-Implementation Assessment Graph of AR-MO on the Self-Assessment Indicator
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' Attitudes Based on the Peer Indicator in Molecular Shape Learning Using the AR-MO Model

The implementation of the AR-MO model demonstrates consistent effectiveness in improving student interaction and collaboration. All 15 schools experienced a shift from the "Fair" category to the "Good" and "Very Good" categories on the peer indicator. SMAN 3 and SMAN 13 nearly eliminated the "Fair" category entirely, with most students moving into the "Good" category. SMA 7, 8, 11, and 12 recorded significant increases, with average scores rising from approximately 2.80–2.85 to 3.39. SMA 3 and SMA 13 also showed sharp increases in the percentage of the "Good" category, from 65% and 77.27% to 95%, respectively. The majority of schools demonstrated a consistent upward trend, indicating that the AR-MO model successfully creates a more collaborative and interactive learning environment. Theoretically, these findings support collaborative learning and constructivist theories, which emphasize the importance of social interaction in knowledge construction. AR technology enables students to work together in exploring concepts, thereby strengthening the learning experience.

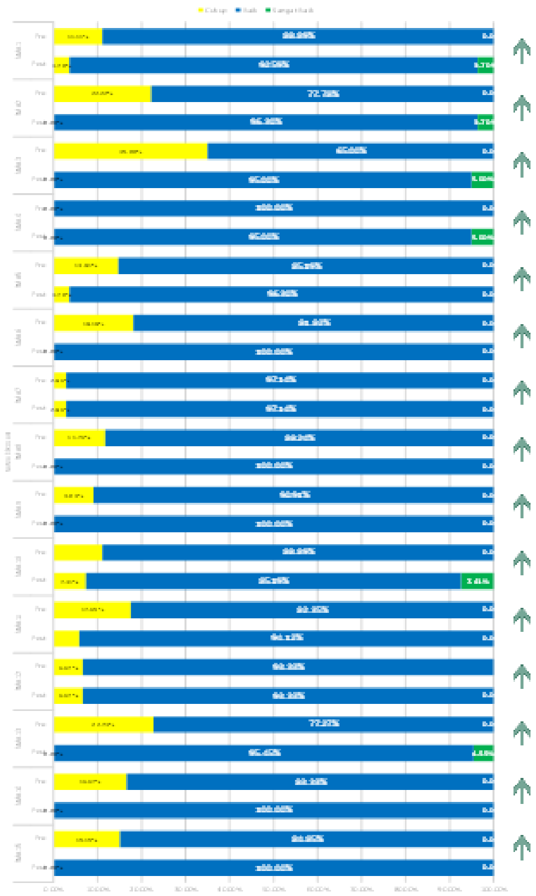

Figure 9. Peer Assessment Graph (Pre- and Post-Implementation of AR-MO) on the Peer Indicator
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' Skills in Molecular Shape Learning Using the AR-MO Model

The AR-MO model has proven effective in improving students' skills across all 15 senior high schools, with a shift from the "Fair" category to the "Good" and "Very Good" categories and no decline in average scores. Although initial levels varied, all schools demonstrated significant improvement after implementation. Theoretically, these findings support the notion that interactive visualization through AR strengthens students' practical skills in understanding and applying chemical concepts. Practically, AR-MO creates a more applicable learning experience and promotes active engagement in chemistry learning.

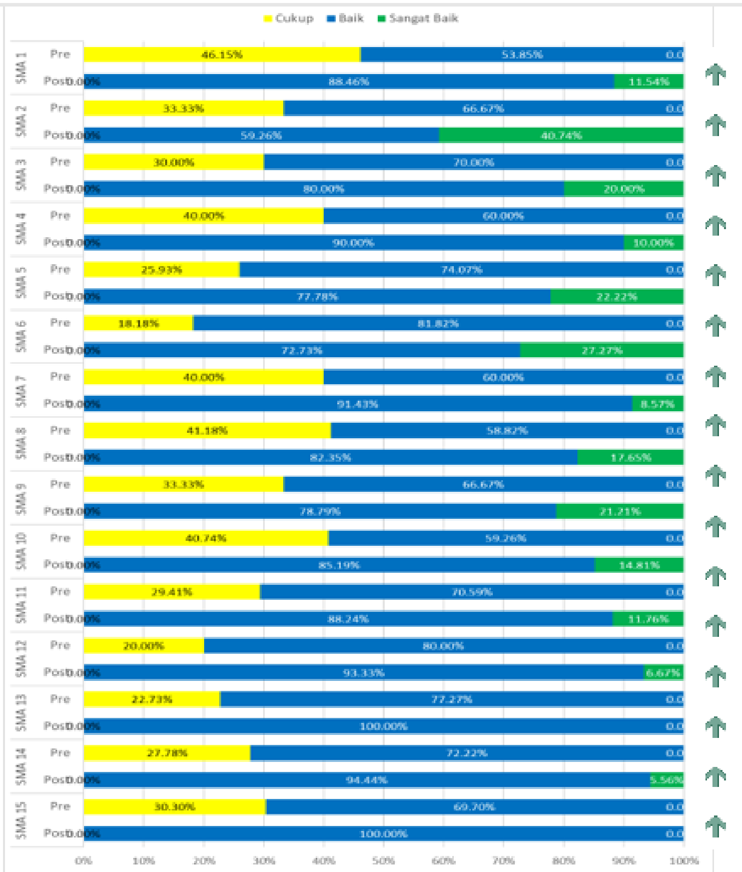

Figure 10. Pre- and Post-Implementation Assessment Graph of AR-MO on the Skills Variable
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' Skills Based on the Project Indicator in Molecular Shape Learning Using the AR-MO Model

The AR-MO model significantly improved students' skills and project quality across all 15 schools. A consistent shift occurred from the "Poor" and "Fair" categories to the "Good" and "Very Good" categories, with no decline in average scores. SMA 2, 4, and 12 successfully eliminated the lower categories entirely. SMA 2 recorded the highest improvement (66.30 → 91.02). SMA 1 and 4 experienced substantial increases in the "Very Good" category, while other schools, such as SMA 3 and 9, showed consistent upward trends. Theoretically, these findings support the view that AR enhances conceptual understanding and project outcomes through interactive visualization. Practically, AR-MO has proven effective in improving the quality of students' chemistry projects and encouraging active engagement in learning.

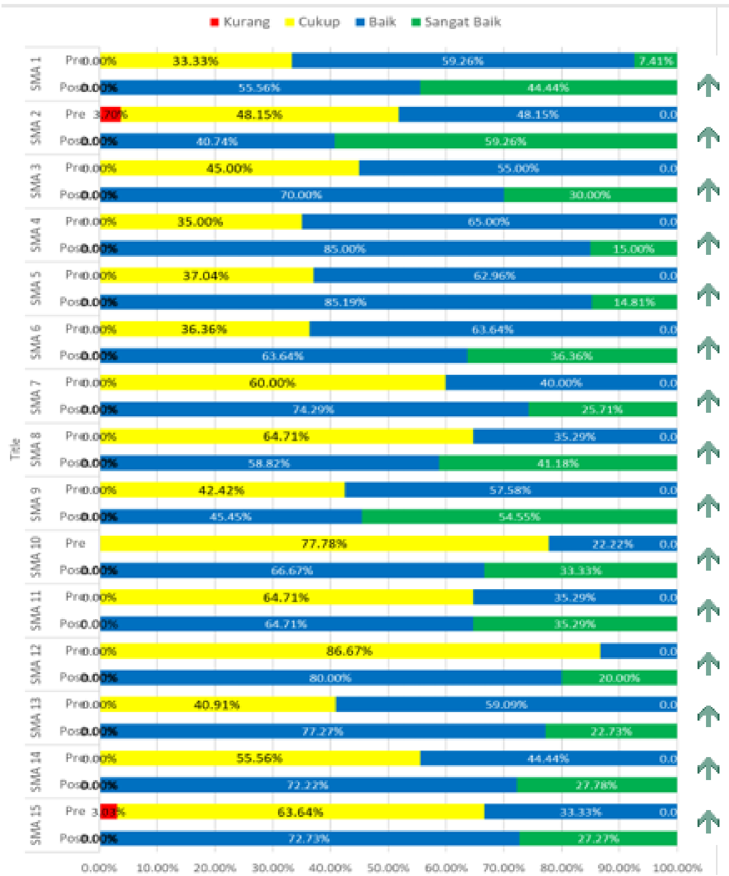

Figure 11. Pre- and Post-Implementation Assessment Graph of AR-MO on the Project Indicator
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' Skills Based on the Portfolio Indicator in Molecular Shape Learning Using the AR-MO Model

The AR-MO model significantly improved students' ability to manage and present portfolios across all 15 schools. There was a shift from the "Fair" category to the "Good" and "Very Good" categories, with no decline in average scores. SMA 3, 9, and 13 successfully reduced the proportion of students in the "Fair" category, with the majority moving to higher categories. SMA 9 recorded the highest increase (2.80 → 3.40), followed by SMA 12, which reached a score of 3.43 from an initial 2.75. Other schools, such as SMA 3 and 13, also showed consistent improvement trends. These findings indicate that AR-MO effectively enhances the quality of students' portfolios through a visual and interactive approach. Theoretically, the results support the view that experiential and interaction-based learning, as facilitated by AR, strengthens students' understanding and presentation skills [6], [9]. Practically, AR-MO can be used as a learning tool to improve students' ability to document, reflect on, and present their learning outcomes in a more structured and engaging manner.

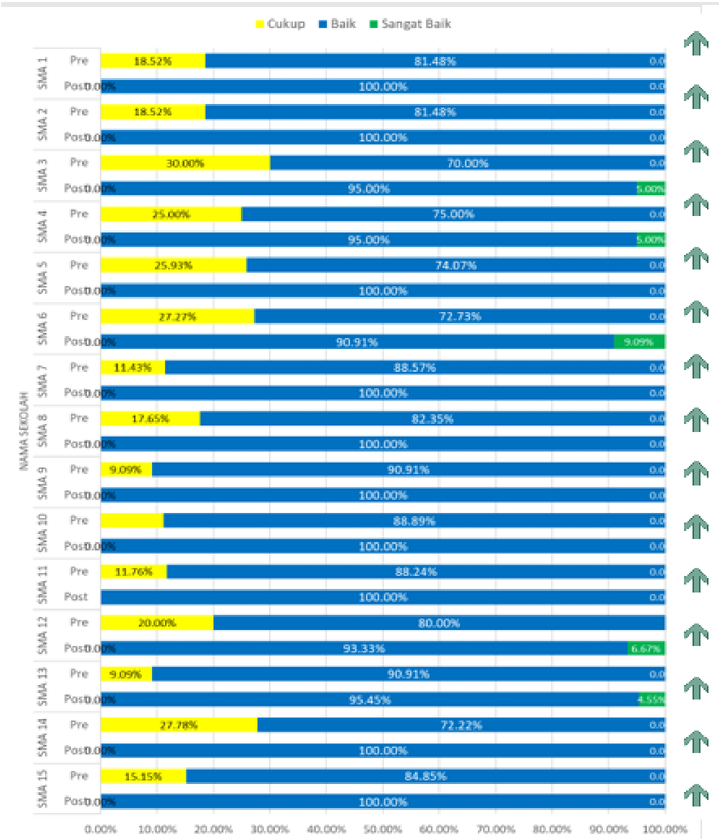

Figure 12. Pre- and Post-Implementation Assessment Graph of AR-MO on the Portfolio Indicator
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' Skills Based on the Practice Indicator in Molecular Shape Learning Using the AR-MO Model

The AR-MO model significantly improved students' practical skills across all 15 schools. A shift occurred from the "Fair" category to the "Good" and "Very Good" categories, with no decrease in average scores. SMA 12 successfully eliminated the "Fair" category, while SMA 6 recorded the highest improvement (75.23 → 91.14). The "Very Good" category increased notably in SMA 6 (45.45%) and SMA 12 (26.67%). SMA 2 also showed consistent improvement, with 37.04% of students reaching the "Very Good" category. Despite variations in initial distributions, all schools demonstrated an upward trend. This indicates that AR-MO is effective in improving practical skills regardless of students' initial abilities. Theoretically, these results support constructivist theory, which posits that active, visually based learning strengthens understanding and applied skills. AR has been shown to enrich learning experiences and enhance practical competencies [6], [9]. In practice, AR-MO can be integrated as an effective strategy in competency-based science learning, particularly in chemistry topics that require strong practical skills.

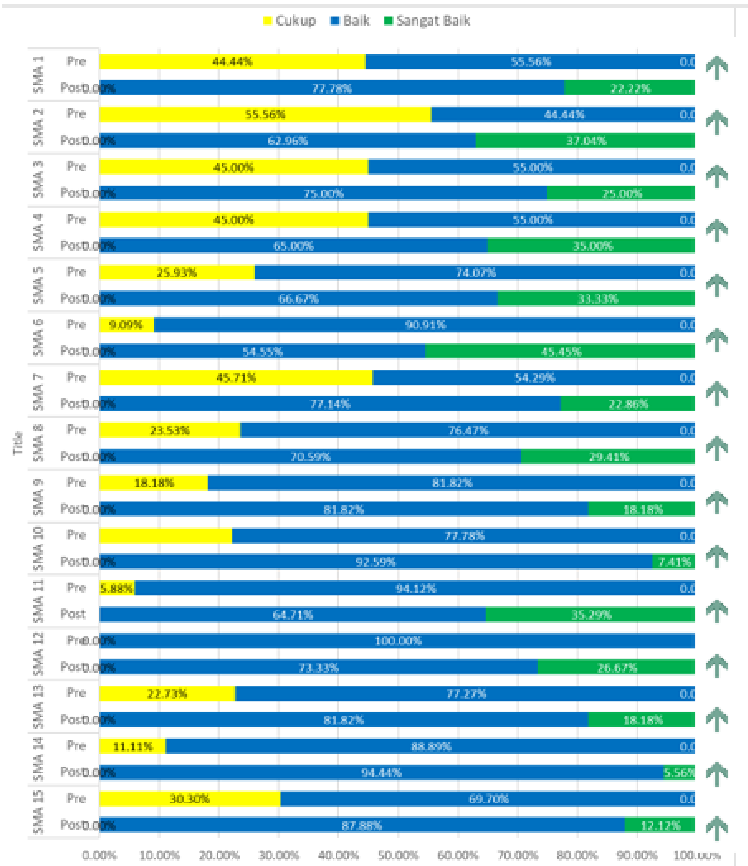

Figure 13. Pre- and Post-Implementation Assessment Graph of AR-MO on the Practice Indicator
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' Skills Based on the Product Indicator in Molecular Shape Learning Using the AR-MO Model

The AR-MO model demonstrates significant effectiveness in improving the quality of students' products. All schools experienced an increase in average scores, with no decline, alongside a shift from the "Fair" category to the "Good" and "Very Good" categories. SMA 2 reduced the "Fair" category from 55.56% to only 3.7%. SMA 3 recorded the highest increase, from 70.00 to 86.00 (an increase of 16 points). SMA 6 had the highest proportion in the "Very Good" category (45.45%), followed by SMA 3 (30%). SMA 1 and SMA 2 showed consistent improvement trends in both the "Good" and "Very Good" categories. These findings indicate that AR-MO can improve product quality consistently across different school contexts. Theoretically, this supports the idea that interactive AR visualization strengthens the understanding of abstract chemical concepts, thereby producing higher-quality outputs [6], [9].

Figure 14. Pre- and Post-Implementation Assessment Graph of AR-MO on the Product Indicator
Source: Processed by the Researcher (2024)

Descriptive Analysis of Students' IT Usage in Learning Molecular Geometry Using the AR-MO Model

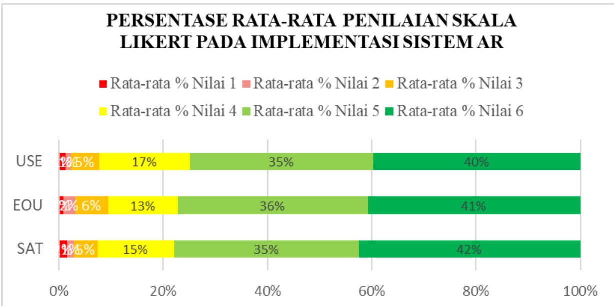

Figure 15. Average Percentage of Likert Scale Ratings in the Implementation of AR-Based Sisains
Source: Processed by the researcher (2024)

The evaluation results indicate that the majority of students responded positively to the AR-MO model. In the SAT (Satisfaction) category, 42% of students assigned the highest score (6), followed by 35% who expressed agreement. The EOU (Ease of Use) category showed a similar pattern, with 41% "strongly agreeing" and 36% "agreeing." Meanwhile, in the USE (Usability) category, 40% of students "strongly agreed," and 35% "agreed." Overall, most students found AR-MO satisfying, easy to use, and useful, with the highest scores on scales 6 and 5. Theoretically, these findings support the notion that AR enhances learning experiences through visual interaction, thereby strengthening understanding of complex concepts, such as chemical bonding [3]. The implementation of AR-MO met user expectations in both functional and pedagogical aspects. In practice, these results reinforce the strong potential for widespread adoption of AR-MO in secondary education and provide a solid basis for educators and policymakers to integrate AR technology as an effective, student-preferred learning medium.

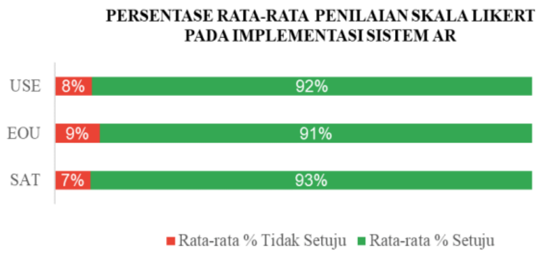

Figure 16. Percentage Chart of User Ratings on the Implementation of AR-Based Sisains

The majority of students responded positively to the implementation of AR-MO. A total of 93% agreed with satisfaction (SAT), 91% with ease of use (EOU), and 92% with system usability (USE). Most respondents assigned high ratings (5 and 6), indicating that AR-MO was very well received. Theoretically, these findings are consistent with the Technology Acceptance Model (TAM), which states that perceived ease of use and usefulness drive technology acceptance [10]. This is also supported by previous studies showing that AR can enhance understanding and learning experiences [3][11]. Practically, the high levels of satisfaction and ease of use indicate that the AR-MO interface design is effective and user-friendly. These results support the use of AR as a learning medium in the chemistry curriculum and guide the development of adaptive features, integration of real-time assessment, and technology-based teacher training.

4. CONCLUSION

In conclusion, the AR-MO instructional model effectively bridges the gap between abstract chemical theories and spatial visualization, significantly improving student outcomes across cognitive, affective, and psychomotor domains. It is effective in improving senior high school students' understanding of molecular geometry concepts, as well as their attitudes and skills. The implementation of AR-MO in 15 public senior high schools in Tangerang resulted in significant improvements in learning outcomes across cognitive (written and oral tests), affective (observations, self-assessments, and daily journals), and psychomotor (practical work, projects, portfolios, and products) domains. The majority of students shifted from the "Fair" category to "Good" and "Very Good" across nearly all measured indicators. In addition to its positive impact on learning achievement, AR-MO also received highly favorable user responses. More than 90% of students reported satisfaction (SAT), perceived the system as easy to use (EOU), and considered it useful (USE). However, several limitations must be acknowledged. First, the successful implementation of AR-MO depends heavily on infrastructure readiness, including the availability of compatible mobile devices and stable internet access, which may vary across Indonesian regions. Second, there is a critical need for teacher training: while the model is user-friendly, educators need initial pedagogical guidance to integrate immersive technology into their existing lesson plans effectively. Future research should explore the long-term retention of knowledge gained through AR-MO and its scalability in rural educational settings with limited resources.

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