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Validity and Practicality of AI-Integrated Interactive Chemical Equilibrium E-Module Based on Structured Inquiry to Improve Students' Critical Thinking Ability

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Abstract: Chemical equilibrium is one of the chemistry topics that is abstract and complex, often causing difficulties for learners in understanding the concepts and their applications. This study aimed to determine the validity and practicality level of an Artificial Intelligence (AI)-integrated interactive e-module on chemical equilibrium based on structured inquiry to improve students' critical thinking ability. This study was a Research and Development (R&D) using the Plomp development model, which includes the Preliminary Research and Development or Prototyping Phase, without conducting the Assessment Phase. The results show that the developed e-module obtained a validation score of 0.92 (valid category) and a very high practicality level of 97%. The findings indicated that the AI-integrated, structured-inquiry-based interactive e-module on chemical equilibrium to improve Phase F students' critical thinking ability is valid and practical.

Keywords: AI; Chemical equilibrium; Critical thinking ability; Interactive e-module; Structured inquiry

Introduction

Advances in science and technology have brought changes to many aspects of life, including education. One of the main challenges in the modern era is preparing young people to have critical, analytical, and innovative thinking abilities to face increasingly complex global dynamics. Learning methods that tend to focus on lectures and memorization are considered less effective for fostering critical thinking ability.

Critical thinking is an essential ability in education, especially for responding to increasingly complex global challenges (Alprianti et al., 2023; Doyan et al., 2022)(Pare, 2023). The ability to objectively analyze information, evaluate arguments, and identify various perspectives enables students to make better decisions and solve problems more effectively (Salsa et al., 2023).

In chemistry learning, critical thinking is crucial for a deep understanding of abstract concepts such as chemical equilibrium. Through critical thinking, students can connect theoretical knowledge with real-world applications, develop evidence-based arguments, and logically evaluate experimental results (Surtiningsih et al., 2024). Therefore, learning that promotes critical thinking is expected to have long-term impacts on students' ability to solve life and career problems in the future (Zubaidah, 2020).

Chemical equilibrium is an important topic in chemistry learning and is highly relevant to developing critical thinking ability (Munawwarah et al., 2022). This topic involves abstract concepts that require a deep understanding of cause-and-effect relationships and the ability to analyze data logically. Understanding chemical equilibrium requires students to relate observable macroscopic phenomena, particle-level (submicroscopic) processes, and symbolic representations in the form of chemical equations and calculations. Students' inability to connect these three

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levels of chemical representation is often a major cause of learning difficulties in chemical equilibrium (Johnstone, 1993; Walidain, 2024).

As technology develops, artificial intelligence (AI) offers opportunities to revolutionize the learning process. AI can be used to develop learning materials that are not only interactive but also adaptive to individual learning needs (Fajriati et al., 2024). In the context of chemistry learning, AI has great potential to help visualize abstract concepts through simulations, dynamic animations, and interactive representations that integrate macroscopic, submicroscopic, and symbolic levels (Wahyuni et al., 2020). With AI support, students can see the relationship between macroscopic changes in reaction conditions, shifts of particles at the submicroscopic level, and changes in symbolic reaction equations, so their understanding of chemical equilibrium becomes more complete and meaningful.

Besides technology integration, selecting an appropriate learning model also plays an important role in improving critical thinking ability. One learning model proven effective in fostering critical thinking ability is the structured inquiry learning model (Prasetiyo et al., 2020; Susilawati et al., 2022). This model provides systematic guidance for students to explore and solve problems. In structured inquiry, students are guided to observe phenomena, formulate hypotheses, collect data, analyze results, and draw evidence-based conclusions. This learning model not only helps students understand the material more deeply but also trains them to think logically, systematically, and analytically (Zion et al., 2012).

Implementing structured inquiry learning in the topic of chemical equilibrium helps students not only understand concepts more deeply but also develop the critical thinking ability needed to face real-world challenges (Ali et al., 2024). The abstract and complex nature of chemical equilibrium requires students to have strong analytical ability and deep conceptual understanding (Walidain et al., 2024). Through structured inquiry, students are actively involved in exploring concepts rather than passively receiving information by observing phenomena, formulating hypotheses, collecting data, analyzing findings, and drawing evidence-based conclusions (Santosa, 2024). Integrating AI into these inquiry stages can strengthen conceptual exploration, especially by helping students visualize phenomena across the three levels of chemical representation simultaneously and in an interconnected way (Sari & Putra, 2023).

Observations from interviews with three chemistry teachers indicated that chemical equilibrium was generally taught using printed learning materials and lecture methods. Most of the materials used did not show the links among the three levels of chemical representation, so learning tended to focus only on the symbolic level in the form of equations and calculations. This condition led to low student interest and motivation and caused chemical equilibrium to be perceived as difficult and less engaging. This finding was supported by student questionnaire results showing that 85% of students considered chemical equilibrium difficult. Although some teachers had applied discussion methods, learning was still dominated by the teacher and thus remained teacher-centered. Students experienced difficulties in chemical calculations and in understanding abstract concepts, which contributed to low learning outcomes; many students had not yet achieved the minimum competency standard.

Several previous studies on the development of chemical equilibrium learning materials reported that such materials were effective in improving students' critical thinking ability. Sundami et al. (2020) developed a structured inquiry-based chemical equilibrium module containing the three levels of chemical representation, with very high validity ($\kappa = 0.82$) and very high practicality ($\kappa = 0.89$ for teachers and $\kappa = 0.82$ for students). Guci et al. (2017) developed a three-level representation-based learning media using Prezi that was declared valid ($\kappa = 0.89$) and practical ($\kappa = 0.92$ for teachers and 0.80 for students). Asmiyunda et al. (2018) also developed an e-module on chemical equilibrium based on the scientific approach and reported very high validity and practicality. These studies suggested that learning materials presenting links among the three levels of chemical representation effectively improved the quality of chemistry learning. However, to date there has been no research that explicitly integrates AI to visualize the three levels of chemical representation in chemical equilibrium learning materials.

Integrating AI technology and structured inquiry learning in the development of an interactive e-module on chemical equilibrium is expected to be an effective solution to existing learning challenges. AI is used to help visualize the relationship between macroscopic phenomena, submicroscopic processes, and symbolic representations, which are rarely presented in an integrated manner in conventional learning materials. Integrating AI into an interactive e-module enables the concepts of chemical equilibrium to be presented more concretely, dynamically, and adaptively to students' needs. With an interactive design and structured inquiry approach, this e-module is designed not only to improve conceptual understanding but also to foster students' critical thinking ability through active exploration and meaningful learning.

Based on the description above, this study aims to determine the validity and practicality level of an AI-integrated interactive e-module on chemical equilibrium based on structured inquiry to improve students' critical thinking ability.

Method

Research Method

This study uses a Research and Development (R&D) approach with the Plomp (2013) development model, which consists of three main stages: (1) preliminary research (Preliminary Research), (2) the development/prototyping phase (Development/ Prototyping Phase), and (3) the assessment phase (Assessment Phase).

This study was conducted at the Faculty of Mathematics and Natural Sciences (FMIPA), Universitas Negeri Padang, and at SMA Negeri 1 Ranto Baek during the even semester of the 2024/2025 academic year. Validity testing was carried out by lecturers and teachers, while practicality testing was carried out by chemistry teachers and students. The object of this research was an AI-integrated, structured inquiry-based chemical equilibrium e-module designed to improve critical thinking ability of Phase F students in Grade XI at the senior secondary level (SMA/SMK).

Research Procedure

Preliminary Research

Needs analysis was conducted by distributing questionnaires and conducting interviews with teachers and students to identify problems in learning the chemical equilibrium topic. In addition, a literature review on e-modules and structured inquiry was carried out.

Needs analysis was conducted by distributing questionnaires and interviewing teachers and students to identify problems in learning the chemical equilibrium topic. In addition, a literature review was carried out focusing on e-modules, structured inquiry, AI, critical thinking ability, and chemical equilibrium.

Development/prototyping Phase

Prototype Design: This stage includes determining the learning material, designing learning activities, setting learning outcomes (CP) and indicators, compiling learning resources, and developing the e-module. Formative Evaluation: Formative evaluation consists of self-evaluation, expert validation conducted by chemistry lecturers, chemistry teachers, and educational technology experts, as well as practicality testing by teachers and students through one-to-one and small group methods.

Research Instruments

The research instruments used in this study included questionnaires for teachers and students at the preliminary research stage; validation sheets and self-evaluation forms at the development stage; and practicality questionnaires for teachers and students.

Data Analysis Techniques

Validity Analysis Technique

For validity analysis, the researcher used Aiken's formula, in which the data from the validators were entered into the formula to obtain the validity results of the developed e-module (Saifudin, 2012). The formula used is Aiken's V, as follows:

$$V = \frac{\sum s}{[n\,(c-1)]} \qquad (1)$$

Where, s = r – lo; lo = the lowest possible validation score; c = the highest possible validation score; r = the score given by a rater; n = the total number of data points or the number of validators.

Table 1. Categories of E-Module Validity Level

Achievement Level	Category
≥ 0.83 – 1.00	Valid
≤ 0.83	Not Valid

Practicality Analysis Technique

The practicality data of the developed e-module were obtained from teacher and student questionnaires. The data were analyzed using the following formula:

$$Practicality\ Score = \frac{\sum Obtained\ Score}{\sum Maximum\ Score}\ x\ 100\% \qquad (2)$$

Table 2. E-Module Practicality Categories

Achievement Level	Category
81 – 100	Very Practical
61 – 80	Practical
41 – 60	Fairly Practical
21 – 40	Less Practical
<20	Not Practical

Result and Discussion

This study followed the Plomp (2013) development model, which consists of three stages, namely preliminary research (Preliminary Research) and the development/prototyping phase (development/ prototyping).

Preliminary Research Phase

Based on interviews with three chemistry teachers, it was found that although efforts have been made to train students' critical thinking ability in learning chemical equilibrium, students still experience difficulties in analyzing abstract chemical concepts and solving problems that require reasoning. Learning practices are still dominated by conventional approaches, such as lectures and exercises focused on calculations, and are not yet adequately supported by innovative learning models. As a result, students perceive chemical equilibrium as a difficult and less interesting topic.

Teachers suggested the need for varied learning models, integration of student worksheets, and the use of interactive and engaging learning modules to improve students' understanding and motivation. Developing a technology-based e-module is considered a relevant solution, because an e-module can present abstract concepts through visualization, interactive exercises, and multimedia elements. In addition, an AI-integrated e-module has the potential to provide adaptive and personalized learning experiences by providing immediate feedback and adjusting learning content based on students' abilities.

In addition, structured inquiry learning was identified as an appropriate model for the chemical equilibrium topic, because it actively involves students in exploring concepts through observing, formulating hypotheses, analyzing data, and drawing evidence-based conclusions (Irwandi, 2011). Therefore, integrating AI technology with a structured inquiry-based e-module is expected to improve students' critical thinking ability. These findings indicate a strong need to develop an AI- integrated, structured inquiry e-module to support more effective and meaningful chemistry learning.

Development/Prototyping Phase Prototype Design

The prototype was designed based on the preliminary study results, which included needs analysis and a literature review. The product developed in this study is an AI-integrated, structured inquiry-based chemical equilibrium e- module. The e-module consists of several main components: a cover page, preface, table of contents, user guide pages for teachers and students, a competency page containing basic competencies and learning objectives, an introduction page, a concept map page, and student activity sheets.

The cover page is the first page displayed, followed sequentially by the preface, table of contents, and user guide pages. The competency page contains the learning objectives to be achieved, followed by the introduction and concept map pages that provide an overview and conceptual structure of the chemical equilibrium topic. The student activity sheet pages present learning activities designed according to the structured inquiry learning model to actively involve students in exploring chemical equilibrium concepts.

Formative Evaluation and Prototype Revision Self-Evaluation Stage

This stage involved the researcher reflecting on the initial e-LKPD prototype to assess its structure, content, and design. Three aspects were evaluated: content/material, visual appearance, and language. Two main weaknesses were identified - unclear instruction language and less attractive visual appearance - and both were revised as needed.

Figure 1. Material page

Expert Review Stage

Validation involved eight experts (four content validators and four media validators). The analysis was performed using Aiken's V. The content validation results are presented in Table 3.

The validation results show that the e-module has a very high level of content feasibility (V = 0.91). The material aligns with the learning objectives and core chemistry learning outcomes/competencies and covers chemical equilibrium concepts comprehensively, from basic principles to applications in daily life and industry. Alignment between content and learning objectives is important for achieving optimal learning outcomes and fostering students' critical thinking ability (Rahmani et al., 2025). The material coverage is also balanced in breadth and depth, enabling students to build a comprehensive understanding the content is based on up to date scientific without excessive cognitive load (Mayer, 2024). knowledge, presented accurately according to IUPAC standards, and supported by visual media such as images and videos to help understand abstract concepts (Arsyad, 2011). AI integration supports adaptive learning and increases student motivation through immediate feedback and engaging content presentation (Dörnyei, 2001).

Table 3. Content Validation Results

Assessed Aspect	Score	Category
Content Aspect	0.91	Valid
Presentation Aspect	0.93	Valid
Language Aspect	0.91	Valid
Contextual Aspect	0.90	Valid
Average	0.91	Valid

The presentation aspect obtained a very high validity score (V = 0.93). The material is organized systematically and logically following the syntax of structured inquiry learning, moving from concept exploration to evidence-based conclusions. Structured presentation helps students understand the relationships among complex concepts more effectively (Mayer, 2024). The use of images, videos, and interactive exercises increases clarity, engagement, and conceptual understanding (Arsyad, 2013). The interactive nature of the e- module supported by AI features enables a more personalized learning experience and encourages active exploration, thereby strengthening students' critical thinking ability (Brusilovsky et al., 2007).

The language aspect also shows a very high level of feasibility (V = 0.91). The language used is clear, communicative, unambiguous, and appropriate for senior high school students. Using simple yet effective language can reduce cognitive load and facilitate understanding of complex chemistry concepts (Sweller, 2010). A communicative and reflective sentence structure motivates students to be actively involved in learning and encourages critical thinking (Elder et al., 2013; Gagné et al., 2005). In addition, the e- module follows proper Indonesian language rules, making instructional delivery clearer and more professional (Doyan et al., 2020; Zandagi et al., 2018).

The contextual feasibility aspect obtained a very high validity score (V = 0.90). The e-module aligns with the curriculum and links chemical equilibrium concepts to real-life contexts and industrial applications, making learning more meaningful (Ayhan, 2019). The structured inquiry approach - including observation, hypothesis formulation, data collection, analysis, and evidence-based conclusion drawing - actively engages students and supports the development of critical thinking ability (Bransford et al., 2000). Contextual and reflective learning activities also encourage students to connect theoretical knowledge with practical application, thereby increasing understanding, motivation, and the relevance of chemistry learning (Elder et al., 2013; Hmelo-Silver, 2004).

Table 4. Media Validation Results

Assessed Aspect	Score	Category
Visual Appearance	0.92	Valid
Programming	0.93	Valid
Usability	0.95	Valid
Average	0.93	Valid

The validation results show that the visual aspect of the e-module falls into the valid category. The visual design - including the cover, layout, typography, color scheme, and graphic elements - is well arranged and aligned with the chemical equilibrium material, thereby increasing student engagement and learning comfort (Dini et al., 2024). A systematic layout supports ease of navigation and comprehension, while clear typefaces, appropriate color contrast, and well-organized paragraphs improve readability (Lupton, 2017; Norman, 2013; Snyder et al., 2014; Ware et al., 2012). In addition, relevant images and videos effectively help visualize abstract chemistry concepts and improve students' understanding (Mayer, 2024).

The programming aspect shows that the e- module is user-friendly, responsive, and interactive. An intuitive interface, well-functioning navigation buttons, and fast system responses enable students to operate the e-module smoothly without technical obstacles. Consistency in navigation design supports structured inquiry-based learning because students can move between learning stages easily. Interactive features, such as quizzes and AI-based automatic feedback, encourage active learning and improve conceptual understanding (Mayer, 2024; Brusilovsky & Millán, 2007).

The utilization aspect indicates that the e- module is effective in supporting the learning process and increasing students' motivation. Clear user instructions help students navigate the module efficiently and reduce confusion (Ferdiansyah et al., 2025). Visual appeal, interactivity, and AI integration enable a personalized and adaptive learning experience, thereby increasing students' interest and concentration in studying chemical equilibrium (Muilenburg et al., 2005; Sweller, 2010). In addition, integrating real-life contexts and personalized feedback can foster intrinsic motivation and encourage students' active engagement in the learning process (Ryan et al., 2000).

Teacher Practicality Test

The usefulness (usability) aspect shows that the developed e-module is very beneficial in supporting chemistry learning, especially for the chemical equilibrium topic that is often perceived as difficult by students. The validation results indicate that the e-module helps teachers achieve learning objectives through flexible and interactive learning. AI integration enables adaptive learning by adjusting content difficulty to students' level of understanding, thereby encouraging more independent and directed learning. The interactive nature of the e-module and its flexible accessibility facilitate faster understanding and increase students' learning independence (Gunawan, 2016). The ease-of-use aspect indicates that the e- module is easy to operate for both teachers and students. Teachers can easily use the e-module to introduce material and provide exercises, while students can learn at their own pace without feeling burdened. A clear and intuitive interface allows users to navigate the module efficiently, so students can focus more on the learning content than on technical issues. Easy-to-use digital learning materials contribute to increased learning independence and overall learning quality (Fitri, 2021).

Table 5. Teacher Practicality Test

Assessed Aspect	Score	Category
Usefulness	96	Very Practical
Ease of Use	98	Very Practical
Attractiveness	95	Very Practical
Clarity	95	Very Practical
Efficiency	100	Very Practical
Average	96	Very Practical

The attractiveness (appealing) aspect shows that the e-module's visual design effectively increases student engagement, especially for abstract material such as chemical equilibrium. The module was developed with attention to visual aesthetics, including cover design, color schemes, illustrations, and images. Relevant and engaging visual elements help students understand complex chemistry concepts and increase learning motivation, while balanced color composition maintains visual comfort and focus on the learning content (Hendrawensi et al., 2024).

The clarity aspect confirms that the e-module presents learning objectives, material, and instructions clearly and in a structured manner. Well-organized material and the integration of real- life phenomena help students connect theoretical concepts with practical applications. Clear presentation reduces cognitive load and facilitates a deeper understanding of abstract chemistry concepts, enabling students to concentrate on achieving learning objectives without confusion (Mayer, 2024).

The efficiency aspect indicates that the e- module can be accessed easily through various devices, including computers and smartphones, without requiring additional applications. This accessibility saves time and reduces technical barriers for teachers and students. Efficient access enables flexible learning, so students can review material and practice problems anytime and anywhere, supporting mastery of chemistry concepts more effectively and efficiently.

One-to-One Practicality Test

Table 6. One-to-One Practicality Test

Assessed Aspect	Score	Category
Ease of Use	100	Very Practical
Attractiveness	97	Very Practical
Efficiency	100	Very Practical
Usefulness	98	Very Practical
Average	99	Very Practical

Small Group Practicality Test

Table 7. Small Group Practicality Test

Assessed Aspect	Score	Category
Ease of Use	99	Very Practical
Attractiveness	96	Very Practical
Efficiency	91	Very Practical
Usefulness	98	Very Practical
Average	96	Very Practical

The ease-of-use aspect obtained a very good validation score, indicating that the e-module is easy to understand and practical for learners. Clear instructions make it easier for learners to access the material and available features, while systematic organization and simple language support understanding, especially for learners who are just beginning to study abstract chemistry concepts such as chemical equilibrium. The use of clear, readable fonts also improves accessibility and reduces adaptation difficulties to the digital interface, which is a common challenge in technology-based learning (Wahyuni et al., 2020).

The attractiveness aspect also showed good results. The e-module has an appealing cover design, attractive content layout, and readable typography that can increase learners' motivation and learning engagement. The integration of relevant images and videos supports understanding of abstract chemistry concepts by connecting theory with real-life applications. Visually engaging presentation has been shown to increase learning interest and encourage learners to participate more actively in learning (Lupton, 2017).

In terms of efficiency, the e-module simplifies the learning process and optimizes study time. It allows learners to access the material anytime and anywhere, supporting learning at each learner's own pace without time and place constraints. This flexibility helps learners manage their study schedules more effectively and reduces barriers commonly found in conventional learning, thereby increasing learning productivity (Hidayah, 2020).

Regarding the usefulness aspect, the e-module provides significant benefits in supporting independent learning, improving conceptual understanding, and fostering learning interest. Clearly presented material enables learners to study independently without always relying on teacher guidance. AI integration provides real-time feedback so learners can identify and correct misconceptions more efficiently (Hukom, 2025). This adaptive and interactive approach increases learners' confidence, motivation, and engagement in studying chemical equilibrium through structured inquiry-based activities (Sundahry, 2021).

Conclusion

The developed e-module obtained a validation value of 0.92 (valid category) and a very high practicality level of 97%. The results showed that the AI-integrated, structured-inquiry-based interactive e-module on chemical equilibrium designed to improve students' critical thinking ability was valid and practical.

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Author Contributions
Adi Susanto: writing-original draft preparation; results; discussion; methodology; conclusion. Minda Azhar: study design; research monitoring/ supervision; proofreading; review and editing. Yerimadesi and Umar Khalmar Nizar: providing suggestions and feedback. Salsabilla Putri Serli: paper validator.

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The authors declare that there are no conflicts of interest.

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