



Development and validation of chemarine: An augmented reality learning application for maritime chemistry education based on IMO model course 7.04

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Abstract

Background: Students in maritime chemistry courses often experience difficulty understanding abstract chemical concepts because many microscopic chemical processes cannot be directly visualized using conventional instructional materials. This challenge highlights the need for interactive learning media aligned with the competency requirements of the IMO Model Course 7.04.

Purpose: This study aimed to develop ChemARine (Chemistry Augmented Reality of Marine), an Augmented Reality (AR)-based learning application for maritime chemistry, and to evaluate its content validity, media validity, and practical usability.

Methods: A Research and Development (R&D) approach using the ADDIE model was employed. ChemARine was developed as a marker-based Android AR application using Unity and the Vuforia Engine. Content and media validity were evaluated by expert validators, while a limited implementation involving 43 maritime engineering students assessed the application's practicality.

Result: Expert validation yielded scores of 93.33% for content and 97.91% for media quality, both classified as very valid. Student responses produced a practicality score of 84.45%, indicating very good usability. Expert and user feedback was incorporated to improve the interface, three-dimensional visualization, explanatory content, marker recognition, and application performance.

Conclusion: ChemARine is a feasible and practical AR learning application for maritime chemistry aligned with the IMO Model Course 7.04. The study demonstrates that competency-based maritime chemistry content can be systematically integrated into a marker-based AR learning environment. Further experimental or quasi-experimental studies are required to evaluate its effectiveness in improving students' conceptual understanding and learning outcomes.

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INTRODUCTION

Maritime education plays a strategic role in preparing competent marine engineers who can meet the operational and safety requirements of the global shipping industry. To ensure

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standardized competencies, the International Maritime Organization (IMO) established the IMO Model Course 7.04 for Officer in Charge of an Engineering Watch, which specifies the knowledge and skills required of prospective marine engineering officers, including fundamental competencies in maritime chemistry (IMO, 2014). Within this framework, students are expected not only to understand basic chemical principles but also to apply them to practical engineering contexts, such as corrosion prevention, water testing and treatment, fuel and lubricant management, and other chemical processes essential for safe and efficient ship operations.

Despite its importance, learning maritime chemistry remains challenging because many of its concepts involve microscopic structures, molecular interactions, and dynamic chemical processes that cannot be directly observed. Students are therefore required to connect symbolic chemical representations with phenomena occurring at the molecular level while simultaneously understanding their practical applications in maritime engineering. Previous studies have shown that such abstract representations often impede conceptual understanding, particularly when instruction relies primarily on conventional two-dimensional learning materials (Keller et al., 2021). Furthermore, learning resources specifically designed for maritime chemistry remain limited, creating additional challenges in delivering chemistry instruction that is both conceptually meaningful and contextually relevant to maritime education.

Addressing these instructional challenges requires learning approaches that enable students to visualize abstract chemical phenomena while actively engaging them in the learning process. Such an approach is consistent with the principles of Student-Centered Learning (SCL), which emphasizes learners' active participation in constructing knowledge through meaningful learning experiences (Kerimbayev et al., 2023). In chemistry education, meaningful conceptual understanding depends on students' ability to connect macroscopic observations, microscopic representations, and symbolic chemical expressions. However, conventional instructional media often provide only two-dimensional representations, making it difficult for students to establish these conceptual relationships (Behmke et al., 2018; Singhal et al., 2012).

Among various educational technologies, Augmented Reality (AR) has attracted considerable attention because it integrates virtual three-dimensional objects into real-world environments and allows learners to interact with digital representations in real time (Silva et al., 2019). Unlike conventional visualization media, AR enables students to observe, manipulate, and explore chemical structures and processes from multiple perspectives, thereby supporting the visualization of phenomena that cannot be directly observed. These characteristics make AR particularly suitable for chemistry education, where many learning concepts involve microscopic structures and dynamic molecular interactions (Barocio et al., 2021; Wahid et al., 2017). Consequently, AR offers considerable potential as a visualization tool for maritime chemistry education, in which students are required to understand abstract chemical principles and relate them to authentic maritime engineering applications.

Although AR technology has been widely applied in chemistry education, most prior studies have focused on general chemistry topics, such as molecular structure, chemical bonding, and laboratory simulations, within conventional educational settings. Studies specifically addressing maritime chemistry education remain limited and have primarily focused on isolated practical topics, such as density and viscosity experiments, rather than the development of competency-oriented digital learning media (Luis et al., 2013). More importantly, no previous study has reported the development and validation of an Augmented Reality-based learning application specifically designed for maritime chemistry education in accordance with the competency framework of the IMO Model Course 7.04. This gap highlights the need for contextualized, technology-enhanced learning media that align with international maritime training standards and support competency-oriented maritime chemistry education.

Maritime chemistry differs from general chemistry because students are expected not only to understand chemical principles but also to apply them in engineering contexts specified by the IMO Model Course 7.04, including corrosion control, seawater testing and treatment, fuel and lubricant management, and environmental protection. Consequently, developing competency-oriented AR learning media in this context is scientifically important because it enables chemistry instruction to be more closely aligned with professional maritime competencies and supports the visualization of abstract concepts in authentic engineering contexts.

Based on the identified research gap, this study was conducted to develop and evaluate ChemARine (Chemistry Augmented Reality of Marine), an Augmented Reality-based learning application designed to support maritime chemistry education in accordance with the competency requirements of the IMO Model Course 7.04. The study specifically pursued three objectives: (1) to develop a contextualized AR learning application for maritime chemistry, (2) to evaluate its content validity and media validity through expert assessment, and (3) to examine its practicality through a limited implementation involving maritime engineering students.

The scope of the present study was intentionally limited to product development, expert validation, and practicality evaluation as the initial stage of educational media development. Consequently, the study was not designed to examine instructional effectiveness or learning outcomes. Evaluation of the educational effectiveness of ChemARine through experimental or quasi-experimental research designs is therefore recommended as an important direction for future research.

LITERATURE REVIEW

Augmented Reality (AR) has been increasingly recognized as an effective instructional technology for chemistry education because it enables learners to visualize abstract concepts that are difficult to represent through conventional instructional media (An et al., 2020). Numerous studies consistently report that AR facilitates the understanding of microscopic structures, molecular interactions, and dynamic chemical processes by integrating three-dimensional virtual objects into real-world learning environments. Through interactive visualization, students can manipulate molecular structures, observe chemical phenomena from multiple perspectives, and connect symbolic, microscopic, and macroscopic representations more effectively than with traditional two-dimensional materials (Singhal et al., 2012; Keller et al., 2021; Cole et al., 2021). These findings collectively suggest that the principal educational value of AR lies in supporting conceptual visualization rather than simply providing attractive visual content.

Previous AR applications have been developed across a wide range of chemistry topics. These include chemical reactions (Setiawan et al., 2019; Kusdiana et al., 2019; Nishihamat et al., 2010), molecular geometry and VSEPR theory (Prasetyo et al., 2020; Singhal et al., 2012), chemical bonding (Irsyad, 2016), atomic structure and periodic systems (Taçgin et al., 2016), organic chemistry (Ya Midak et al., 2022), and stereochemistry (Keller et al., 2021). Although these studies consistently demonstrate the effectiveness of AR in improving visualization quality and facilitating spatial reasoning, they primarily focus on individual chemistry topics within general science education. Consequently, their instructional contributions remain largely confined to disciplinary chemistry learning and provide limited evidence regarding the application of AR in specialized vocational contexts.

Beyond topic-specific applications, several comprehensive AR-based learning systems have also been introduced to support chemistry education. MoleculARweb (Barocio et al., 2021), ARChemistry Learning (Macariu et al., 2020), Archemy (Abdinejad, Ferrag, et al., 2021), and ARChemistry (Prasetyo et al., 2020) have demonstrated that AR environments can increase learner

engagement, improve conceptual visualization, and encourage active interaction with learning materials. Similarly, AR has been successfully implemented in chemistry laboratory education to simulate experimental procedures, reduce safety risks, and provide opportunities for repeated practice before conducting actual laboratory experiments (An et al., 2020; Dave et al., 2019). Collectively, these studies indicate that AR functions not only as a visualization tool but also as an interactive learning environment that supports active learning. Nevertheless, the majority of these applications were developed for general chemistry curricula and laboratory instruction rather than for competency-based vocational education.

Recent studies further suggest that AR contributes to cognitive and affective aspects of learning by increasing learner engagement, motivation, curiosity, and self-directed learning while supporting spatial visualization skills that are essential for understanding chemistry (Ibáñez & Carlos, 2018; Saadon et al., 2020; Weng et al., 2019; Ya Midak et al., 2022). However, despite these documented benefits, previous research has largely emphasized general chemistry learning outcomes without explicitly integrating professional competency standards or occupation-specific instructional contexts. As a result, current evidence provides limited guidance regarding how AR can be systematically adapted to support competency-oriented learning in vocational disciplines such as maritime engineering education.

METHOD

Research Design

This study employed a Research and Development (R&D) approach to develop and validate an Augmented Reality-based learning application, ChemARine, for maritime chemistry education aligned with the IMO Model Course 7.04. The ADDIE instructional design model (Analysis, Design, Development, Implementation, and Evaluation) was selected because it provides a systematic and iterative framework for educational media development, allowing learning needs to be identified, instructional content to be designed, products to be validated by experts, and refinements to be made based on user feedback (Candido & Cattaneo, 2025). These characteristics make ADDIE particularly well-suited to developing technology-enhanced learning media for educational implementation. The present study focused on product development, expert validation, and limited practicality evaluation rather than examining instructional effectiveness.

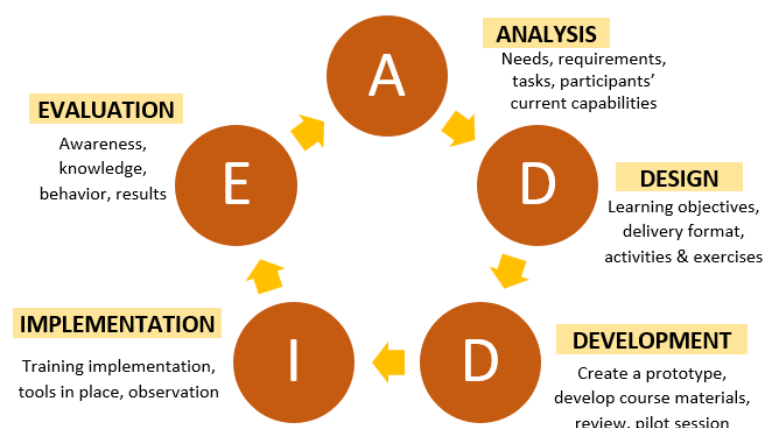


Figure 1. ADDIE Model

Participant

Participants in this study consisted of 43 maritime engineering students from two maritime higher education institutions in Indonesia, namely Politeknik Maritim Negeri Indonesia and

Universitas Maritim AMNI Semarang. The number of participants was considered adequate for a limited practicality evaluation because the primary objective of the implementation stage was to obtain representative user feedback on the usability and practicality of the developed application, rather than to evaluate instructional effectiveness. Students participated only during the implementation stage because the preceding analysis, design, and development phases required expert judgment for product validation rather than end-user evaluation.

Population and the Methods of Sampling

The population of this study comprised maritime engineering students enrolled in chemistry courses based on the IMO Model Course 7.04. A purposive sampling technique was employed to select participants who had completed or were currently enrolled in the maritime chemistry course and were willing to participate in the implementation stage. Students who had not taken the course or completed the implementation activities were excluded from participation. The selection was also based on institutional accessibility, as the implementation was conducted at two maritime higher education institutions that had integrated the IMO Model Course 7.04 into their curricula. Consequently, the findings should be interpreted within the context of limited practicality evaluation rather than broad population generalization.

Instruments

The study employed three instruments to collect data throughout the development process: a material expert validation sheet, a media expert validation sheet, and a student response questionnaire. The material expert validation sheet evaluated the alignment of the learning content with the IMO Model Course 7.04, scientific validity, the depth and breadth of the material, language and readability, and the suitability of the content for Augmented Reality (AR)-based learning. The media expert validation sheet assessed the application in terms of interface design, interactivity and navigation, visualization and multimedia quality, technical feasibility, and educational and aesthetic value. The student response questionnaire was administered during the implementation stage to evaluate students' perceptions of the application's appearance and design, ease of use (usability), support for material comprehension, interactivity and AR features, and its usefulness in enhancing the learning experience.

All instruments employed a 4-point Likert scale ranging from strongly disagree (1) to strongly agree (4). A four-point scale was intentionally adopted to avoid neutral responses and encourage participants to express clear judgments regarding each evaluation criterion. Prior to implementation, the instruments were reviewed by two chemistry lecturers serving as material experts and two experts in instructional media and information technology to examine the relevance, clarity, and appropriateness of each instrument item. Revisions were subsequently made based on their recommendations to improve wording, content relevance, and alignment with the research objectives. This expert review established the appropriateness of the instruments' content before implementation. Because the present study focused on educational media development and feasibility evaluation rather than psychometric instrument development, formal statistical analyses of instrument validity and reliability, such as content validity indices or reliability coefficients, were not conducted. Accordingly, the student response questionnaire was intended to evaluate perceived usability and practicality rather than objective learning performance, and the findings should therefore be interpreted within the scope of educational media development and limited implementation.

Procedures and Time Frame

The study was conducted using the ADDIE development model, which consists of five stages: Analysis, Design, Development, Implementation, and Evaluation. During the analysis stage, field observations and semi-structured interviews were conducted with maritime engineering students

from Politeknik Maritim Negeri Indonesia and Universitas Maritim AMNI Semarang to identify learning difficulties in maritime chemistry. The observations focused on existing instructional practices, learning resources, and students' difficulties in understanding abstract chemistry concepts, while the interviews explored students' perceptions of learning needs and challenges. The collected qualitative information was summarized descriptively and used to determine the learning needs and system specifications for developing the ChemARine application. A literature review was also undertaken to examine the requirements of the IMO Model Course 7.04, Student-Centered Learning (SCL) principles, and the application of Augmented Reality (AR) in chemistry education.

In the design stage, the learning content, system architecture, and user interface were planned and structured. Storyboards were developed to organize the navigation flow and learning activities, including the main menu, AR camera feature, instructional pages, and 3D visualization components. These designs served as the foundation for the application development process. During the development stage, the ChemARine application was developed using Unity LTS version 2022.3.x as the primary development platform, Blender for three-dimensional (3D) object modeling, and the Vuforia Engine SDK to support marker-based Augmented Reality. Functional testing was conducted to verify menu navigation, marker recognition, three-dimensional object visualization, animation, user interaction, and overall application stability across Android smartphones with different hardware specifications. The testing confirmed that all core functions operated properly without critical technical errors prior to expert validation. Subsequently, expert validation was conducted involving two chemistry lecturers as material experts and two experts in instructional media and information technology as media experts. Experts were selected purposively based on their academic qualifications and professional experience. The validation evaluated the scientific content, alignment with IMO Model Course 7.04, interface design, technical feasibility, visualization quality, usability, and educational value. Revisions were subsequently made based on the experts' recommendations.

The implementation stage involved a limited trial with 43 maritime engineering students from Politeknik Maritim Negeri Indonesia and Universitas Maritim AMNI Semarang. The implementation was conducted during one 100-minute classroom session within the maritime chemistry course. Students explored the ChemARine application, observed the Augmented Reality visualizations, completed the learning activities provided in the application, and subsequently completed the student response questionnaire. The collected responses were used to evaluate the practicality, usability, appearance, interactivity, and overall learning experience provided by the developed application.

Finally, the evaluation stage focused on refining the ChemARine application based on feedback obtained from both expert validators and student users. The revisions included improving the consistency and responsiveness of the user interface, refining the positioning and scaling of three-dimensional objects, revising explanatory texts to improve scientific clarity and readability, optimizing marker recognition through barcode-based markers, and conducting technical debugging to improve application stability across Android devices. These improvements resulted in the final version of ChemARine used in this study.

Analysis Plan

Data were analyzed using descriptive statistical techniques to evaluate the feasibility and practicality of the developed ChemARine application. Expert validation data and student response data were summarized as percentage scores to describe the level of agreement regarding the quality and usability of the application. The scores obtained from the material expert validation sheet, media expert validation sheet, and student response questionnaire were converted into percentage values using Equation (1).

$$P = (F/N) \times 100\%$$

where (P) represents the percentage score, (F) is the total score obtained, and (N) is the maximum possible score.

The obtained percentages were subsequently interpreted using the validity and practicality criteria presented in Table 1. The categorization and evaluation process were based on established principles for educational media evaluation and quality assessment (Akbar, 2013; Marciniak, R. & Cáliz Rivera, 2021). Expert validation results were used to determine the content and media feasibility of the ChemARine application, whereas student response data were used to evaluate its practicality and user acceptance during the limited implementation stage.

Table 1. Validity Percentage Categories and Response Assessment

Validity/Response Criteria (%)	Validity/Response Level	Description
85.01–100	Very valid/Very good	Can be used without revision
70.01–85.00	Valid/Good	Can be used with minor revisions
50.01–70.00	Less valid/Less good	Recommended not to be used due to significant revisions
00.00–50.00	Invalid/Not good	Should not be used

No inferential statistical analyses were performed because this study focused on the development, expert validation, and practicality evaluation of the ChemARine application rather than examining its effectiveness in improving students' learning outcomes. Therefore, the findings should be interpreted within the scope of educational media development and limited implementation.

RESULTS AND DISCUSSION

Results

Analysis Stage

The analysis stage identified the learning needs and instructional requirements for developing the ChemARine application. Data were obtained through classroom observations, semi-structured interviews, and needs analysis involving 20 maritime engineering students from Politeknik Maritim Negeri Indonesia and Universitas Maritim AMNI Semarang. The needs analysis showed that 17 of the 20 participants (85.0%) experienced difficulties in understanding abstract maritime chemistry concepts, particularly in visualizing three-dimensional molecular structures and relating microscopic chemical processes to maritime engineering applications. Students also indicated that the existing learning resources relied predominantly on text and two-dimensional illustrations, making it difficult to connect theoretical concepts with practical maritime contexts. Furthermore, the needs analysis indicated that 18 students (90.0%) expressed the need for more interactive and visual learning media, while 16 students (80.0%) preferred learning materials that could be accessed independently using mobile devices. In addition, 17 students (85.0%) stated that they were interested in using an Augmented Reality (AR)-based application for learning maritime chemistry.

The materials analysis produced the content framework for the ChemARine application by mapping the competencies specified in the IMO Model Course 7.04 (IMO, 2014) into learning topics suitable for AR-based visualization. Five major content areas were identified: Fundamentals, Acidity/Alkalinity, Corrosion, Water Testing and Treatment, and Introduction to Fuels and Lubricants. Within these chapters, several abstract concepts—including atomic models, molecular structures, corrosion mechanisms, water hardness, and combustion reactions—were selected as priority topics for three-dimensional visualization. The resulting material mapping is presented in Table 2.

Table 2. ChemARine Content Aligned with IMO Model Course 7.04

No.	Chapter	ChemARine AR Subtopics
1	Fundamentals	Atomic models (Dalton, Thomson, Rutherford, Bohr, and quantum mechanics), the Rutherford alpha-particle experiment, subatomic particles, and molecular structures (H ₂ O, NaCl, and Fe)
2	Acidity/Alkalinity	Arrhenius, Brønsted–Lowry, and Lewis acid–base theories, ocean acidification, and sulfuric acid in ship batteries
3	Corrosion	Corrosion reactions, oxygen and carbon dioxide compounds, and CO ₂ -induced corrosion processes
4	Water Testing and Treatment	Salt compounds causing temporary and permanent water hardness, and anti-corrosion coating compounds used on ship hulls
5	Introduction to Fuels and Lubricants	Sulfur content in marine fuels, complete and incomplete combustion reactions, viscosity, and water contamination in fuels

Design Stage

The design stage culminated in the final instructional and interface designs for the ChemARine application, which served as the blueprint for subsequent development. The learning content was organized according to the competency structure of the IMO Model Course 7.04, ensuring that each learning module corresponded to the required maritime chemistry competencies. The finalized storyboard defined the application workflow and navigation structure, consisting of a main menu that provides access to learning materials, user profile, instructions, the AR camera, and the exit function.

The completed interface design incorporated a marker-based Augmented Reality (AR) module capable of displaying three-dimensional chemical objects, animations, and interactive features, including zooming and object manipulation. The application was designed for the Android platform to support accessibility in maritime learning environments (Stavropoulos et al., 2022). In addition, the finalized design integrated image-target markers with the maritime chemistry e-module, enabling direct recognition of learning materials and interactive visualization of chemical concepts (Suryaningsih et al., 2025). The interface adopted a user-centered design with a simple navigation structure, intuitive menus, and consistent visual elements to facilitate students' interaction with the application. These finalized design specifications subsequently served as the reference for the application development stage.

Development Stage

The development stage culminated in the completion of the ChemARine application, an Android-based Augmented Reality learning medium for maritime chemistry. The completed application integrates marker-based Augmented Reality (AR) technology with three-dimensional (3D) visualization of maritime chemistry concepts, interactive learning materials, and a user-friendly navigation system. The application provides five main menus: learning materials, profile, user instructions, AR camera, and exit. Through the AR camera feature, users can scan image markers embedded in the maritime chemistry e-module to display interactive three-dimensional molecular structures, chemical processes, animations, and object manipulation features such as rotation and zooming. The completed interface and main menu of the ChemARine application are presented in Figure 2, while examples of the marker design and AR visualization are shown in Figures 3 and 4. The application was implemented using Unity LTS version 2022.3.x as the primary development platform integrated with the Vuforia Engine SDK for marker recognition and Augmented Reality visualization, while three-dimensional objects were created using Blender (Kusdiana et al., 2019). The final application integrated all planned instructional features into a single Android-based platform that presents interactive maritime chemistry content through real-time AR visualization.

Prior to expert validation, functional and compatibility testing confirmed that all application features operated as intended. Menu navigation, marker recognition, AR camera activation, three-

dimensional object visualization, animation playback, object manipulation, and learning content display functioned properly, with no critical technical errors. Compatibility testing further demonstrated that the application could be installed and executed successfully on Android smartphones with different hardware specifications while maintaining stable AR visualization and responsive user interaction.

To improve application performance, optimizations and debugging were performed by compressing three-dimensional models and textures, optimizing the Vuforia image-target database, and refining performance across different Android devices. The final ChemARine application was deployed as an Android Package Kit (APK) with a file size of 65.5 MB and included 26 AR simulation modules covering the maritime chemistry topics developed in this study. Stability testing indicated that the application maintained reliable performance during repeated marker detection, three-dimensional visualization, and user interaction. Continuous evaluation was also performed by collecting user feedback, fixing identified bugs, and preparing additional feature improvements to accommodate future user needs and curriculum updates. Following internal testing, the completed ChemARine application was evaluated by two chemistry lecturers acting as material experts. The evaluation focused on alignment with IMO Model Course 7.04, scientific accuracy, conceptual depth, readability, and the suitability of the learning content for AR-based instruction. The validation results are presented in Table 3.

Table 3. Material Validation Results

Aspects	Percentage (%)	Criteria
Material alignment with IMO 7.04	91.67	Very Valid
Scientific validity	91.67	Very Valid
Depth and breadth of material	91.67	Very Valid
Skills and readability	100	Very Valid
Suitability for AR media	91.67	Very Valid
Overall Score	93.33	Very Valid

The overall material validation score reached 93.33%, indicating that the learning content was considered highly feasible for implementation. In addition to the quantitative ratings, the material experts recommended several minor improvements, including refining scientific terminology, improving the clarity of explanatory texts, and strengthening the consistency between the learning materials and the competencies specified in the IMO Model Course 7.04. These recommendations were incorporated into the revised version of the ChemARine application prior to implementation. Media validation was subsequently conducted by one instructional media expert and one information technology (IT) lecturer to evaluate the application's interface design, interactivity and navigation, visualization and multimedia quality, technical feasibility, and educational and aesthetic value. The validation results are presented in Table 4.

Table 4. Media Validation Results

Aspects	Percentage (%)	Criteria
Interface design	93.75	Very Valid
Interactivity and navigation	95.83	Very Valid
Visualization and multimedia quality	100	Very Valid
Technical feasibility	100	Very Valid
Educational and aesthetic value	100	Very Valid
Overall Score	97.91	Very Valid

The media validation produced an overall feasibility score of 97.91%, indicating excellent technical and visual quality of the ChemARine application. The validators particularly appreciated the intuitive interface, stable AR visualization, and ease of navigation. Minor recommendations

included improving the consistency of button placement, refining the scaling and positioning of several three-dimensional objects, and optimizing marker recognition under different lighting conditions. These suggestions were implemented before the limited implementation stage.

Based on recommendations from both material and media experts, several revisions were implemented before classroom use. The major revisions included (1) improving the consistency and responsiveness of the user interface, (2) refining the positioning and scaling of three-dimensional objects, (3) revising explanatory texts for greater scientific clarity and readability, (4) optimizing barcode-based marker recognition to improve scanning stability, and (5) technical debugging to enhance application performance across different Android devices. These revisions primarily improved interface consistency, marker recognition stability, visualization accuracy, and application performance before classroom implementation.

Figure 2 presents the main interface of the ChemARine application, illustrating the organization of the learning menus that provide access to instructional materials, user guidance, and the AR visualization feature. Figure 3 shows the barcode-based marker embedded in the accompanying e-module, which functions as the trigger for three-dimensional visualization. Figure 4 demonstrates representative AR visualizations developed for several maritime chemistry topics, including atomic structure, acid-base theory, chemical bonding, crystal structures, and electrochemical reactions. Together, these figures illustrate the integration of learning materials with marker-based AR visualization implemented in the ChemARine application.



Figure 2. The interface and main menu of the ChemARine application on Android

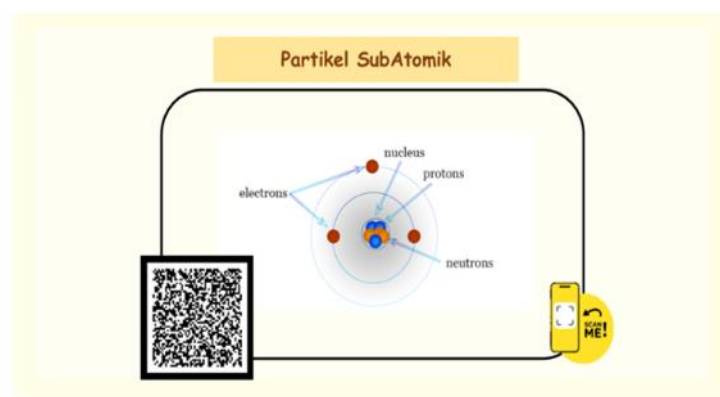


Figure 3. Example of a marker display on an e-module that can be scanned using the ChemARine application

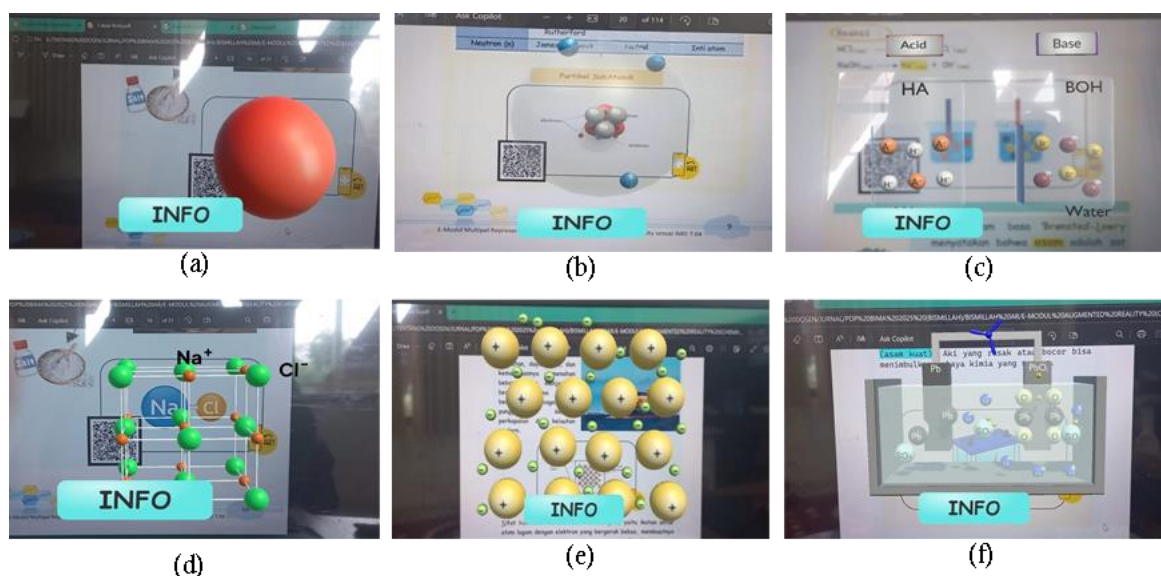


Figure 4. Example of AR display in the ChemARine application for several sub-chapters of the material: (a) Dalton's atomic model, (b) Subatomic Particles, (c) Acid-Base Theory, (d) NaCl Crystals, (e) Metal Bonds, (f) Chemical Reactions of Ship Batteries

Implementation Stage

The implementation stage involved the limited use of the finalized ChemARine application by 43 engineering students at a maritime higher education institution. During this stage, students used the application together with the maritime chemistry e-module in learning activities. Subsequently, they completed a response questionnaire to evaluate the practicality and user experience of the developed learning media. The questionnaire assessed five aspects: application appearance and design, usability, conceptual understanding, AR interactivity, and learning experience.

The results of the student response questionnaire are presented in Table 5. The overall response score reached 84.45%, which falls into the Very Good category according to the assessment criteria. Among the evaluated aspects, AR interactivity obtained the highest percentage (85.27%), followed by appearance and design (84.49%), material comprehension (84.30%), ease of use (84.10%), and usefulness and learning experience (84.10%). The relatively higher score for AR interactivity indicates that students responded particularly positively to the application's interactive visualization features, while the consistently high scores across the remaining aspects suggest favorable perceptions of its usability, appearance, and support for learning activities. The student responses collected during this stage were subsequently used to guide the evaluation and refinement of the ChemARine application.

Table 5. Student Response Results

Aspects	Percentage (%)	Criteria
Appearance and design	84.49	Very Good
Ease of use (usability)	84.10	Very Good
Material comprehension	84.30	Very Good
Interactivity and AR features	85.27	Very Good
Usefulness and learning experience	84.10	Very Good
Overall Score	84.45	Very Good

Evaluation Stage

The evaluation stage focused on identifying whether further revisions were required following the limited implementation. Student responses indicated that the ChemARine application was positively accepted across all evaluated aspects, including appearance and design, usability, conceptual support, AR interactivity, and learning experience. Consequently, no major revisions

were required. Minor refinements were implemented based on qualitative feedback, primarily involving interface responsiveness, three-dimensional object positioning, explanatory text clarity, and marker recognition stability. These refinements resulted in the finalized version of the ChemARine application used in this study.

Discussion

The present study resulted in the development and validation of ChemARine, an Augmented Reality (AR)-based learning application specifically designed for maritime chemistry education in accordance with the IMO Model Course 7.04. The high material validity (93.33%), media validity (97.91%), and positive student practicality responses indicate that the developed application satisfied the pedagogical and technical requirements established for this study. These findings suggest that a systematic instructional design process can support the development of competency-oriented digital learning media for maritime chemistry education. Similar observations have been reported in previous studies indicating that structured instructional design approaches contribute to the quality and usability of educational technology products (Branch, 2009; Sugiyono, 2019).

One important finding of the present study concerns the visual design and usability of ChemARine. Students provided highly positive evaluations of the application's appearance, navigation, and ease of use, indicating that the interface successfully supported learning activities with minimal technical difficulty. The high usability scores were also consistent with the media experts' evaluations, suggesting that the application met important criteria for interface design, navigation, visualization quality, and technical feasibility. The positive evaluations suggest that students perceived the interface as intuitive and easy to navigate, allowing them to focus on the learning activities with minimal operational difficulty. Previous studies have similarly emphasized that effective interface design, intuitive navigation, and user-centered interaction contribute positively to learners' acceptance of educational technologies (Mumpuni & Nurbaeti, 2019; Maham Sheikh et al., 2021). However, whereas previous studies have generally examined these design principles in broader educational contexts, the present study demonstrates their feasibility within a competency-based maritime chemistry learning application aligned with the IMO Model Course 7.04. Nevertheless, the present findings should be interpreted as evidence of the application's usability and practicality rather than as direct evidence of improved learning performance.

Another important finding concerns students' perceptions of conceptual understanding. The positive responses suggest that ChemARine helped students visualize abstract maritime chemistry concepts by combining contextual instructional materials with interactive three-dimensional representations. Topics such as atomic structure, chemical bonding, acid-base theory, corrosion, water treatment, and fuel combustion involve microscopic processes that are often difficult to visualize using conventional instructional resources. Through marker-based AR visualization, students were able to observe these concepts more concretely and relate them to authentic maritime engineering applications. Similar findings have been reported in previous studies demonstrating that AR facilitates conceptual visualization, improves spatial reasoning, and supports conceptual understanding by allowing learners to observe and manipulate three-dimensional representations of abstract chemical phenomena (Nuñez et al., 2008; Krüger et al., 2019; Liono et al., 2021; Keller et al., 2021; Abdinejad; Talaie, et al., 2021; Ratna Ningsih, 2020; Weng et al., 2019; Yuni & Afriadi, 2020; Cole et al., 2021). However, previous studies have also reported that the educational benefits of AR are not always consistent because their effectiveness depends on instructional design quality, learning context, and the integration of AR activities into meaningful learning experiences. Therefore, the present findings indicate that ChemARine provides a feasible and practical visualization tool for maritime chemistry learning, although its effectiveness in improving students' conceptual achievement requires further investigation.

Students also provided highly positive evaluations of the AR interactivity and overall learning experience. The interactive visualization features, including real-time marker recognition, three-dimensional object manipulation, and animated chemical models, were perceived as engaging and easy to operate during classroom activities. These findings indicate that the developed AR features functioned as intended and successfully supported students' interaction with the learning materials. This finding is consistent with previous studies showing that immersive AR environments encourage learners to interact more actively with instructional content through real-time visualization and direct object manipulation (Silva et al., 2019). Previous studies have likewise reported that interactive AR environments can enhance learner engagement and encourage active participation when appropriately integrated into instructional activities (Harackiewicz et al., 2016; Ibáñez & Carlos, 2018; Saadon et al., 2020). However, the present study evaluated students' perceptions of usability and learning experience rather than instructional effectiveness. Because no comparison group or pretest-posttest assessment was included, the positive responses should be interpreted as evidence of the application's practicality and user acceptance instead of evidence that AR improves learning outcomes. Consequently, although ChemARine was perceived positively by students, further experimental research is necessary to determine its impact on academic achievement and conceptual understanding. To highlight the contribution of the present study, Table 6 compares ChemARine with representative AR-based chemistry-learning applications reported in prior studies.

Table 6. Comparison of ChemARine with Previous AR-Based Chemistry Learning Applications

Study	Learning Context	Main Focus	IMO 7.04 Alignment
Barocio et al. (2021)	General chemistry	Molecular visualization	No
Keller et al. (2021)	General chemistry	Stereochemistry	No
Abdinejad et al. (2021)	General chemistry	Molecular and organic chemistry	No
Liono et al. (2021)	General chemistry	Chemical bonding	No
This study (ChemARine)	Maritime chemistry	Competency-based maritime chemistry	Yes

A notable contribution of the present study is the development of ChemARine, an Augmented Reality (AR)-based learning application specifically designed for maritime chemistry education, which aligns its instructional content with the competency requirements of the IMO Model Course 7.04. As summarized in Table 6, previous AR applications in chemistry education have primarily focused on general chemistry topics, including molecular visualization, chemical bonding, molecular geometry, stereochemistry, and laboratory simulations, without explicitly addressing competency-based maritime education (Barocio et al., 2021; Ibáñez & Carlos, 2018; Weng et al., 2019; Liono et al., 2021; Keller et al., 2021; Abdinejad, Talaie, et al., 2021). In contrast, ChemARine integrates maritime-specific chemistry topics, including corrosion mechanisms, seawater testing and treatment, marine fuels and lubricants, and ocean acidification, within a single marker-based AR learning environment directly aligned with the maritime curriculum. Rather than introducing a new AR technology, this study demonstrates how established AR visualization techniques can be systematically adapted to support vocational maritime chemistry education. The expert validation results indicate that both the instructional content and the application design were considered appropriate for maritime chemistry instruction, while the positive student responses demonstrate that the developed application is practical and acceptable for its intended users. Nevertheless, because this study focused on product development, expert validation, and practicality evaluation, no conclusion can yet be drawn regarding whether curriculum-specific AR applications provide greater educational benefits than existing general chemistry AR applications. Accordingly, future studies employing experimental or quasi-experimental research designs are needed to investigate the effectiveness of contextualized maritime AR learning media compared with existing instructional approaches.

Implications

The present study demonstrates that a competency-oriented Augmented Reality (AR) learning application can be feasibly developed for maritime chemistry education in accordance with the IMO Model Course 7.04. Based on expert validation and student practicality evaluation, ChemARine may serve as a supplementary digital learning resource for maritime higher education, particularly to support the visualization of abstract concepts in maritime chemistry during classroom instruction. Because the present study focused on product development and feasibility evaluation, these implications should be interpreted as evidence of practical applicability rather than evidence of instructional effectiveness.

From a theoretical perspective, the present study extends previous research on AR-based chemistry learning by demonstrating that established AR visualization techniques can be systematically adapted to a competency-based vocational curriculum. While previous AR applications have primarily focused on general chemistry topics (Barocio et al., 2021; Keller et al., 2021; Abdinejad, Talaie, et al., 2021; Liono et al., 2021), this study shows that curriculum-specific adaptation to the IMO Model Course 7.04 is feasible and acceptable within maritime chemistry education. Accordingly, the study provides empirical support for the development of contextualized AR learning media in vocational maritime education.

Limitations and Suggestions for Future Research

This study has several limitations. First, the implementation stage was limited to collecting students' responses regarding the usability and practicality of the developed application. Therefore, the findings primarily reflect users' perceptions and provide evidence regarding the application's feasibility and practicality rather than its effectiveness in improving students' conceptual understanding or learning outcomes. Second, the implementation involved only 43 maritime engineering students from two maritime higher education institutions in Indonesia. Consequently, the findings should be interpreted with caution, as their generalizability to other educational contexts and learner populations remains limited. Third, ChemARine currently covers selected maritime chemistry topics specified in the IMO Model Course 7.04 and does not yet include more advanced chemistry topics or broader engineering competencies. Accordingly, the current version represents only a partial implementation of the maritime chemistry curriculum. Finally, the application was developed exclusively for Android devices, limiting its accessibility for users of other operating systems such as iOS.

Future research should prioritize experimental or quasi-experimental studies to evaluate the effectiveness of ChemARine in improving students' conceptual understanding and learning outcomes. Such studies are also recommended to involve larger and more diverse samples from maritime education institutions to examine the application's effectiveness across broader educational contexts and learner populations. From a product development perspective, future work may include extending platform compatibility to iOS and other mobile operating systems, enriching the application with additional maritime chemistry topics and advanced engineering content, and integrating more interactive features such as virtual laboratory simulations, adaptive learning modules, and learning analytics. Future studies may also explore the applicability of contextualized AR learning media in other maritime and vocational STEM disciplines.

CONCLUSION

The findings demonstrate that ChemARine is a feasible and practical Augmented Reality-based learning application for maritime chemistry education aligned with the IMO Model Course 7.04. Expert validation confirmed that the application satisfied the required pedagogical and technical standards, while students' responses indicated that it was practical, usable, and well accepted as a

digital learning medium for maritime chemistry. The study contributes to the development of contextualized digital learning media by demonstrating that competency-based maritime chemistry content can be systematically integrated into a marker-based AR environment aligned with the IMO Model Course 7.04.

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AUTHOR CONTRIBUTIONS STATEMENT

Khoirotun Nafillah conceived the study, designed the research methodology, developed the ChemARine application, conducted the data analysis, and drafted the manuscript. Encis Indah Suryaningsih contributed to the research design, validation procedures, and manuscript review. Aprillina participated in the development of the learning content and data collection. Helena Devi Ariyani contributed to the validation process, data interpretation, and manuscript revision. Dhesi Wulan Sari assisted in the implementation of the study and data analysis. Lia Retian Asfirah contributed to the preparation of learning materials and data collection. Purwanto provided supervision, reviewed the research methodology, and critically revised the manuscript. Widanto Mukti Adi contributed to the augmented reality application development, technical validation, and manuscript review. Kirtyana Ninditas participated in the validation process, interpretation of the findings, and final editing of the manuscript. All authors read and approved the final version of the manuscript.

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