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Development of Smart Ethno-STEM (System of Mobile Augmented Reality Technology) in Organic Chemistry to Enhance Students' Metacognitive Skills and Scientific Literacy

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Abstract: Learning in Stereochemistry still tends to lack contextualization and the integration of technology and ethnosciences. This study aims to develop and evaluate Smart Ethno-STEM (System of Mobile Augmented Reality Technology) as an innovative learning medium in organic chemistry, particularly on stereochemistry topics, to enhance students' metacognitive skills and scientific literacy. The research employed a Research and Development (R&D) design using the ADDIE model, involving validation, practicality, and effectiveness testing. The data were analyzed using descriptive validation and practicality scores, N-Gain, and MANOVA analysis. Validation results from one media expert and two material experts indicated that the media was categorized as highly valid (average score 4.46). Practicality tests conducted with 16 students showed a very practical use (average score of 4.75). The effectiveness test showed significant improvements in both metacognitive skills and scientific literacy, with N-Gain scores in the high category in the experimental group (metacognition 0.75; literacy 0.72) and in the medium category in the control group (metacognition 0.59; literacy 0.57). MANOVA results confirmed a significant influence of the class factor on both variables simultaneously (Sig. Hotelling's Trace = 0.013). These findings demonstrate that Smart Ethno-STEM effectively enhances students' higher-order thinking skills and connects scientific concepts with socio-cultural contexts, offering a contextual and technology-based solution for organic chemistry learning.

Keywords: Augmented reality; Metacognition; Organic chemistry; Scientific literacy; Smart ethno-STEM

Introduction

Higher education during the Industrial Revolution 4.0 and Society 5.0 must cultivate graduates who perform academically and possess 21st-century competencies, including critical thinking, creativity, collaboration, and effective communication (Klaharn et al., 2025; Mingaleva & Vukovic, 2020; Şenyiğit & Bakırcı, 2025). Graduates need to be able to adapt to technological developments (Rodríguez-Abitia & Bribiesca-Correa, 2021) as well as understand the socio-cultural context (Harjono et al., 2025). These challenges are increasingly complex in chemistry education because of the abstract, symbolic, and demanding nature of chemistry (Erlina et al., 2023). One topic that requires a high mastery of spatial visualization skills is stereochemistry in organic chemistry.

Stereochemistry studies the spatial configuration of molecules and three-dimensional isomerization that cannot be represented through two-dimensional text or

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images alone (Wong et al., 2025). The absence of interactive visual teaching media causes students to have difficulty understanding the orientation of molecular space and the relationship between the shape of molecules and their physical properties and biological activities (Echeverri-Jimenez & Oliver-Hoyo, 2023). This difficulty often leads to misconceptions and low learning outcomes among students, especially in aspects of higher-level thinking (Azid et al., 2022) such as metacognition and scientific literacy. Good mastery of stereochemistry is crucial because many real applications, for example in the pharmaceutical, cosmetics, and biotechnology industries, depend on a precise understanding of stereoisomers (Casselman et al., 2021).

Chemistry learning in higher education today still tends to be textual, less contextual, and has not fully utilized the potential of local wisdom as a learning resource (Sumarni, 2023; Wahyudiati & Fitriani, 2021). Traditional Indonesian practices such as the fermentation of natural ingredients, essential oil extraction, and natural coloring processes are rich with authentic and relevant organic chemistry concepts. The use of local wisdom in learning not only serves as a bridge between science and culture, but also strengthens students' identities as learners rooted in local values (Andayani et al., 2021; Foa et al., 2024). The integration of ethnoscience into chemistry learning enriches the student learning context (Fahrozy et al., 2022; Prasetyo et al., 2023), increasing their emotional and cultural involvement in the learning process (Hidayati & Julianto, 2024), as well as fostering an appreciation for the nation's cultural heritage as an integral part of science (Kamaludin et al., 2024).

The significance of this research stems from the pressing necessity for a contextual, collaborative, and technology-driven approach to organic chemistry education while preserving local cultural foundations. Smart Ethno STEM or System of Mobile Augmented Reality Technology is offered as an innovative solution that combines the Ethno STEM approach, namely the integration of arts, culture, science, technology, engineering, and mathematics with the value of local wisdom (Sari et al., 2022) with a mobile system-based augmented reality. This medium allows students to explore the shape of stereochemical molecules interactively and intuitively (Levy et al., 2024). Spatial visualization of molecules through augmented reality encourages conceptual learning while providing a more immersive, active, and reflective learning experience (Parinussa et al., 2024). The use of augmented reality also facilitates the representation of three-dimensional molecular objects (Elford et al., 2021) and supports independent and distance learning (Prasetyo et al., 2025).

The novelty of this research lies in the integration of three main components, namely ethno-STEM, augmented reality, and stereochemical concepts, in one digital technology-based learning media. The use of local wisdom as a context for organic chemistry learning, not only as a complement, but as a major part of the scientific exploration process. Strengthening metacognitive competencies and scientific literacy are the main indicators in 21st-century education and are one of the focuses in the indicators of higher education graduate achievement (Chestnut & Johnson, 2025; Shagrayeva et al., 2025).

The Smart Ethno STEM approach is directed at strengthening students' metacognition skills, namely the ability to plan, monitor, and evaluate their own thought processes, which is a very important competency in mastering complex organic chemistry (Prasetyo et al., 2023). Strengthening sciemntific literacy is also the main target because students need to be able to relate scientific concepts to social and cultural contexts, understand scientific processes holistically, and participate in science-based decision-making in real life (D. Eliza et al., 2025). The findings of this study are expected to yield a learning paradigm that is not only novel and contextual, but also applicable to global and local concerns. Smart Ethno STEM is intended to serve as a bridge between the intricacies of modern science and traditional knowledge, as well as between digital technology and human values, aligning with the path of higher education transformation in Indonesia.

Method

This study was conducted between July and September 2025 in the Chemistry Education Study Program, Universitas Lambung Mangkurat. The sample of this study was students enrolled in the Organic Chemsitry course, whereas the development phase involved expert lecturers and students who had already completed the subject.

This research is a Research and Development (R&D) model that is intended to be carried out for a period of one year with the purpose of evaluating the efficacy of a product that has been developed (Rothwell et al., 2015). The product that is generated as a result of this research is in the form of Smart Ethno-STEM learning media. This learning method is intended to assist in the preservation of cultural traditions as a component of the study of chemistry. Branch (2009) states that the ADDIE model, which stands for Analysis, Design, Development, Implementation, and Evaluation, is the model that is referred to as the development process. According Antoñanzas et al. (2023) this particular development model is deemed suitable and pertinent for the purpose of developing tools and

resources for learning. All of the students who are enrolled in the Chemistry Education Study Program at Lambung Mangkurat University and are attending Organic Chemistry classes are included in the research population.

The analysis phase was conducted to ascertain the learning requirements and attributes of pupils as prospective media users. The requirements analysis encompasses the delineation of course learning outcomes pertinent to stereochemistry content. This phase also assesses students' learning challenges, including inadequate comprehension of spatial representation and the correlation between stereochemical ideas and cultural contexts.

The design phase encompasses the organization of the media's structure and content based on the findings of the needs assessment. Design efforts encompass the production of materials and the aggregation of textual, visual, and audiovisual content, along with the preliminary design of augmented reality (Smart Ethno-STEM) media.

The development phase commences with the creation of AR (Smart Ethno-STEM) media in accordance with the established design. The media production approach utilizes Chem3D, Blender, Open Babel UI, and Unity tools to create a three-dimensional model of stereoisomers that is more realistic, interactive, and navigable. The original product was subsequently validated by three evaluators: one media expert from a computer science education background and two material experts from a chemical education background.

The implementation phase is conducted through multiple trial stages to assess the efficacy of media within the framework of actual learning. A small group experiment engaged 8 fifth-semester chemistry education students to evaluate the comprehension and applicability of the media. Additionally, a field trial was conducted utilizing an experimental design, comprising 16 students in the experimental group and 16 students in the control group from the third semester.

The evaluation phase is conducted both formatively and summatively, informed by the trial outcomes and students feedback as users. Formative review occurs at each revision stage to enhance the content and presentation of the media, and summative evaluation is conducted post-completion to evaluate overall viability. The examination of the merits and demerits of media pertains to student feedback about the utilization of augmented reality and the integration of ethnoscience.

Data were gathered utilizing questionnaire methodologies and testing approaches. The questionnaire method was employed to gather data concerning the validity of the media and the practicality of Smart Ethno-STEM media. The media is endorsed by three specialists: one media expert and two educational professionals. The validated aspects are content feasibility, language utilization, instructional design, and media quality. The efficacy of Smart Ethno-STEM media products is assessed using data from student response questionnaires, the application of teaching materials, and feedback from lecturers. We conducted the evaluation thrice, specifically during small group trials, field tests, and operational trials, using a Likert scale ranging from 1 to 5. The testing method was employed to gather data on media effectiveness, specifically for metacognitive skills and scientific literacy.

Metacognitive skills were assessed using descriptive problem-based assessments (Antoñanzas & Salavera, 2023; Prasetyo et al., 2023). The measurement concentrates on five facets of metacognitive skills: representation, planning, monitoring, evaluation, and transfer skills (Syahmani et al., 2020). The scientific literacy instrument was created by modifying the OECD PISA 2018 framework, encompassing three primary dimensions: scientific knowledge (conceptual, procedural, and epistemic), scientific competence (the capacity to elucidate phenomena, assess investigations, and interpret data), and the application of science in real-world contexts (OECD, 2019). This instrument also considers the characteristics of scientific attitudes, including curiosity, openness to evidence, and knowledge of socio-science challenges (Sadler & Zeidler, 2009). This instrument was created as questionnaires and problem-based assessments, adapted to the educational setting of organic chemistry and ethnoscience practices rooted in local knowledge.

Table 1. Validity and Practicality Criteria of Smart Ethno-STEM Media

Validity	Interval	Practicality	Interval
Highly Valid	$4.25 \leq V < 5.00$	Very Practical	$4.25 \leq P < 5.00$
Valid	$3.50 \leq V < 4.25$	Practical	$3.50 \leq P < 4.25$
Quite Valid	$2.75 \leq V < 3.50$	Quite Practical	$2.75 \leq P < 3.50$
Less Valid	$1.75 \leq V < 2.50$	Less Practical	$1.75 \leq P < 2.50$
Invalid	$1.00 \leq V < 1.75$	Impractical	$1.00 \leq P < 1.75$

This study employs a data analysis technique that integrates qualitative and quantitative descriptive methods. Descriptive statistical analysis is employed to evaluate data from the product validation process, conducted via expert judgment to characterize the quality of learning outcomes, referencing adapted criteria from (Nieveen, 1999), which encompasses relevance (content validity), consistency (construct validity), and practicality (ease of use). The validation of developmental products encompasses several elements, including Smart Ethno-STEM media, instructional materials, Semester Learning Plans, and assessment

tools. The validity and practicality of the product were assessed descriptively (Syahmani et al., 2017) and are presented in Table 1.

The effectiveness of Smart Ethno-STEM was analyzed using descriptive statistical analysis techniques in the form of percentages, as well as normalized gain score tests (Hake, 1998). Improvements in each skill are analyzed based on specific criteria detailed in Table 2.

Table 2. Criteria for Improving Metacognitive Skills and Scientific Literacy

N-gain	Category
(g) > 0.7	High
0.3 < (g) ≤ 0.7	Middle
(g) ≤ 0.3	Low

The effectiveness data were subsequently evaluated using inferential statistics through a one-tailed test to evaluate the impact on enhancing creativity and literacy within the educational setting. The testing phases comprise: a) a normality assessment conducted via SPSS software utilizing the Mahalanobis test; b) a homogeneity of variance examination to ascertain the equivalence of variance among group pairs, analyzed through Box's M test; and c) a MANOVA test to evaluate the enhancement in N-gain of metacognitive skills and scientific literacy among students in both the experimental and control groups.

Result and Discussion

The development process employs the ADDIE model, encompassing the stages of analysis, design, development, implementation, and evaluation. This model was selected for its capacity to offer a systematic framework for the design, validation, and testing of learning media in stages, ensuring that the final products align with user requirements and academic standards.

The analysis phase was conducted to ascertain the learning requirements and attributes of pupils as prospective media users. The requirements analysis encompasses the delineation of course learning outcomes pertinent to stereochemistry content. This phase also assesses students' learning challenges, including inadequate comprehension of spatial representation and the correlation between stereochemical ideas and cultural contexts. The findings of this investigation inform the construction of augmented reality-based Smart Ethno-STEM media, anticipated to deliver interactive, contextual, and competency-based learning experiences.

The design phase encompasses the organization of the media's structure and content based on the findings of the needs assessment. Design efforts encompass the production of materials and the aggregation of textual, visual, and audiovisual content, along with the preliminary design of augmented reality (Smart Ethno-STEM) media. The incorporation of ethnoscience aspects involves linking the chemical culture of the Banjar people, as shown by the practice of batimung bathing with spices that contain chiral flavonoid chemicals. Students participate in projects aimed at identifying compounds rooted in Banjar culture, assessing their chiral qualities, and producing pertinent visual representations (Ranuharja et al., 2021).

The development phase commences with the creation of AR (Smart Ethno-STEM) media in accordance with the established design. The media production approach utilizes Chem3D, Blender, Open Babel UI, and Unity tools to create a three-dimensional model of stereoisomers that is more realistic, interactive, and navigable. The original product was subsequently validated by three evaluators: one media expert from a computer science education background and two material experts from a chemical education background. The validation results serve as a foundation for revision, ensuring the medium possesses high validity prior to student testing (Ding & Toran, 2025).

The implementation phase is conducted through multiple trial stages to assess the efficacy of the media within the framework of actual learning. A small group experiment engaged 20 fifth-semester chemistry education students to evaluate the comprehension and applicability of the media. Additionally, a field trial was conducted utilizing a quasi-experimental design with a non-equivalent control group design, comprising 16 students in the experimental group (using Smart Ethno-STEM learning media) and 16 students in the control group (using direct instruction) from the third semester. Changes occur after each phase of the trial: the preliminary post-test, the principal trial, and the operational test. This implementation method ensures the medium's technical operation and its successful enhancement of students' metacognition and scientific literacy skills.

The evaluation phase is conducted both formatively and summatively, informed by the trial outcomes and students' feedback as users. Formative review occurs at each revision stage to enhance the content and presentation of the media, and summative evaluation is conducted post-completion to evaluate overall viability. The examination of the merits and demerits of the media pertains to student feedback about the utilization of augmented reality and the integration of ethnoscience. This assessment ascertains whether Smart Ethno-STEM has successfully enhanced students' metacognition and scientific literacy and evaluates its feasibility for broader implementation in organic chemistry education.

Smart Ethno-STEM learning media was developed to provide an interactive, contextual, and three-dimensional visualization-based learning experience. The app helps students explore stereochemical models directly through mobile devices, so abstract concepts can be visualized more clearly. The appearance of several media pages is presented in Figure 1.

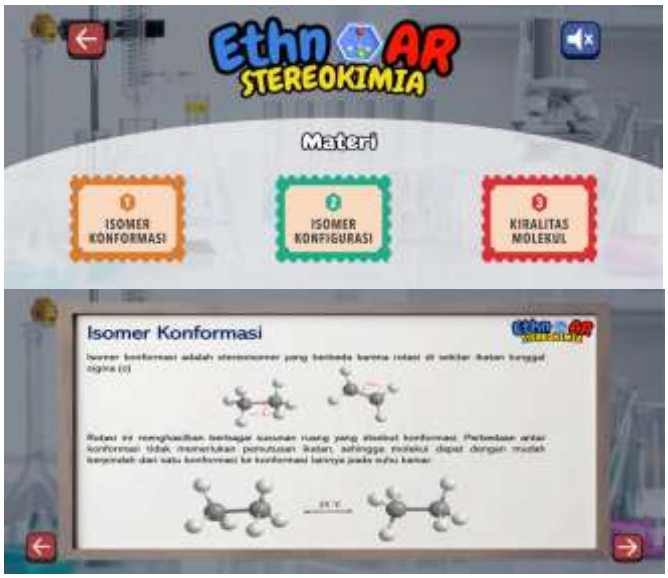

Figure 1. Display of Smart Ethno-STEM learning media interface for stereochemistry visualization

The integration of ethnoscience into stereochemistry highlights how molecular structures are embedded in cultural practices and local traditions (Ardyansyah, 2024). In the context of Banjar culture, for instance, the traditional "*mandi batimung*" ritual employs herbs and spices such as kaffir lime leaves, cloves, lemongrass, and turmeric, many of which contain chiral compounds like limonene, menthol, and citronellal (Almubarak et al., 2024; Prasetyo et al., 2023). These compounds exhibit stereochemical properties that determine their aroma, physiological effects, and cultural significance. By linking stereochemistry to traditional practices, students can appreciate how chiral molecules function both as scientific entities and as part of cultural heritage. This ethno-perspective situates stereochemistry as a discipline that connects molecular theory with the lived experiences and wisdom of local communities (Junaidi et al., 2025).

The Smart Ethno-STEM augmented reality (AR) media embeds the STEM process within stereochemistry learning, allowing students to engage in scientific inquiry, technological application, engineering design, and mathematical reasoning simultaneously (Amanah et al., 2025; Zan & Asrizal, 2024). In the science aspect, students analyze stereochemical concepts such as chirality, R/S configuration, and optical activity. Through technology, they utilize AR platforms and molecular modeling software to visualize and manipulate three-dimensional molecular structures. The engineering dimension is emphasized when students design and construct models, whether digitally or physically, by selecting appropriate materials, colors, and spatial orientations to represent chiral centers (Rasyid et al., 2024; Zan & Asrizal, 2024). The mathematics component is integrated through quantitative analysis, such as determining the number of stereoisomers, calculating bond angles, or interpreting optical rotation data. Together, these STEM components ensure that learning stereochemistry through AR media is comprehensive, contextual, and reflective of authentic scientific practices (Reyes & Villanueva, 2024).

This study's results reveal conclusions derived from a sequence of development procedures and the implementation of Smart Ethno-STEM learning media concerning stereochemistry materials. The study centers on three primary aspects: validity, practicality, and effectiveness, which serve as the criteria for assessing the quality of a learning product. The three characteristics are methodically presented to offer a full picture of the feasibility, use, and influence of the media on enhancing students' metacognitive skills and scientific literacy.

Validity of Smart Ethno-STEM media

The validity of Smart Ethno-STEM learning media was assessed by three validators consisting of two material experts and one media expert. The validation process is carried out to ensure the suitability of content, display quality, and the feasibility of media used in stereochemical learning. The assessment covers four main aspects, namely learning design (content), software functionality and engineering, visual and aesthetic communication, and interactivity. The results of the assessment of these experts are presented in Table 3.

Table 3. Expert Validation Results of Smart Ethno-STEM Learning Media

Aspects	Value	Category
Learning Design (Content)	4.53	Highly Valid
Functionality & Software Engineering	4.33	Highly Valid
Visual & Aesthetic Communication Aspects	4.42	Highly Valid
Interactivity	4.56	Highly Valid
Average	4.46	Highly Valid

The Learning Design (Content) aspect obtained an average score of 4.53 with a very valid category. The assessment shows that the content of stereochemical material is in accordance with the set competencies, including basic concepts, molecular representations, and real applications in the fields of pharmaceuticals, cosmetics, and biotechnology. The accuracy of the

material and the integration between theory and practice are considered very good by material experts.

The Functionality and Software Engineering aspect obtained a score of 4.33 in the very valid category. The media is considered stable on mobile devices, the navigation feature is responsive, and the system can be run without significant interruptions. The performance of the software supports the student learning process, especially since the application allows quick access to stereochemical 3D models. This makes the learning experience more efficient and supports optimal visual exploration of molecules (Habibi & Agustini, 2022).

The Visual and Aesthetic Communication aspect obtained an average score of 4.42 with a very valid category. The graphical display is judged to be consistent, the color selection is aligned, and the information layout supports the user's focus on molecular visualization. Illustrations displayed through AR reinforce spatial understanding and maintain student engagement. Detailed visualization makes abstract stereochemical material easier to understand and aesthetically appealing (Halawa et al., 2022; Lutfi et al., 2023).

The Interactivity aspect obtained the highest score of 4.56 with a very valid category. Media encourages active student engagement because each molecule can be rotated, magnified, and analyzed directly through AR. The app's high response rate allows students to explore seamlessly, resulting in a more immersive learning experience (Asda et al., 2022). Suggestions for improvement are focused on aspects of learning design and media display. Visual appearance is recommended to be refined through more adaptive layout consistency and color selection, so that the appeal of the media is more optimal. Based on the results of the overall assessment, the average media validity score of 4.46 is included in the very valid category. These findings confirm that Smart Ethno-STEM learning media based on mobile augmented reality is suitable for use as a means of supporting stereochemical learning.

Practicality of Smart Ethno-STEM Media

The results of the practical test of the Smart Ethno-STEM learning media were obtained through a student response questionnaire. The trial was conducted in small groups and field tests by assessing aspects of ease of use, visual appearance, navigation, language, feature support, and feedback clarity. This assessment aims to find out the extent to which media can be used effectively by students in stereochemistry learning (Maasawet et al., 2023; Umamah et al., 2023). The results of the practicality are presented in Table 4.

Table 4. Results of Practicality Test of Smart Ethno-STEM Learning Media Based on Student Responses

Statement	Small Groups	Field Group
The app is easy to use, and the navigation is clear.	4.25	4.56
The augmented reality feature helped me understand the concept of organic chemistry better.	4.63	4.81
The app's appearance is interesting and makes me interested in learning.	4.50	4.56
The material presented in the app is easy to understand.	4.63	4.81
This app improved my metacognition skills in learning chemistry.	4.38	4.81
This app helped improve my science literacy.	4.75	4.81
The application loading time is fast and does not interfere with the learning process.	4.75	4.88
I feel more motivated to learn organic chemistry by using this app.	4.63	4.75
The instructions for using the app are clear and easy to follow.	4.63	4.63
I want to use this application as a learning medium on a regular basis.	4.75	4.88
The app is easy to use, and the navigation is clear.	4.59	4.75

The average score of the practicality test in the small group was 4.59, while in the field test it increased to 4.75. This value indicates that the media is in the category of very practical to use. Aspects that score high include visual display, language clarity, and accessibility on various devices. These results indicate that media is not only easy to understand, but also provides convenience in its use, thus encouraging student motivation to learn.

The interactive features provided, such as quizzes and exercises with feedback, are quite helpful for students in understanding the concept of stereochemistry. The ease of navigation of the menu and the speed of access to content are important points that are appreciated. In addition, the presence of a feature that connects students with scientific information from various sources expands their horizons contextually (F. Eliza et al., 2023; Firman et al., 2024; Istyadji et al., 2022). The students' recommendation to use this media more broadly also shows positive acceptance and high utilization potential in learning organic chemistry.

Effectiveness of Smart Ethno-STEM media

The effectiveness of Smart Ethno-STEM learning media is reviewed from two main variables, metacognitive skills and scientific literacy. The instruments used are validated first before being used for the evaluation of the developed media (Radeswandri et al., 2021). Validation of the content of the instrument showed that all items in the metacognitive variable (5 items) were declared to be very valid. In the scientific

literacy variable, five items included in the category were very valid and two items were considered valid, so that all items could be used for measurement. These results show that the question items are in accordance with the measured indicators and are relevant to the research objectives.

Construct validation indicates that all items in metacognition are valid, however in scientific literacy, item number 3 is deemed invalid. The instrument's reliability demonstrated strong consistency, with a Cronbach's Alpha of 0.742 for scientific literacy and 0.768 for metacognition. This value verifies that the instrument possesses a sufficient degree of dependability for utilization during the assessment of learning media efficacy. The validated instrument is subsequently employed for field tests (Elangovan & Sundaravel, 2021; Susilawati et al., 2023; Kalkbrenner, 2021). Table 5 below presents the summary of the pretest-posttest for the control and experimental class.

Table 5. Summary of Pretest and Posttest Results in Control and Experimental Classes

Variable	Test	Control	Experiment
Metacognitive	Pretest	37.00	36.75
	Posttest	74.00	84.50
Science Literacy	Pretest	34.88	35.25
	Posttest	71.88	81.81

The efficacy test findings on metacognitive skills indicated a substantial enhancement in both the control and experimental groups. The control group's pretest score averaged 37.00 and rose to 74.00 on the posttest. The experimental group exhibited an increase in scores, rising from 36.75 on the pretest to 84.50 on the posttest. The findings on scientific literacy indicated a notable upward tendency, albeit it exhibited a distinct pattern compared to the metacognitive variable. The control group's pretest score was 34.88, which marginally climbed to 35.25 in the posttest. The experimental group exhibited a significant rise from 71.88 in the pretest to 81.81 in the posttest. These results were further evaluated using the n-gain formula to test the effectiveness of the media as shown in Figure 2.

The assessment of N-gain in metacognitive skills revealed that the control group achieved a score of 0.59, categorizing it as medium, but the experimental group attained a score of 0.75, placing it in the high category. The distinction in categories highlights the efficacy of Smart Ethno-STEM media in enhancing students' self-regulation in the study of stereochemistry. Augmented reality-based spatial visualization enhances the learning experience, enabling students to cultivate cognitive strategies, assess their comprehension, and optimize their learning outcomes more effectively than those in the control group (Chen et al., 2023; Mostowfi et al., 2023).

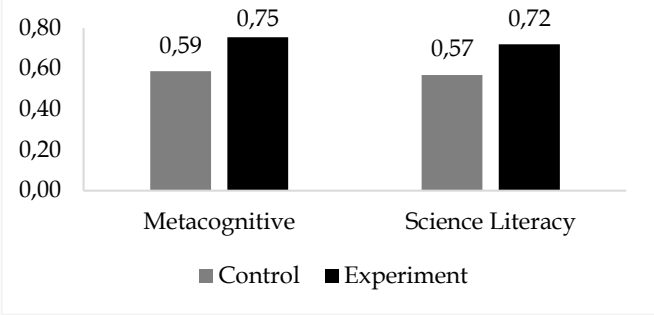

Figure 2. N-gain test

The N-gain outcomes in scientific literacy revealed substantial disparities between the two groups. The control group attained a score of 0.57 in the medium category, but the experimental group secured a score of 0.72 in the high category. This accomplishment demonstrates that the incorporation of ethnoscience in Smart Ethno-STEM learning media effectively connects the principles of organic chemistry with social and cultural contexts. Students can connect it to real phenomena, making the development of scientific literacy more critical, contextual, and pertinent to everyday life (Asyri & Asyri, 2024; Auralia & Juliani, 2024; Fatih et al., 2024; Saputra & Octavia, 2024).

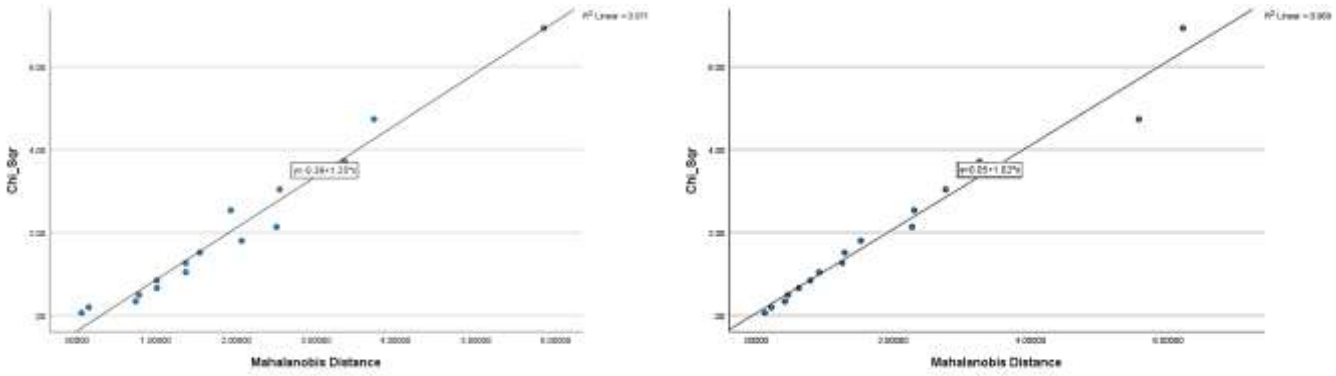

Figure 3. Normality test

The N-gain calculation results were further reinforced using inferential statistical analysis using the MANOVA test. The preliminary phase involves evaluating fundamental assumptions, specifically the normalcy test and the homogeneity test. The normality test evaluates whether the data follows a normal distribution, whereas the homogeneity test assesses the similarity of variance among groups (Hernandez, 2021; Zhou et al., 2023). The satisfaction of these two assumptions is a crucial requirement prior to conducting the mean difference test using an independent t-test. The results of the normality test are shown in Figure 3.

The normality test results, as indicated by the Normal P–P Plot graph comparing the Chi-Square value and the Mahalanobis Distance, reveal that the data points in both the control and experimental groups predominantly align along a diagonal line. This indicates that the data distribution in both groups approximates a normal distribution. The determination coefficient (R^2) was 0.971 for the control class and 0.982 for the experimental class, both indicating a high degree of correlation that supports the conclusion of normal data distribution (Hernandez, 2021). The assumption of normality is fulfilled in both groups so that the data are feasible to use for the homogeneity test shown in Table 6.

The outcomes of the homogeneity test, employing Box's Test of Equality of Covariance Matrices, indicated a Box's M value of 1.000 with a significance level of 0.819 ($p > 0.05$). This signifies that the covariance matrices among groups are equivalent and that no substantial difference exists. Consequently, the assumption of homogeneity of covariance is satisfied. The results of the assumption tests indicate that the data are normally distributed and satisfy the homogeneity assumption, allowing for the continuation of analysis using the parametric test, specifically the MANOVA test.

Table 6. Homogeneity Test

Statistical Test	Value	Sig.	Decision
Box's Test of Equality of Covariance Matrices	M = 1,000	0.819	$p > 0.05 \rightarrow$ Homogeneity assumption is met

The Multivariate Analysis of Variance (MANOVA) test results indicated a Hotelling's Trace value of 0.352, an F value of 5.099 with degrees of freedom (2, 29), and a significance level of 0.013. A significance value below 0.05 denotes a substantial difference between the control group and the experimental group regarding the combined variables of metacognition and scientific literacy. The data indicate that the intervention administered to the experimental group significantly affects learning outcomes. The disparity signifies that students in the experimental group undergo distinct skill improvement relative to those in the control group (Sulistina & Hasanah, 2024). These results substantiate the argument that the employed learning strategies influence the quality of student accomplishment.

The analysis of the MANOVA results indicates that class factors exert a concurrent influence on the two dependent variables: metacognitive skills and scientific literacy. This indicates that the alterations are not confined just to metacognitive thinking abilities but also extend to students' competencies in comprehending and implementing scientific topics. The correlation between these two variables indicates that the learning tactics employed in the experimental class facilitate a more holistic learning experience. Students are encouraged to manage their cognitive processes and are also required to connect that understanding to pertinent scientific literacy (Cahyana et al., 2023). The concurrent effect reinforces the assertion that instructional interventions can enhance student learning outcomes more effectively than the learning implemented in the control group.

Conclusion

The development of Smart Ethno-STEM learning media via mobile augmented reality has been demonstrated to be legitimate, practical, and effective for organic chemistry education, especially in the area of stereochemistry. Expert validation affirmed that the medium adhered to elevated standards of content correctness, functionality, aesthetics, and interactivity. Practicality assessments revealed that students perceived the media as user-friendly, interesting, and conducive to autonomous learning. The effectiveness study revealed substantial enhancements in metacognitive skills and scientific literacy, with the experimental group N-gain scores in the high category, while the control group was in the medium category. MANOVA results further validated that the class factor significantly impacted the combined variables, indicating that Smart Ethno-STEM promotes the concurrent development of higher-order thinking skills and scientific literacy. These findings underscore the possibility of amalgamating augmented reality with ethnoscience contexts to develop participatory, culturally pertinent, and technologically enriched learning experiences in higher education. Therefore, media integrating augmented reality and ethnoscience is highly recommended for application in other courses to enhance metacognitive skills and scientific literacy, as well as a sense of pride in the culture that develops in society.

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Conflicts of Interest
The authors declare that there are no conflicts of interest regarding the publication of this article.

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