JTK: Jurnal Tadris Kimiya 11, 1 (June 2026): 14-24
Website: http://journal.uinsgd.ac.id/index.php/tadris-kimiya/index
ISSN 2527-9637 **(online) ISSN** 2527-6816 **(print)**

Profiling Students' Critical Thinking and Multiple Representation Skills in Buffer Solution Learning Using a Web-Based Assessment Tool

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Received: December 2025; Accepted: April 2026; Published: June 2026

Abstract

Critical thinking and multiple representation skills are essential competencies for meaningful chemistry learning, particularly when students are required to connect macroscopic phenomena, microscopic particle behavior, and symbolic chemical representations. However, evidence regarding students' achievement in these skills remains limited, especially in the context of buffer solution learning. This study aimed to profile secondary students' critical thinking and multiple representation skills using a previously validated web-based assessment instrument. A quantitative descriptive design was employed involving 74 eleventh-grade students from three secondary schools in Riau Province, Indonesia. Data were collected through an electronic assessment administered via Jotform and analyzed using descriptive statistics. The assessment measured five critical thinking dimensions (interpretation, analysis, inference, evaluation, and explanation) and three representation levels (macroscopic, microscopic, and symbolic). The findings revealed that students' critical thinking skills ranged from moderate to good levels across schools, with explanation emerging as the strongest dimension. In terms of multiple representations, students demonstrated better performance in symbolic and macroscopic representations than in microscopic representations. Students from School A achieved the highest scores in both critical thinking and multiple representation skills, whereas students from School B showed the lowest performance. The results indicate that students continue to experience difficulties in interpreting microscopic chemical phenomena despite demonstrating satisfactory understanding of symbolic and macroscopic aspects. These findings provide valuable insights for chemistry educators in designing instructional and assessment strategies that better support the development of higher-order thinking and representational competence in chemistry learning.

Keywords: buffer solutions, critical thinking, e-instrument, learning evaluation, multiple representations

DOI : https://doi.org/10.15575/jtk.v11i1.51053

1. Introduction

The Industrial Revolution 4.0 marks an era in which information technology, big data, artificial intelligence (AI), and the internet of things (IoT) have become key pillars in various sectors, including education. The impact of the Industrial Revolution 4.0 on education is not only related to the use of technology in the teaching and learning process, but also to the quality of human resources produced by the education system itself (Lase, 2019). The quality of education in Indonesia is a crucial issue that requires research and improvement, especially given the increasingly competitive global demands. Current developments in information technology require the world of education to continuously improve the quality of education, including through the use of information and communication technology, especially in the learning process (Yunita et al., 2018). Amid the abundance of information and ever-evolving technology, individuals must be able to analyze, evaluate, and integrate information effectively to receive it wisely (Trixa & Kaspar, 2024). These competencies are closely associated with critical thinking skills, which enable individuals to process information in a logical, reflective, and systematic manner. This situation highlights the importance of critical thinking as a vital skill that students must develop.

Critical thinking not only helps students discern valid and relevant information but also equips them to make rational decisions, solve complex problems, and avoid bias when responding to various issues. According to Facione (2015), critical thinking is a purposeful form of thinking (for example, proving a point, interpreting meaning, or solving a problem), but it can also be a collaborative, non-competitive endeavor. Therefore, critical thinking should not be considered a supplement to the curriculum, but rather an integral part of the overall educational process.

According to the World Economic Forum (2020), critical thinking is among the top 10 most in-demand skills for the future, particularly amid rapid technological and digital development. Critical thinking enables students to sort information accurately and serves as an intellectual filter; this skill also encourages the search for accurate information to understand a phenomenon or process comprehensively (Magrabi et al., 2018). This ability is crucial in preparing students to become active citizens in a democratic and civil society (Barnett, 2015). It enables them to recognize fake news, critically evaluate information, deconstruct misinformation, and mitigate the threats posed by misleading content. To support this urgency, a survey of 167 science graduates compared the development of various skills during college with the skills needed in the workplace (Sarkar et al., 2016). The results showed that 30% of full-time working graduates identified critical thinking as one of the five key skills that should have been further developed during their undergraduate studies.

To ensure optimal development of this skill, assessment tools are needed that can accurately measure critical-thinking achievement. Such tools must be designed to be valid and reliable so that they genuinely reflect essential indicators of thinking, such as interpretation, analysis, inference, evaluation, explanation, and self-regulation (Facione, 2015). Interpretation involves categorizing the problem, defining its characteristics, decoding, and clarifying its meaning. Analysis is used to distinguish the relationship among things. Evaluation involves making judgments on the credibility of statements. Inference involves reasoning and making logical conclusions. Explanation is to state results, to justify procedures, and to present arguments. Self-regulation involves reflecting on one’s cognitive activities, making self-assessments, and correcting errors (Facione, 2015).

In addition to critical thinking, another important aspect that needs to be considered in science education, especially chemistry, is the use of multiple representations (Takaoglu, 2024). Chemical concepts are generally abstract and cannot always be observed directly, so they require various forms of representation, such as macroscopic phenomena, microscopic particle models, and chemical symbols and equations to aid students' understanding. Johnstone explains that a complete understanding of chemistry requires the interconnection of these three levels of representation, known as Johnstone's triangle. Furthermore, the use of multiple representations allows students to view a concept from various perspectives and build meaningful connections between representations. The ability to shift and connect macroscopic, microscopic, and symbolic representations is not only central to scientific competence but also reflects higher-order thinking skills, including critical thinking (Sari & Seprianto, 2018).

Although the ability to represent and interpret scientific information is strongly emphasized at the university level, such competencies should be systematically developed during high school education to prepare students for more advanced learning contexts. Equipped with these abilities, learners are expected to generate complex visualizations that aid both individual understanding and communication of scientific ideas. A person with strong representational ability is characterized by the ability to present information concisely and efficiently, making it easy for others to understand (Fatmawati et al., 2022). Moreover, learning through multiple representations supports students in transferring knowledge and applying understanding across different contexts by enabling them to coordinate visual, symbolic, and verbal forms of representation (Ainsworth et al., 2020).

Rexigel et al. (2024) stated that integrating various forms of representation, such as text, formulas, graphs, diagrams, and other visual representations, can enhance students’ learning and problem-solving performance in STEM education. In today's workforce, particularly in fields such as science, technology, and industry, the ability to interpret and analyze data through various forms of representation has become increasingly important. As such, chemistry education must not only transmit conceptual knowledge but also cultivate critical, reflective, and adaptive thinking. Exercises that engage learners in interpreting multiple representations are crucial for supporting the development of these competencies. Therefore, the design and implementation of assessment instruments that holistically measure both critical thinking and multiple representation abilities constitute a strategic response to the evolving demands of contemporary education and the labor market.

Buffer solutions are an inherently complex topic and are well suited for assessing students' critical thinking and dual representation skills. This concept requires the simultaneous integration of three aspects of representation: the symbolic aspect (through chemical equations and calculations), the macroscopic aspect (through observation of pH changes), and the most abstract microscopic aspect (i.e., the interaction of weak acid/base particles and their salts that maintain pH). Students encounter difficulties when attempting to connect these three representations, for example, from symbolic composition to particle behavior (Gkitzia et al., 2020). The ability to connect and interpret data from these three representations is a process that requires rigorous analysis, inference, and evaluation, making it a key indicator of effective critical thinking. To solve complex problems, students must employ key critical thinking competencies such as interpretation, analysis, inference, evaluation, and explanation, as well as self-regulation on data presented in various formats (visual, equations, and narratives).

The selection of this topic is also supported by literature findings regarding students' widely reported learning difficulties. Research by Firdaus et al. (2021) showed that students have low levels of understanding and experience significant difficulties, particularly in relating buffers to chemical equations and in calculating solution pH. Similarly, Rudi et al. (2023) reported that students frequently struggle in writing and balancing reaction equations, distinguishing between strong and weak acids in buffer systems and selecting appropriate formulas for pH calculations. These difficulties may indicate barriers in integrating representations, especially microscopic representations, and in applying higher-order reasoning skills. Therefore, buffer solutions provide an appropriate context for assessing these competencies, as solving buffer-related problems requires students to connect multiple forms of representation while engaging in critical thinking processes.

The researchers conducted open-ended interviews with three chemistry teachers of eleventh-grade at SMAN 1 Sungai Apit, SMAN 2 Sungai Apit, and MA Nurul Hidayah to explore current assessment practices. The data from the interviews were analyzed through transcription. Based on the interviews with chemistry teachers at the three schools, it appears that students' critical thinking skills have not been assessed systematically. Teachers tend to evaluate learning outcomes only in terms of mastery of content knowledge, without assessing critical thinking or representation skills. The assessment tools used, both essay questions and Minimum

Competency Test questions, have not been designed with indicators that explicitly measure these two abilities. Although essay questions can provide opportunities for students to argue and express their reasoning, the absence of critical-thinking indicators makes the cognitive assessment results less meaningful. This makes the assessment practices may not fully support the development of 21st-century competencies. In addition, the tools used to assess student learning outcomes remain conventional. Thus, there is a need for flexible online assessment tool that can facilitate teachers' review of student learning outcomes. One online platform that can support this purpose is Jotform.

Jotform is an online form-building platform for collecting and managing data obtained from student responses. Jotform offers two form display options for its users: a classic form and a card form. The classic form displays all questions on a single full page, while the card form displays questions sequentially, one at a time (Dewantara et al., 2022). The use of digital platforms for assessment has become increasingly important because assessment and evaluation processes are often still conducted manually, resulting in inefficiencies in data collection and management. This is supported by a study by Imawanty and Fransiska (2019), which found that the implementation of assessment and evaluation in guidance and counselling were frequently carried out manually, limiting the effectiveness of data processing and analysis. Therefore, the integration of digital technologies, such as online form platform, is necessary to improve the effectiveness and efficiency of assessment and evaluation processes. In this context, Jotform provides a practical alternative for administering assessments and managing student learning data.

Based on the literature and preliminary findings, the identification of students' critical thinking and multiple representation abilities needs to be carried out using appropriate instruments. In this case, web-based e-instruments represents a relevant alternative in response to ongoing developments in educational technology. Therefore, this study aims to assess students' critical thinking and multiple representation abilities in buffer solution learning using a previously developed e-instrument administered through Jotform. This focus is particularly important because critical thinking enables students to analyze information rationally, evaluate the credibility of information sources, and respond effectively to misinformation in a democratic society. At the same time, the ability to interpret multiple representations is a key competency in the 21st century, particularly in academic and professional contexts that require individuals to understand and analyze information presented in various forms, such as tables, graphs, symbols, and other visual representations.

2. Research Method

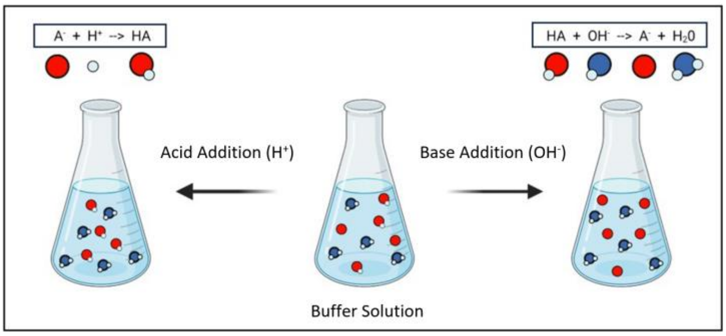
This study uses a quantitative approach. The application of the quantitative approach in this study includes analyzing students' critical thinking and multiple representations abilities using statistical calculations presented in graphical form. The data collection technique employed utilized electronic instruments (e-instruments) that had been previously developed. These instruments contained questions that referred to indicators of critical thinking ability as defined by Facione (2015); the ability to interpret, analyze, evaluate, draw conclusions, provide further explanations, as well as classify items into multiple representations, including macroscopic, symbolic, and microscopic.

There are eighteen multiple-choice questions with open-ended answers in the e-instrument that will be used. This e-instrument was developed in a previous instrument-development study conducted by the authors. This e-instrument has undergone validation by three subject matter experts with qualifications in chemistry and learning evaluation, where the aspects assessed were the material, question construction, answer choice construction, language, critical thinking skills, and multiple representations, which were found to be highly valid. This e-instrument has also passed the item characteristic test stage, where 23 of the 30 items were declared construct valid, with high item reliability with an index value of 0.772, a difficulty level dominated by the moderate category, and a discrimination power in the moderate to good category. Therefore, 18 items were selected based on the time and conditions of the test administration and in accordance with the distribution of critical thinking and multiple representation indicators. An example item from the e-instrument is presented in Figure 1.

Indicators	**Learning Objective Competency Indicators**
Cognitive Level : C4 Critical Thinking Indicator : Analysis Representation Type : Microscopic Representation Form : Image	Students are asked to detect the effect of adding a small amount of strong acid and a small amount of strong base on the buffer solution mechanism through illustrations at the molecular level.

Question

Look at and observe the following image!



Based on the image above, which depicts the addition of strong acid (H^+) to a buffer solution, analyze which of the following statements most accurately describes the changes that occur at the molecular level.

a. The added H^+ ions will immediately bind with all existing A^- ions, causing the pH of the solution to change drastically.
b. The added H^+ ions will react with some of the A^- ions to form HA molecules, but the pH of the solution will remain relatively stable.
c. The added H^+ ions will not react with the components of the buffer solution, so the pH of the solution will increase.
d. The existing HA molecules will dissociate into H^+ ions and A^- ions, causing the pH of the solution to decrease drastically.
e. The addition of H^+ ions will not affect the equilibrium in the buffer solution

Figure 1. Example Question from the Electronic Instrument

This test assesses critical thinking and multiple representations simultaneously because students are required to perform indicator analysis, which is the ability to analyze information and recognize relationships between concepts and representations. In this question, students must analyze the relationship between the addition of H^+ ions, buffer solution components (HA and A^-), and the shift in the acid-base reaction equilibrium. This analysis process cannot be done through verbal description alone, but requires students to interpret microscopic representations in the form of images of particles showing interactions between chemical species at the molecular level. These microscopic representations serve as conceptual tools that help students understand the mechanism of buffer reactions, specifically how H^+ ions react with some A^- ions to form HA, resulting in a relatively small change in pH. Students must translate microscopic images into conceptual reasoning, so that representations are not decorative, but functional. Thus, this question not only measures conceptual understanding but also analytical skills within the Facione framework and the ability to integrate microscopic representations with the concept of equilibrium. By presenting microscopic representations as the main source of information, this question requires students to perform conceptual analysis as defined by the analysis indicator, so that critical thinking skills and the ability to manage multiple representations can be measured simultaneously in a single question.

The research locations were SMAN 1 Sungai Apit, SMAN 2 Sungai Apit, and MA Nurul Hidayah, which were identified as A, B, and C, respectively. These schools were selected because no previous research had focused on them as subjects, such as learning evaluation and learning models, particularly in chemistry. Therefore, the research data obtained will be relatively free from external influences so that the instruments used to measure student abilities can produce objective and accurate data. The research sample consisted of 74 eleventh-grade students majoring in natural sciences from the three schools. The sampling technique used was purposive sampling, based on the consideration that the selected sample consisted of students who had studied buffer solutions and had never interacted with e-instruments, which primarily require students to think critically and to hone their ability to work with multiple representations.

The research data were analyzed using descriptive statistics. The variables examined in this study were students' critical thinking and multiple representation abilities, which were analyzed separately. Descriptive statistical analyses included percentage-based categorization, measures of central tendency (mean scores), and measures of dispersion (standard deviation and score range). Percentage scores were used to describe overall achievement levels, while mean scores and standard deviations were employed to examine score distribution and variability across critical thinking indicators and representation types. The researchers calculated the final score by dividing the total score obtained by the students by the maximum total score, which was then multiplied by 100, following the calculation formula used by Lestari and Roesdiana (2021) in their study.

3. Result and Discussion

The results of the e-instrument test were analyzed to determine the percentage of students' critical thinking ability categorized according to Riduwan's (2018) framework. The results of the thinking analysis of essential ability from three schools are presented in Figure 2.

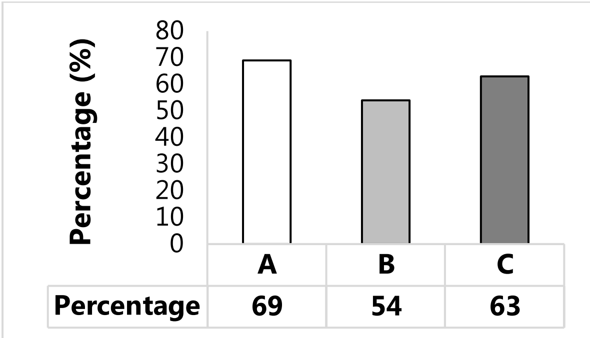


Figure 2. Critical Thinking Ability Level

Based on Figure 1, it can be seen that students from school A showed the highest level of critical thinking ability compared to the other two schools, with a score of 69%, which falls into the good category. School C followed this with a percentage of 63%, which also falls into the good category. Meanwhile, students from school B achieved the lowest score (54%), which falls within the moderate category. Comparing these results with a study by Khoirunnisa and Sabekti (2020) on 190 high school students in Tanjungpinang City, which examined chemical bonds, reveals that only 1.58% of students were classified as having very high critical thinking ability, with a similar percentage falling into the high category. Most students were categorized as moderate (26.84%), low (33.16%), and very low (36.84%). This indicates that the distribution of critical thinking ability levels among high school students in Tanjungpinang is significantly lower than in this study, which showed that all students from the three schools were above the very low category, with two schools even reaching the moderate category.

To complement the percentage-based results and provide a more detailed description of students' performance, descriptive statistical analysis using mean scores and standard deviations was conducted to examine score distribution and variability. Accordingly, Table 1 presents the average percentage, mean score, and standard deviation of students' critical thinking abilities for each indicator assessed in the field test.

Table 1. Percentage of Critical Thinking Ability per Indicator

No	School	Representation Ability	Mean	Standard Deviation (SD)	Percentage (%)	Ability Category
1	A	Interpretation	3.5	11.0	64	Good
		Analysis	3.0	17.2	68	Good
		Inference	4.0	13.4	65	Good
		Evaluation	3.0	0.70	61	Good
		Explanation	3.7	64.7	84	Excellent
2	B	Interpretation	2.2	6.0	28	Less
		Analysis	2.7	10.4	32	Less
		Inference	2.8	6.3	28	Less
		Evaluation	2.5	13.4	37	Less
		Explanation	4.2	50.4	50	Moderate
3	C	Interpretation	2.7	15.3	58	Moderate
		Analysis	3.0	14.1	64	Good
		Inference	3.1	18.0	62	Good
		Evaluation	2.6	18.7	63	Good
		Explanation	4.3	70.3	87	Excellent

According to the data in Table 1, students at School A performed well in all indicators, with the highest score in Explanation at 84% and the lowest in Evaluation at 61%. This indicates that students can effectively explain reasons and information, and are sufficiently competent in evaluating them. School B showed low achievement in all indicators. The percentages range from 28% to 50%, with the dominant category being "below average." This suggests that students at this school exhibit a low level of critical thinking ability. Finally, school C achieved satisfactory to excellent results, with the highest achievement in the Explanation indicator at 87% and the weakest in Interpretation at 58%. This reflects that students' ability to explain has developed well, but there is still room for improvement in interpreting information.

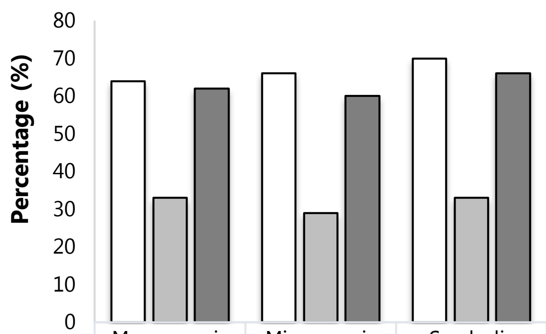
These results suggest that students' critical thinking ability varies from one school to another. Schools that have an active and practical learning approach (such as School A and C) tend to have higher levels of critical thinking ability than less supportive schools, such as School B. The Explanation indicator dominates across all schools, indicating that students find it easier to explain their ideas or arguments but struggle when it comes to interpreting, evaluating, or drawing conclusions from new data or information.

This study was compared with a study conducted by Andraini et al. (2021), which measured critical thinking ability in redox materials using the same indicators and achieved an average score of 56.14% (enough to be considered a category). The Interpretation and Evaluation indicators in that study were relatively low, at 40% each. This aligns with the results of this study, which indicate that Evaluation and Interpretation are also still relatively low, particularly at school B. However, there is a significant difference in the Explanation indicator in this study, especially at school C, where the indicator reached 87% in the excellent category. In contrast, at MAN 1, as reported in the study by Andraini et al. (2021), the rate was only 63% in the adequate category. This may indicate differences in teaching methods or learning strategies applied.

Students' critical thinking abilities can be developed through continuous practice, as every student already has the potential to think critically. Therefore, the role of teachers is crucial in stimulating the development of critical thinking ability, one of which is by regularly providing practice questions (Andraini et al., 2021). As stated by Fatmawati et al. (2014), through the process of completing these exercises, students begin to learn how to formulate problems, plan solutions, analyze the steps taken, and make assumptions when encountering incomplete data. This process serves as an essential means of developing critical thinking ability.

Furthermore, when compared to the research by Anisah et al. (2025), which analyzed the critical thinking ability profile of phase F students in chemistry learning on acid-base material, there were significant differences in the achievement of each indicator. The study reported interpretation percentages of 36.93%, analysis 17.12%, inference 21.17%, evaluation 33.33%, and explanation 36.04%, all of which fall into the low to very low category. This comparison reveals that the achievements of this study, particularly at school A and C, surpass those of Anisah et al.'s study across all indicators, with a notable difference in the explanation indicator, which ranges from 84% to 87%, compared to 36.04% in Anisah et al.'s study. This difference in results may be due to the different characteristics of the material, specifically the buffer solution used in this study, which was presented using an e-instrument with each question integrated with multiple representations, compared to the acid-base material in Anisah et al.'s study, which only utilized critical thinking ability indicators. Additionally, the presence of multiple representations in the questions of the e-instrument in this study has the potential to provide richer visual, symbolic, and conceptual stimuli, thereby fostering the development of critical thinking ability, particularly in the ability to provide explanations. Meanwhile, the results of the multiple representation ability analysis are presented in Figure 3.

Based on the results of the data analysis in Figure 3, it was found that the multiple representation ability of students in completing the e-instrument at School A showed the highest score, with a macroscopic representation ability percentage of 64%, a microscopic 66%, and a symbolic 70%, all of which were in the good category. Meanwhile, school C also achieved satisfactory results, particularly in macroscopic and symbolic representation, with percentages of 62% and 66%, respectively. However, the microscopic representation percentage was only 60%, which is still considered moderate. Conversely, School B showed lower overall achievements, with macroscopic and symbolic percentages of only 33% and microscopic percentages of 29%, all three falling into the lower category.



	Macroscopic	Microscopic	Symbolic
A	64	66	70
B	33	29	33
C	62	60	66

Figure 3. Multiple Representation Ability Levels

These results indicate that, in general, students have a better grasp of symbolic and macroscopic aspects than microscopic aspects, particularly in two schools; school A and C, which are in the higher category. This trend suggests that students are more familiar with concrete and visual concepts (macroscopic) as well as calculations and formulas (symbolic), but still struggle to comprehend abstract concepts related to particles and mechanisms (microscopic).

These results are similar to those found in a study by Hikmayanti and Utami (2019) on eleventh-grade students at MAN 1 Pekanbaru, which examined acid-base titration material. The study also found that macroscopic and symbolic representations were aspects that students mastered relatively better than microscopic representations. However, a notable difference lies in the percentage achievements, where Hikmayanti and Utami's study reported that students' representation abilities tended to fall into the categories of adequate to very good in three aspects: macroscopic at 95.33%, symbolic at 64.58%, and microscopic at 41.11%. Meanwhile, in this study, two schools, school A and C, demonstrated good achievement in two aspects (macroscopic and symbolic) and adequate performance in the microscopic aspect, resulting in overall better outcomes in their research. The characteristics of the material may influence these differences, the learning strategies employed, and the measurement context through e-instruments, which may provide more varied stimuli in eliciting students' multiple representation ability.

In comparison to Zahro and Ismono's (2021) research on chemical equilibrium material, the study found that 31 senior high school students achieved a macroscopic percentage of 35.01% (insufficient), a microscopic percentage of 40.59% (insufficient), and a symbolic percentage of 50.55% (sufficient). The results of this study are significantly higher, particularly in macroscopic and symbolic representation, at the two schools, namely, schools A and C. Moreover, the microscopic scores of students at these two schools are in the good range (60–66%). Conversely, research conducted by Zahro and Ismono (2021) indicates that most students possess representation abilities that fall into the insufficient category, both in microscopic and macroscopic aspects.

4. Conclusion

Based on the results obtained from the three schools, the developed e-instrument was effective in assessing students' critical thinking and multiple representation abilities. In general, the instrument demonstrated its usefulness in evaluating these skills in the context of buffer-solution learning. The highest critical thinking ability was demonstrated by students at school A, with a percentage of 69% (good category), followed by school C (63%, good category), and the lowest at school B (54%, moderate category). The explanation indicator achieved the highest scores in all three schools, while the interpretation and evaluation indicators were relatively low, particularly at school B. Meanwhile, the highest multiple representation ability was also demonstrated by students at school A, who excelled in all aspects of macroscopic (64%), microscopic (66%), and symbolic (70%) representation. These findings indicate that students find it easier to understand concrete concepts (macroscopic and symbolic) than abstract concepts (microscopic). A comparison with previous studies shows that student achievement in this study is relatively higher, particularly in the explanation indicator and the symbolic aspect. Therefore, the developed e-instrument has the potential to serve as a tool for measuring critical thinking ability and multiple representations in chemistry education, and can be adapted to enhance the quality of more authentic and meaningful learning evaluations.

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