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Development of Assessment Tools for Understanding Submicroscopic Representations in Acid-Base Material

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Abstract
Acid-base material should ideally be evaluated holistically through the triplet of macroscopic, submicroscopic, and symbolic representations. However, the assessments conducted so far have primarily not evaluated the ability to understand submicroscopic representations and still focus on macroscopic and symbolic representations. Therefore, this research aims to develop an instrument for assessing submicroscopic understanding of acid-base material and analyze its feasibility. The research method used is the 4D model development, carried out up to the develop stage. The results of the content validation by expert validators yielded an average score of 91.2%, which falls into the very valid category. The empirical test results on 116 chemistry teachers and prospective chemistry teachers showed that all items on the instrument were valid with a reliability of 0.60, which falls into the reliable category. Moreover, the instrument has varying levels of difficulty index and discrimination power. The test items' character in the instrument assesses understanding of submicroscopic representations of acid-base concepts such as solution properties, acid strength, acid constant, pH, and degree of dissociation. The recommendation for further research is the need to develop and apply submicroscopic understanding questions in other chemistry topics as a reinforcement in the assessment and evaluation process of chemistry learning.

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INTRODUCTION

The triplet representation used to understand chemistry is macroscopic, submicroscopic, and symbolic, including on acid-base material. Students' success in mastering acid-base material can be measured by their ability to use the triplet of chemical representations to solve problems. (Farida et al., 2010; Sari & Helsy, 2018). In acid-base material, macroscopic representation includes factual knowledge that can be perceived using the senses. For example, blue litmus paper turns red when dipped in an acidic substance, and the sour taste in fruits is caused by the presence of acid. Submicroscopic representation includes conceptual knowledge involving the depiction of particles, molecules, compounds, or atoms to explain the macroscopic phenomena that occur. For example, a hydrochloric acid solution is depicted with hydrogen ions and chloride ions in water without the presence of hydrogen chloride molecules.

Symbolic representation encompasses procedural knowledge in the form of symbols or equations to quantify the facts or concepts present in a phenomenon. For example, the pH formula is used to factually prove whether a substance is acidic or basic while simultaneously demonstrating the acid-base concept using the depiction of hydrogen ions or hydroxide ions contained in the substance. Mastery of the three representations above is necessary to prevent a fragmented understanding of chemistry (Khaeruman et al., 2017).

(Hulyadi et al., 2024) State a holistic understanding of chemistry requires the ability to interrelate among macroscopic, submicroscopic, and symbolic representations. If the interrelation fails to be established, the understanding of chemistry becomes fragmented. One of the key representations in a comprehensive understanding of chemistry is the submicroscopic representation. Submicroscopic representations are essential in explaining experimental observation results, evaluating student understanding, and identifying student misconceptions (Devetak et al., 2009).

Many chemical phenomena can only be explained by understanding the changes in the arrangement and movement of atoms and molecules (Harrison & Treagusf, 2002), making submicroscopic representations crucial for students' conceptual understanding. Nevertheless, mastery of chemical representations poses a unique challenge for students. The causes of these student difficulties are the lack of learning experience in the macroscopic aspect, misconceptions about the particle concept, insufficient ability to visualize particulate entities, inadequate ability to express chemistry in the symbolic aspect, difficulty in transitioning between representations (Gilbert & Treagust, 2009) and the minimal introduction of submicroscopic representations in textbooks (Hrast & Savec, 2017).

Research reports that the submicroscopic understanding achievement of high school students in solution chemistry topics is only 43%. (Devetak et al., 2009). Students often hold several misconceptions regarding the arrangement of solute particles in a solution and the concept of concentration at the particulate level. They also face challenges in drawing submicroscopic representations of ionic compounds in solution, as well as of saturated and diluted solutions. Additionally, high school students frequently struggle with transitioning between submicroscopic and symbolic representations, although they tend to be more successful when moving from macroscopic to submicroscopic representations. (Sari & Helsy, 2018). Research also revealed that the average achievement of multiple representation abilities of eleventh-grade students in acid-base material falls into the low category (Hidayah & Ardhana, 2024), whereas in chemical equilibrium material, the lowest level is at the submicroscopic level compared to the macroscopic and symbolic levels (Ahmar et al., 2020; Indrayani, 2013).

Prospective chemistry teacher students also struggle to accurately represent the submicroscopic aspects of precipitation reactions (Nakiboğlu & Nakiboğlu, 2019). In the acid-base material, students were reported to have submicroscopic misunderstanding errors, meaning they could not provide a submicroscopic depiction of strong acid solutions, strong base solutions, weak acid solutions, weak base solutions, and salt solutions because the students did not master the concept of ionization that occurs (Indrayani, 2013).

Several studies have undertaken efforts to develop comprehension question instruments on acid-base-related materials. The evaluation instrument for higher-order thinking skills (HOTS) on the topic of acids and bases (Siregar et al., 2023; Sukarma et al., 2024) as well as solubility equilibria and solubility product (Sarah et al., 2021) has been successfully developed and meets the aspects of validity and reliability. The research successfully developed an instrument based on multiple representation interconnections on the buffer solutions topic (Fadhilah et al., 2018) and a diagnostic instrument for students' mental model representations of acid-base material (Devi & Azra, 2023). Efforts to improve understanding through submicroscopic approach learning (Indrayani, 2013) and problem-based learning (Kasanah & Ardhana, 2024) have proven to enhance students' abilities in solving macroscopic, submicroscopic, and symbolic problems compared to conventional classes. Using multimedia in the material on electrolyte and non-electrolyte solutions can also help students' understanding, especially at the submicroscopic and symbolic levels (Eliyawati et al., 2018). Developing virtual lab media on acid-base material by integrating submicroscopic representations also yields high validity (Muslim & Ardhana, 2023).

Several studies mentioned above indicate that many assessment instruments have been developed to evaluate students' understanding of solution-related material. Many instruments have been developed in the acid-base material to test students' understanding of multiple representations. However, the development of instruments specifically evaluating students' understanding of submicroscopic representations has not been widely conducted. Evaluation of understanding submicroscopic representations in chemistry concepts is rarely conducted because chemistry education mainly represents only two levels, namely the macroscopic and symbolic levels, while the submicroscopic level tends to be neglected (Ariani et al., 2020; Mashami et al., 2021; Sagita et al., 2017).

However, evaluating understanding of submicroscopic representations can be used by teachers to enhance students' overall understanding of chemistry concepts (Winarti et al., 2019). Field analysis results also show that teachers actually need instruments for assessing submicroscopic understanding but are hindered by inadequate reference sources and a lack of time due to the need to create questions using several applications. Thus, the instrument developed in this study is expected to be not only valid and reliable but also a comprehensive assessment tool for evaluating and enhancing students' understanding of submicroscopic concepts in acid-base material. In addition, the instrument can also contribute to the process of diagnosing students' holistic understanding regarding the particulate aspects of acid-base material.

METHOD

The instrument development in this study refers to Thiagarajan's Research and Development (R&D) design. The development steps referred to are 4D (define, design, develop, disseminate) carried out up to the develop stage. The 4D model was chosen because of its flexibility in developing instruments that require thorough validation. This research is limited to the develop stage because it focuses more on producing valid and reliable instruments before being tested more broadly. The first stage is define, which aims to determine the specifications of the instrument development product. The steps taken at this stage are needs analysis, subject analysis, concept analysis, and submicroscopic representation analysis. The needs analysis is conducted to identify the issues related to the necessity of developing submicroscopic representation questions. Subject analysis is conducted to determine the subjects for empirical trials by the characteristics of the developed submicroscopic ability questions. Concept analysis is conducted to determine the material and sub-material that will be developed in the test instrument. Analysis of submicroscopic representation is conducted to determine the aspects of particulate imagery that will be developed in the questions. The analysis method was conducted at the define stage through questionnaire completion and document study.

The second stage is design, which aims to develop the instrument design that will be created. The steps taken at this stage include determining the form of the questions, compiling the blueprint and question indicators, adjusting the cognitive dimension levels of the questions, and creating answer keys and assessment rubrics. The third stage is develop, which aims to produce the question instrument based on the established specifications and design. The developed instrument product is then subjected to content validation by two expert validators, one chemistry lecturer and one chemistry teacher, who assess it in terms of concept, appearance, construction, and language. After the content validation was conducted, the instrument was revised according to the suggestions and feedback provided by the validators.

An empirical validation process is conducted to obtain the validity and reliability values of the instrument. At this stage, the instrument was tested on 116 teachers and students. The trial results were then analyzed statistically using the SPSS version 26 application. The instrument's validity was analyzed using the Pearson correlation test, while the reliability of the instrument was analyzed using the Alpha-Cronbach analysis. A valid item means it can accurately measure the established competency. As for reliable test items, they show consistent results when applied to different subjects.

In addition to validity and reliability tests, a descriptive quantitative analysis of the items was also conducted, which involved reviewing the items based on empirical test data to obtain a more in-depth description of each item. The quantitative analysis of the test items in this study includes the level of difficulty and discrimination power of the items, which is conducted using the ANATES version 4 application. This application can automatically generate each item's discrimination power and difficulty level after inputting the raw data from the trial. The difficulty index is the difficulty level of a question based on the proportion of test-takers who answered correctly compared to all test-takers. Discriminating power is the ability of a test item to differentiate between students with high and low abilities. In other words, the discriminating power is related to the degree to which a test item can effectively differentiate test-taker behavior in answering the developed test instrument. The criteria for empirical validity, difficulty level, and item discrimination power are presented in Table 1 below.

Table 1. Criteria for empirical validity, difficulty level, and discrimination power of the question item (Miterianifa & Zein, 2016)

Empirical Validity	**Criteria**	**Difficulty Level**	**Criteria**	**Discrimination Power**	**Criteria**
$r_{hitung} > r_{tabel}$	Valid	0,00 – 0,32	Difficult	0,00 – 0,20	Poor
$r_{hitung} < r_{tabel}$	Invalid	0,33 – 0,66	Moderate	0,21 – 0,40	Satisfactory
		0,67 – 1,00	Easy	0,41 – 0,70	Good
				0,71 – 1,00	Excellent
				Negative	Bad

RESULTS AND DISCUSSION

At the define stage, the needs analysis results conducted with students show that high school teachers have not introduced submicroscopic representations in teaching or assessment processes. Submicroscopic representations are introduced during lectures, although they have not yet been fully integrated into the assessment process. Student respondents stated that the character of chemistry assessments in high school tends to be rote memorization and calculations. This indicates that chemistry assessments are still focused on macroscopic and symbolic representations. Based on this, submicroscopic representation becomes important to evaluate through the assessment instrument that will be developed.

The results of the subject analysis show that solving submicroscopic ability problems requires the ability to interrelate with other representations, namely macroscopic and symbolic. This interrelation requires an abstract to formal thinking level that teenagers possess to adults. Thus, the selected subjects are chemistry teachers and prospective chemistry teachers because they have met the level of abstract and formal thinking abilities used to solve the problems. The selection of subjects used a non-probability approach, namely the convenience sampling technique, considering the available chemistry teachers and prospective chemistry teacher students. The selected subjects meet several relevant criteria, namely prospective chemistry teacher students who have at least completed the basic chemistry course and chemistry teachers who teach chemistry subjects at their respective schools.

The results of the concept analysis show that the chemistry topic closely related to submicroscopic representation is solutions. One of the materials in the topic of solutions is acids and bases. This material is suitable for use as content in instrument development because it has sufficiently broad submicroscopic characteristics to understand its material, where each acid-base subtopic can be developed into submicroscopic questions. The subtopics developed in the submicroscopic question instrument are acid-base theory, acid-base strength, acid-base pH, and degree of dissociation.

The results of the submicroscopic representation analysis indicate that the developed indicators are determining the submicroscopic representation of acidic, basic, and neutral solutions (question item number 1); determining the submicroscopic representation of strong acid, weak acid, divalent strong acid, strong base, and weak base solutions (question item numbers 2-6), ordering several submicroscopic representations of solutions from weak to strong acidity (question item number 7), ordering the pH of solutions from the lowest to the highest based on submicroscopic representations (question item number 8); calculating the degree of dissociation from the submicroscopic representation of acidic solutions (question item number 9); and calculating the K_a value from the submicroscopic representation of acidic solutions (question item number 10).

At the design stage, the form of the questions is determined to be multiple-choice with reasoning. Multiple-choice questions are easy to answer in the assessment process. Moreover, multiple-choice questions cannot evaluate enough students' procedural knowledge patterns during the problem-solving process. Therefore, in this study, multiple-choice questions are supplemented with reasoning to address this weakness. Providing reasons for multiple-choice questions can reveal students' thinking systems in understanding the submicroscopic representation of solutions and their ability to transition between chemical representations. The developed grid is derived from concept analysis and submicroscopic representation analysis results. The answer key for the multiple-choice section is determined by giving 1 point for a correct answer and 0 points for an incorrect answer. In contrast, the reasoning section is developed by awarding points according to the completeness of the answer. The test instrument was developed using the ChemDraw Professional 2D 16.0 and Chem3D 16.0 applications. Chem3D 16.0 is used to create submicroscopic images of specific particles in a solution, while ChemDraw Professional 2D 16.0 is used to arrange the particles in a complete solution image.

At the develop stage, the instrument received an average content validation score of 91.2% from expert validators, which falls into the very valid category. The results of the empirical trial with 116 teachers and students statistically produced data on empirical validity, difficulty level, and item discrimination power, as shown in Table 2.

Table 2. Results of the analysis of empirical validity, difficulty level, and discrimination power for question item

Item	**Empirical Validity**		**Criteria**	**Total Correct Answer**	**Difficulty Level**	**Criteria**	**Daya Beda**	**Criteria**
	r_{hitung}	r_{tabel}						
1	0,193*	0,181	Valid	109	0,940	Easy	0,129	Poor
2	0,672**	0,181	Valid	39	0,336	Moderate	0,742	Excellent
3	0,561**	0,181	Valid	38	0,328	Moderate	0,548	Good
4	0,601**	0,181	Valid	23	0,198	Difficult	0,581	Good
5	0,571**	0,181	Valid	35	0,302	Moderate	0,710	Excellent
6	0,612**	0,181	Valid	42	0,362	Moderate	0,742	Excellent
7	0,570**	0,181	Valid	54	0,466	Moderate	0,710	Excellent
8	0,249**	0,181	Valid	69	0,595	Moderate	0,258	Satisfactory
9	0,394**	0,181	Valid	94	0,810	Easy	0,452	Good
10	0,343**	0,181	Valid	24	0,207	Difficult	0,323	Satisfactory

Based on the empirical validity results in the table above, the r_{hitung} values of all questions exceed the r_{tabel}, which means that all the developed items are valid. The difficulty level of the questions is distributed such that there are easy, moderate, and difficult questions, with the majority being moderate. The discrimination power of the questions is also distributed from the category of poor to very good. The results of the instrument reliability test yielded a score of 0.60, which falls into the reliable category (Arikunto, 2021). Valid and reliable instruments complement the development of instruments on other solution topics, such as diagnostic tests to see the mental model representation in acid-base material (Devi & Azra, 2023) and multiple representation-based instruments on buffer solution material (Fadhilah et al., 2018).

The character and model of the submicroscopic understanding instrument in several test items are described as follows. First is the question developed from item number 4, which tests the understanding of the submicroscopic representation of an acid solution shown in the following Figure 1.

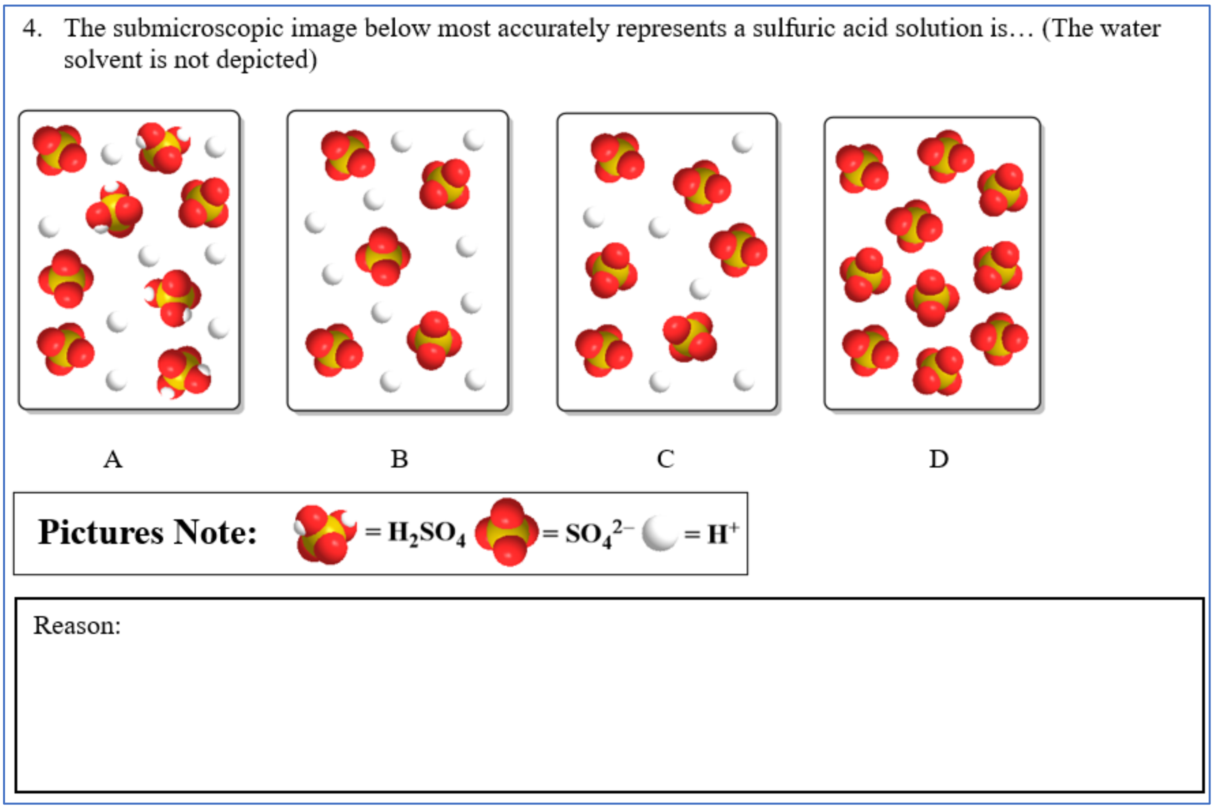
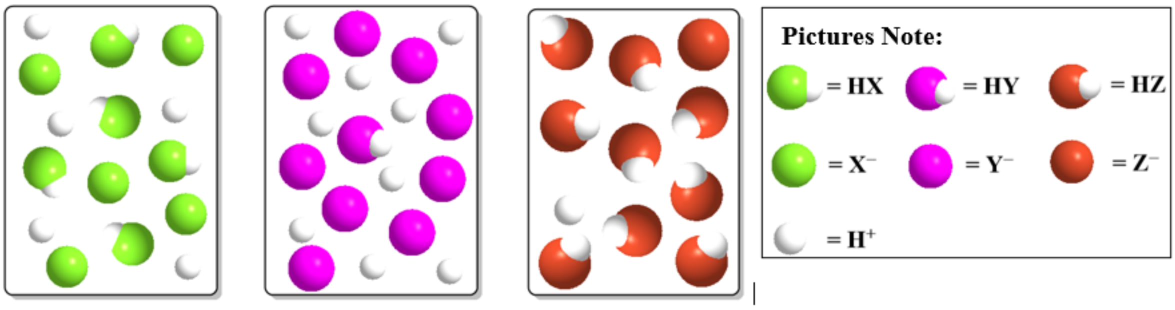


Figure 1. The result of the development of question number 4

Based on the analysis at the define stage, question number 4 above aims to test the understanding of the submicroscopic representation of a strong acid solution with a valence of more than one, namely sulfuric acid, which in this case is related to the stoichiometry of its dissociation reaction. Based on the results of empirical testing, the above question has a difficulty level categorized as difficult and a discrimination power categorized as good. This question falls into the difficult category because most participants were misled into choosing option C, while the correct answer is option B. The test subjects correctly identified that sulfuric acid is a strong acid that completely dissociates in water, leaving only hydrogen and sulfate ions in its solution, as shown in options B and C. However, as shown in option B, they do not comprehensively understand that sulfuric acid completely dissociates to produce hydrogen and sulfate ions in a stoichiometric ratio of 2:1. Thus, the correct representation is option B, where the number of hydrogen ions is 10 and the number of sulfate ions is 5 with a ratio of 2:1. As for option C, it is incorrect because the ratio of hydrogen ions to sulfate ions is the same, which is 1:1. The question above has a good discrimination power, meaning it can differentiate between upper and lower group subjects. In this case, more subjects from the upper group answered correctly than those from the lower group. The results of the trial on this question, which show students' difficulty in understanding the submicroscopic representation of strong acids with more than one valence, support the findings regarding students' misconceptions about the concept of ionization. (Indrayani, 2013).

The second is the development of question number 8, which tests the ability to relate pH to the submicroscopic depiction of several acid solutions shown in Figure 2 below.

8. Observe the submicroscopic images of the acid solutions HX, HY, and HZ below! (The solvent water is not depicted)



HX HY HZ

The order of submicroscopic images of the solution from the highest to the lowest pH is …

A. HX → HZ → HY
B. HZ → HY → HX
C. HZ → HX → HY
D. HY → HX → HZ

Reason:

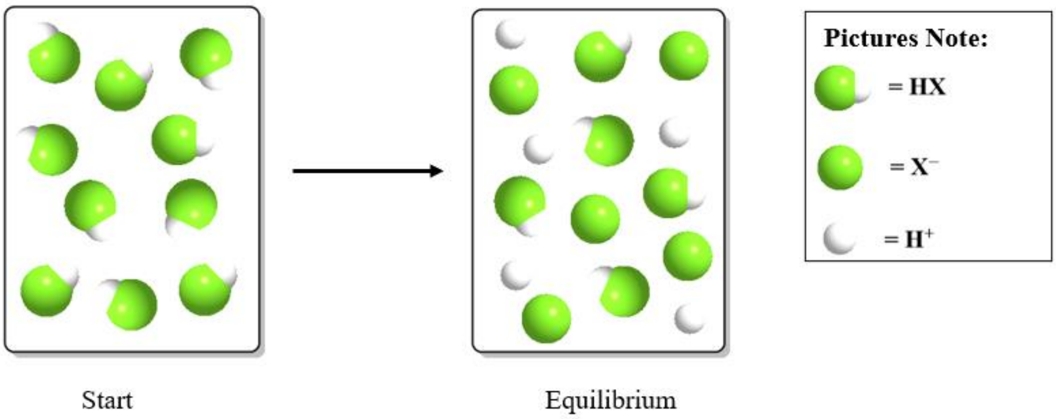
Figure 2. The result of the development of question number 8

Based on the analysis at the define stage, the question above aims to test the understanding of ordering the pH of several submicroscopic solution images from high to low. The question above has a difficulty level in the moderate category and a discrimination power in the sufficient category. This question falls into the moderate difficulty category because half of the test subjects answered option D correctly. This means that the subjects have a sufficient understanding that the concept of pH in acidic solutions is related to the amount of hydrogen ions that dissociate in the solution. The more hydrogen ions dissociate, the stronger the acid and the lower the pH value. Conversely, the fewer hydrogen ions dissociating, the weaker the acid strength and the higher the pH value. Thus, the lowest pH is shown by the acid solution HY with the highest number of hydrogen ions, while the highest pH is shown by the acid solution HZ with the lowest number of hydrogen ions.

The question above has a moderate level of discrimination power, meaning it can differentiate between the upper and lower group subjects. In this case, more upper-group subjects answered correctly than lower-group subjects, although the difference was not very significant. The trial results on this question support previous research that shows the difficulty in linking the concept of pH with the dynamics of its constituent particles. (Hidayah & Ardhana, 2024).

Third is the development of question item number 9, which tests the ability to relate the degree of dissociation concept with the submicroscopic depiction of an acid solution shown in the following Figure 3.

9. Observe the submicroscopic illustration of the HX acid solution below! (The solvent water is not depicted)



Based on the illustration above, the degree of dissociation of acid HX is …

A. 0,10
B. 0,25
C. 0,50
D. 0,75

Reason:

Figure 3. The result of the development of question number 9

Based on the analysis at the define stage, the question above aims to test the understanding of calculating the degree of dissociation of an acid solution when given a submicroscopic depiction at the initial and equilibrium conditions. The question above has a difficulty level categorized as easy and a discrimination power categorized as good. This question falls into the easy difficulty category because most of the test subjects answered option C correctly. This means that most subjects understand the concept of degree of dissociation, which is expressed as the number of moles that dissociate divided by the initial number of moles.

In this case, one mole of acid is represented by one image of the HX molecule. At the initial condition, there are ten molecules of HX, whereas at equilibrium, five molecules of HX dissociate into H^+ and X^-, leaving five molecules of HX that remain undissociated. Thus, the degree of dissociation of the HX acid solution is 5/10 = 0.5. The question above has a good discrimination power, meaning it can differentiate between the upper and lower groups of subjects. In this case, more subjects from the upper group answered correctly than subjects from the lower group. The results of this question trial are consistent with previous research that shows students' understanding of the concept of degree of dissociation from the initial and equilibrium particle representations. (Aisy & Ardhana, 2023).

The development of questions on submicroscopic representation understanding is important because students' understanding of chemistry is demonstrated by their ability to connect macroscopic phenomena, the submicroscopic world, and symbolic representations to solve chemistry problems (Farida, 2009). Submicroscopic representations become a key factor in that process, as the inability to understand these representations can hinder problem-solving related to macroscopic phenomena and symbolic representations. Moreover, students' ability to explain macroscopic phenomena depends on their understanding of particle behavior at the submicroscopic representation (Al-Balushi, 2013; Treagust & Chittleborough, 2007). The instrument developed can be used in the learning process in diagnostic tests at the beginning of the learning or quizzes in the middle of the learning. In addition, the instrument can also be used as a reference in formative or summative assessments to evaluate the learning of acid-base material that has been conducted.

CONCLUSION

A question instrument has been developed to test the understanding of sub-microscopic representations in acid-base material. The question instrument received a score of 91.2% in the content validity stage by expert validators, categorized as very valid. At the empirical testing stage, ten questions were declared statistically valid and received a reliability score of 0.60, which falls into the reliable category. The items on the instrument also have varying levels of difficulty and discrimination power. The characteristics of the test items in the instrument are to assess understanding of sub-microscopic representations, namely understanding the depiction of acid and base solutions, relating acid strength to pH, and analyse the degree of dissociation and acid strength constant based on the provided sub-microscopic depiction.

RECOMMENDATIONS

Based on the results of the instrument development in this study, it is recommended that chemistry teachers and prospective chemistry teachers introduce submicroscopic ability questions in both the teaching process and assessment. In formulating submicroscopic ability questions, chemistry teachers and prospective chemistry teachers also need to be very careful in relating the submicroscopic depiction of solutions to the stoichiometric concepts involved. Further research that can be proposed is to explore the submicroscopic understanding of acid-base material among students, university students, and chemistry teachers, considering that this material is key to understanding other solution materials such as buffer solutions, salt hydrolysis, and solubility.

Future researchers hope to develop instruments for submicroscopic understanding questions on other chemistry topics while also analyzing the profiles and thinking systems of students, prospective chemistry teachers, and chemistry teachers. In practical use, teachers can use some or all of the questions in the developed instrument in learning assessments by combining them with available cognitive questions. In addition, the instrument can also be integrated into enrichment activities.

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