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ENHANCING CHEMISTRY LEARNING THROUGH A CRITICAL THINKING ASSESSMENT TOOL

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ABSTRACT

The aim of this research is to create an instrument for critical thinking in chemistry education, particularly with regard to chemical bonding content. This instrument was developed in 4 steps, namely determining aspects, compiling indicators, compiling questions, and validation which includes content validation and empirical validation. Two expert lecturers validated the content. Aiken (font was used to analyse the critical thinking skills questionnaire. The analysis's findings revealed that, of the six questions, all had a validity coefficient value of more than 0.35 and were declared valid. The empirical validation stage involved 275 students. The empirical validation analysis was carried out using the Rasch model. Based on the results of the analysis, 6 fit questions were obtained and had a cronbach's alpha reliability estimate value of 0.82 and were reliable for use in measuring students' critical thinking skills.

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INTRODUCTION

The field of education is greatly impacted by the existence of society 5.0 in the advancement of science and technology. As the present industrial revolution developed, educational practices, skills and competences, teaching and learning methodologies, and collaborative skills in the digital age underwent a shift that gave rise to Education 4.0 (Tikhonova & Raitskaya, 2023). Education 4.0 requires educators to be ready to change, explore new knowledge, and improve their skills for teaching and learning emphasising multidisciplinary abilities (Catal & Tekinerdogan, 2019; Kipper et al., 2021). Various innovations and curriculum adjustments are made to open a new world window in the field of education.

One of the factors that affect initiatives to raise the quality of education is the instruments used in the learning process. Learning instruments are tools used to measure the achievement of a competency and serve as the main key to determining the success of learning objectives. If a learning instrument satisfies the criteria of validity, dependability, practicality, and efficacy, it is considered viable (Ansori et al., 2019). Good learning instruments can stimulate students' thinking skills in solving problems. In the midst of scientific and technological development, skills are needed that can help students innovate, learn effectively, collaborate, and contribute to society. These 21st-century skills are known as the 4Cs: creative, communication, collaboration, and critical thinking. Several assessment alternatives introduced in Education 4.0 include portfolios, project papers, skill demonstrations, assessment scales, and alternative assessments that measure these high-level thinking skills (Hussin, 2018).

Among these higher-order skills, critical thinking is particularly fundamental. The ability to assess facts from concepts in order to determine the best course of action and verify the veracity of information, allowing us to determine whether or not it is acceptable, is referred to as critical thinking skills (Chen et al., 2019). As a result, critical thinking is a crucial ability for the future in dealing with disruptive situations (Boonsathirakul & Kerdsomboon, 2023). By honing these skills, students will become accustomed to thinking critically in solving problems systematically and in a directed manner. Fostering creativity, logical reasoning, decision-making, presentation, language proficiency, and academic performance all depend heavily on critical thinking abilities (Yanti et al., 2018; Shamboul, 2022).

Critical thinking improves students' capacity for information analysis, evaluation, and synthesis in the context of science education. asserts that critical thinking encompasses interpretation, analysis, assessment, inference, and explanation—skills necessary for making decisions and addressing problems. In chemistry learning specifically, students must develop these abilities to understand complex chemical concepts, make logical connections between macroscopic and sub-microscopic phenomena, and apply knowledge in real-world contexts (Avargil, Herscovitz, & Dori, 2012). According to research, students frequently find it difficult to connect theoretical chemistry knowledge to real-world scenarios, underscoring the necessity of teaching methods that foster critical thinking (Tsaparlis & Zoller, 2003). Additionally, it has been demonstrated that students' analytical reasoning abilities in scientific fields are greatly enhanced by specific critical thinking teaching (Mulnix, 2012), with argumentation-based learning approaches being particularly effective in developing critical evaluation abilities (Osborne, Simon, & Collins, 2003).

Instruments used in the learning outcome evaluation process allow for the identification of students' critical thinking abilities during the learning process. Out of 81 nations and territories evaluated in the PISA test, Indonesia came in at number 71 in reading, number 70 in maths, and number 67 in science (OECD, 2023). PISA serves as an evaluation tool that gives educators and decision-makers with a deep understanding of the effectiveness of the education system. These results indicate that the level of reasoning and high-level thinking skills of Indonesian students is still comparatively low, underscoring the urgent need for educational interventions, particularly in developing effective assessment instruments that can accurately measure and subsequently help develop students' critical thinking skills.

Along with the demands of increasing critical thinking skills, educators must also become accustomed to developing instruments that refer to high-level thinking. Recent efforts have focused on creating such instruments tailored to the chemistry domain. For example, a study aimed at developing an assessment tool for collaborative problem-solving skills in chemistry demonstrated the importance of context-specific evaluations, providing insights into both students' critical thinking and teamwork skills (Danczak, Thompson, & Overton, 2017). A significant advancement in this area is the integration of experiential learning with thinking-based learning pedagogies, which has been demonstrated to successfully foster higher-order thinking abilities in students as compared to traditional learning environments, is a noteworthy development in this field (Smith & Jones, 2024). Another innovative method involves the use of scientific storytelling to assess higher-order thinking skills, revealing that storytelling could serve as a valuable tool in evaluating and enhancing students' critical thinking capabilities (Brown et al., 2025).

Despite these advancements in chemistry-specific assessment tools, a significant gap remains. Much of the existing research has focused on developing critical thinking assessments for general science or broad chemistry skills, often overlooking the unique conceptual demands of specific foundational topics. The availability of standardized and well-validated critical thinking evaluation instruments, particularly for specific chemistry topics like chemical bonding, remains a significant challenge. Chemical bonding is an abstract concept where students frequently struggle to connect macroscopic properties with sub-microscopic representations—a core aspect of critical thinking in chemistry. Furthermore, many available instruments are not explicitly designed to align with the principles of Education 4.0, which calls for assessments that are not only valid and reliable but also practical, contextual, and capable of stimulating higher-order thinking through varied formats. Developing such instruments also presents the challenge of ensuring they comprehensively encompass the diverse range of critical thinking skills, including analysis, evaluation, inference, and explanation as outlined by Facione (1990). Additionally, the dynamic nature of the chemistry field necessitates continuous updates to assessment tools to reflect current scientific understanding and practices. These gaps are particularly concerning for abstract concepts such as chemical bonding, where the need for effective critical thinking assessment is most acute.

Therefore, this study aims to address this gap by developing a critical thinking skills instrument specifically for chemistry learning, with a particular focus on the topic of chemical bonding. The unique contribution of this research lies in the design of an instrument that is not only rigorously tested for validity and reliability based on modern psychometric standards, but also contextualized within the challenges of learning abstract chemical concepts. By focusing on chemical bonding, the instrument is tailored to assess students' ability to analyze, evaluate, and create explanations for chemical phenomena—key indicators of critical thinking. The instruments developed are expected to be tested validly and reliably so that they can be used to evaluate student learning outcomes, providing educators with a much-needed tool to diagnose and enhance students' higher-order thinking skills in this crucial area of chemistry.

METHODS

This research used a research and development design to create an instrument for teaching chemistry students how to think critically about chemical bonding.. The instrument development procedure followed four main stages: aspect determination, item development, content validation, and empirical validation. The first stage involved determining the aspects of critical thinking to be measured. A comprehensive literature review was conducted, synthesizing various sources including books and journal articles on critical thinking in science education. Based on the synthesis of multiple frameworks, four core aspects of critical thinking were selected: providing simple explanations, analyzing and evaluating, building basic skills, and concluding (Ennis, 1962; Beyer, 1995; Walker & Finney, 1999; Ghadi et al., 2013; Utami et al., 2017). These aspects were then operationalized into specific indicators and sub-indicators relevant to chemical bonding concepts. The second stage was item development. Based on the established indicators, six constructed-response questions were developed to assess students' critical thinking skills on chemical bonding topics, including concepts such as ionic bonds, covalent bonds, metallic bonds, and intermolecular forces.

The third stage was content validation, which involved two types of expert review. First, two chemistry education experts from the chemistry department evaluated the content relevance and alignment of the items with chemical bonding concepts. Second, a psychometric expert from the psychology department assessed the theoretical alignment of the items with critical thinking constructs. Each item was graded by experts using a validation sheet, and the content validity of the results was assessed using Aiken's V coefficient. The Aiken's V formula is:

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

Description:
s = r – lo
lo = lowest validity assessment number
c = highest validity assessment number
r = number given by an expert
n = number of assessors (experts)
(Aiken, 1985).

The last stage was empirical validation to examine the instrument's psychometric properties. The validated instrument was administered to 275 tenth-grade students from six public senior high schools in Yogyakarta, Indonesia. The schools were selected using random sampling techniques to ensure representativeness. All students had received instruction on chemical bonding topics prior to data collection, ensuring they possessed the prerequisite knowledge to respond to the assessment items.

The Rasch model is then used to analyse the empirical validation data in order to identify reliable and valid statement items. According to Lia et al. (2020), the Rasch model increases computation accuracy by identifying inaccurate responses, predicting missing data scores, differentiating respondents' abilities with the same raw scores, and identifying signs of guessing and cheating. The QUEST software was utilised in this study to examine the instrument's validity and reliability.

FINDINGS AND DISCUSSION

The instrument produced in this study is a question of critical thinking skills on chemical bonding material. This instrument consists of 6 essay questions developed to measure students' high-level thinking skills. Through context-based chemistry, essay questions are utilised to assess pupils' comprehension of scientific ideas and develop higher-order thinking abilities (Nieswandt & Bellomo, 2009; Avargil, Herscovitz, & Dori, 2012). The development of critical thinking instruments begins with determining the critical thinking aspects obtained from the synthesis of 5 journals and books. Determination of critical thinking aspects from the synthesis of various sources can be seen in table 1.

Table 1. Synthesis Of Critical Thinking Indicators

References	Definition	Aspect
Ennis (1962)	Critical thinking is thinking in a reasoned and reflective manner with an emphasis on making decisions about what to believe or do.	• Providing simple explanations • Building basic skills • Drawing conclusions • Providing further explanations • Setting strategies and tactics.
Beyer (1995)	Critical thinking is the ability to determine the credibility of sources, distinguish the relevant from the irrelevant, distinguish facts from judgments, identify and evaluate unstated assumptions, identify biases, identify points of view, and evaluate evidence offered to support claims.	• Determine the credibility of sources • Distinguish between the relevant and the irrelevant • Distinguish facts from judgments • Identify and evaluate unstated assumptions • Identify existing biases, identify points of view • Evaluate evidence offered to support claims
Walker & Finney (1999)	Critical thinking is an intellectual process in conceptualizing, applying, analyzing, synthesizing, and/or evaluating various information obtained from observations, experiences, reflections, where the results of this process are used as a basis for taking action.	• Conceptualizing • Applying • Analyzing • Synthesizing • Evaluating various information
Utami et al (2017)	Critical thinking is a process that is not just about reflecting, drawing conclusions, and synthesizing information, but also encourages someone to think rationally both in the classroom and in everyday life.	• Reflecting • Making conclusions • Synthesizing information • Thinking rationally
Ghadi et al (2013)	Critical thinking is the ability to analyze, evaluate, deduct, induce, solve problems, formulate conclusions, make several possibilities, and make a decision.	• Analyze • Evaluate • Deduce and induce • Solve problems • Formulate conclusions

	• Create several possibilities • Make a decision.

Based on statements by several experts, critical thinking can be seen as a person's ability to test their ideas when facing a problem so they can find the right solution. There are 4 aspects of critical thinking skills obtained from the synthesis results: providing simple explanations, analyzing and evaluating, building basic skills, and concluding (Ennis, 1962; Beyer, 1995; Walker & Finney, 1999; Ghadi et al., 2013; Utami et al., 2017).

The critical thinking skills instrument was developed based on the results of the synthesis of critical thinking skills aspects. The development of critical thinking skills questions is categorized into four aspects: providing simple explanations, analyzing and evaluating, building basic skills, and concluding. The first aspect, providing simple explanations, focuses on identifying and formulating questions, as well as considering possible answers. The question is:

> Table salt ($NaCl$) is a common seasoning used in various dishes. Interestingly, it is formed from sodium (Na), a highly reactive metal, and chlorine (Cl_2), a toxic gas. However, when these elements combine, they create a stable and essential compound for human consumption. (Atomic number: Na = 11, Cl = 17).
> a. What scientific issues or questions can be identified from this statement?
> b. Explain the chemical principles that account for this transformation!

Students are asked to identify the problems in the statement and explain the observed phenomena. Additionally, another question asks students to explain the concept of ionic and covalent bonds by analyzing everyday compounds:

> Various compounds are commonly found in everyday life, including $NaBr$, $MgCl_2$, HI, and CH_4. Among these, $NaBr$ and $MgCl_2$ are classified as ionic compounds, while HI and CH_4 are examples of covalent compounds. (Atomic numbers: Na = 11, Cl = 17, H = 1, Mg = 12, C = 12, Br = 35).
> a. Briefly explain the concepts of ionic and covalent bonds!
> b. Provide additional examples of compounds that exhibit ionic and covalent bonding!

The second aspect, analyzing and evaluating, emphasizes predicting results from limited information, evaluating data, and applying theoretical concepts. Students analyze an environmental issue:

Look at the following picture!

Figure 1. Acid Rain In The Cheyabinsk Area, Russia

The image depicts a region in Chelyabinsk, Russia, that frequently experiences acid rain. This environmental issue is caused by the release of sulfur dioxide (SO_2) gas from gold mining operations in the area. (Atomic numbers: S = 16, O = 8).

a. What type of chemical bond is formed between sulfur (S) and oxygen (O) in the SO_2 molecule?
b. Illustrate the Lewis structure of SO_2!
c. Describe the physical properties of SO_2 based on its chemical characteristics!

The third aspect, building basic skills, involves determining the reliability of sources and understanding the properties of compounds.

Indonesians are known for their love of spicy food, which gets its heat from chilies used as a seasoning. But what makes chilies taste spicy? The burning sensation comes from capsaicin and other compounds present in chilies. Capsaicin is a nonpolar molecule, meaning it does not dissolve in water. As a result, drinking water after consuming spicy food does not effectively reduce the heat. The most effective way to neutralize the spiciness is by consuming foods or drinks that contain fat or oil, as these substances can dissolve capsaicin, helping to alleviate the burning sensation. Is this explanation accurate? Connect your answer to the properties of different substances!

The final aspect, concluding, emphasizes induction and drawing conclusions based on facts.

NaCl is a solid compound, whereas CCl_4 exists in liquid form. Both are classified as chloride compounds, yet they exhibit different behaviors in water. In its solid state, NaCl (salt crystals) does not conduct electricity. However, when dissolved in water, it completely dissociates into ions, allowing it to conduct electricity. In contrast, CCl_4 does not dissolve in water and remains unable to conduct electricity. (Atomic numbers: Na = 11, Cl = 17, C = 12). Based on this information, what conclusions can be drawn regarding the properties of ionic and covalent compounds?

Another question challenges students to explain why oil and water do not mix, leading to an understanding of polarity and molecular interactions.

Look at the picture below!

Figure 2. Oil In Water

When oil is combined with water, the two substances do not mix. Even after stirring, they will eventually separate again.

a. What is the reason behind the inability of oil and water to mix?
b. What types of chemical bonds are present in oil and water?

Each aspect is linked to specific indicators, competency achievements, and question items designed to enhance students' higher-order thinking, assessed through Bloom's Taxonomy. These questions promote C4 (analyzing) and C5 (evaluating) in Bloom's Taxonomy, strengthening students' ability to form scientific conclusions based on experimental observations. Overall, these structured critical thinking questions encourage students to analyze real-world chemistry problems, evaluate information critically, and apply their knowledge to practical contexts. By integrating different cognitive domains, the instrument effectively supports the development of students' higher-order thinking skills in chemistry education.

A total of 6 critical thinking skills questions were then validated by 2 expert lecturers. Expert validators consider the suitability of indicators and test items. The validation results can be seen in Table 2.

Table 2. Aiken V Results

No. Item	Aiken's V
1	0.75
2	0.75
3	1.00
4	1.00
5	1.00
6	0.75

The results of the Aiken validity coefficient (V) are then interpreted based on the uncorrected correlation coefficients guidelines with provisions as in table 3 (Emery & Bell, 2009).

Table 3. Interpretation Of The Validity Coefficient

Validity Coefficient	Interpretation
> 0.35	Very useful
0.21 – 0.35	Can be useful
0.11 – 0.20	Depends on the circumstances
< 0.11	Not useful

Instrument items can be used if they have an Aiken's V value of more than the validity coefficient value of 0.35 with very useful interpretation results. According to the study of the critical thinking skills question instrument, each of the six questions has a validity coefficient value more than 0.35. It may be concluded that the six critical thinking skills questions are valid based on the validation analysis's findings. This expert validation is a content validation. This content validation is based on experts who understand the measurement of student self-efficacy (expert judgment). This is consistent with earlier studies showing that content validation is done rationally in accordance with current and relevant expertisem (Yang, 2011).

The empirical validation process was conducted with 275 students from several high schools. Empirical validation is the second validation that is useful for determining which items are invalid if used in measurement based on student responses. The empirical validity results using the RASCH model with the QUEST program is displayed in Table 4.

Table 4. Empirical Validation Results

No. Item	Infit MNSQ
1	0.97
2	0.97
3	1.05
4	0.96
5	1.13
6	0.90

A question item is said to be valid if it has an Infit Mean Square of 0.77 to 1.30. The results of the analysis show that the MNSQ infit value of all questions is valid. While the acceptable reliability is in the range of 0.70 to 0.95 (Tavakol & Dennick, 2011). Reliability of one measuring instrument (6 items) of 0.82. This is in accordance with previous research that the amount of reliability received is in the range of 0.70 to 0.95

(Tavakol & Dennick, 2011). The item reliability result is 0.82 so that the question items are declared reliable. The results of this empirical validation show that 6 questions are declared valid and reliable and can be used in the process of measuring students' critical thinking skills in learning chemistry.

An integrated approach is used to evaluate student learning outcome, not only assessing what has been learned, but also assessing each process and student skills in working on each step of problem solving. The findings of this investigation are consistent with earlier studies demonstrating the use of essay questions in HOTS assessments can improve students' thinking skills (Abosalem, 2016; Dry et al., 2019). Recent research has shifted by focusing on instruction to enhance high-level thinking abilities, such as formulating arguments, solving problems, analysing case-based articles applied in creative real world, and posing challenging questions (Dwyer et al 2012; Sumarni, 2018). As a result, the creation of this tool can serve as a substitute for enhancing students' critical thinking abilities during the educational process.

The validation results indicate that the instrument successfully captures multiple dimensions of critical thinking skills. With the instrument, students were able to answer complex, context-based chemistry questions demonstrates that this type of assessment is effective in measuring deeper cognitive engagement. This supports the argument that essay-based and real-world problem-solving questions are more effective than multiple-choice formats in assessing critical thinking (Abrami et al., 2008). Additionally, the strong reliability score (0.82) confirms that the assessment tool is suitable for repeated use in different educational settings. According to a comparison with other research, well-crafted critical thinking tools can greatly enhance students' capacity for knowledge analysis, synthesis, and evaluation (Lipman, 2003; Halx & Reybold, 2006; Kalinggoru et al., 2018). Future research could examine the long-term effects of these tests on students' academic achievement in more detail. To learn more about the significance of critical thinking in the teaching of chemistry, structured interviews were conducted with three expert lecturers in the field. Their perspectives provide valuable implications for educational practice and future research.

Expert 1 emphasized the importance of critical thinking in chemistry, particularly in grasping abstract concepts such as chemical bonding. He stated,

> "Students must be able to analyze and evaluate information critically, as chemistry requires logical reasoning and problem-solving. Integrating real-life scenarios into the questions could further enhance students' engagement and application of knowledge"

He further highlighted that providing students with challenging tasks that demand justification and evidence-based reasoning is crucial for deeper understanding. According to expert 1, the critical thinking questions developed in this study effectively encouraged students to break down complex chemical problems into simpler components.

Expert 2 pointed out that traditional assessment methods often fail to capture students' critical thinking abilities. He explained,

> "Many assessments focus on rote memorization rather than evaluating students' reasoning and argumentation skills. These types of assessments better measure high-level cognitive processes and encourage students to think critically about chemical reactions, bonding, and molecular structures rather than simply recalling formulas. Evaluating open-ended responses requires significant time and effort, but using rubrics and automated assessment tools can help facilitate this process."

Expert 2 praised the use of essay-based questions and performance tasks. He recommended incorporating collaborative problem-solving tasks to enhance peer discussion and argumentation skills, ensuring that all students, regardless of ability level, can engage meaningfully in critical thinking exercises.

The results of this study add to the expanding corpus of knowledge regarding critical thinking in STEM education. Long-term success in both the personal and professional spheres depends on critical thinking, which can be successfully developed in students through focused interventions (James et al., 2023). By developing critical thinking skills, students will cultivate a habit of systematic thinking, enhance their decision-making abilities, and effectively apply both inductive and deductive reasoning to solve diverse problems (Prastyaningrum et al., 2023). The developed instrument provides a reliable means of assessing critical thinking skills in chemistry learning. Future studies, however, ought to investigate how the use of these tests affects students' learning results in various educational contexts.

CONCLUSION

This study successfully developed and validated a critical thinking skills instrument for chemistry learning, particularly in the topic of chemical bonding. The instrument was designed through a structured process, including determining aspects, formulating indicators, creating questions, and conducting both content and empirical validation. Content validation using Aiken's V analysis confirmed the instrument's validity, while empirical validation with the Rasch model demonstrated its reliability, 0.82 Cronbach's alpha value. The results emphasise how crucial it is to incorporate validated evaluation instruments in order to improve students' critical thinking skills. Higher-order thinking abilities were also found to be effectively fostered by the usage of essay-based questions. The study's findings, which highlight the value of critical thinking in preparing students for upcoming problems, are consistent with the increasing demand for high-quality assessment tools in the Age of Education 4.0. Teachers can use this tool to evaluate and enhance their students' analytical and problem-solving abilities in chemistry classes.

SUGGESTION

Future studies should expand the application of this instrument to diverse chemistry topics and educational contexts, while also investigating the long-term effects of critical thinking assessments on students' academic achievement and the integration of digital platforms to facilitate more efficient evaluation of open-ended responses.

CONFLICTS OF INTEREST: The authors declare no conflict of interest.

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