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Investigating Learners' Conceptual Progression on pH of Solution, Acid-Base Titration, and Buffer Solutions

Eldat Wira Santa[1], Sumari[2], Hadi Nur[2], Nur Candra Eka Setiawan[3], Muntholib[2]*
[1]Doctoral Program of Chemistry Education, Universitas Negeri Malang, Indonesia
[2]Department of Chemistry, Universitas Negeri Malang, Indonesia
[3]School of Education, Universiti Teknologi Malaysia, Malaysia

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***Correspondence Address:**
muntholib.fmipa@um.ac.id

Abstract: This study aims to explore the development of understanding of the concepts of pH, acid-base titration, and buffer solutions among 11th-grade students and 2nd- and 4th-semester university students in chemistry education. It employs a cross-sectional design using open-ended questions and interview guidelines to collect data from 153 11th-grade students, 30 second-semester university students, and 40 fourth-semester university students. The open-ended questionnaire consists of 9 items (2 questions on the pH of solutions, 4 questions on acid-base indicators and titration, and 3 questions on buffer solutions and salt hydrolysis) on a continuous scale, with an Aiken's kappa validity of 0.61 (substantial agreement) and a Cronbach's Alpha reliability (KR-20) of 0.75 (acceptable). The results indicate that scientific understanding of pH concepts, such as the pH of solutions, acid-base titration, and buffer solutions, improves with education. However, comprehension of complex concepts remains low. The study's implications highlight the need for curriculum development and the selection and implementation of learning strategies that enable students to learn in a structured, gradual, and coherent manner. Curriculum development should map out subject matter, distinguish essential from non-essential content, and organize material from simple and essential topics to more complex and non-essential ones.

INTRODUCTION

Conceptual understanding is a fundamental goal of science instruction, including in the field of chemistry. It represents the depth of learners' comprehension of scientific concepts and their ability to apply this knowledge meaningfully. The progression of learners' understanding of a specific topic across different educational levels illustrates their learning progression. This progression not only captures the gradual refinement and expansion of their conceptual knowledge but also reflects their cognitive development. The quality of this cognitive development is closely tied to the nature and effectiveness of the learning experiences they undergo, highlighting the critical role of well-structured and thoughtfully implemented instructional strategies in fostering meaningful and enduring understanding (Jin et al., 2019; Scott et al., 2019; Yang et al., 2023). This means that learning progress is very important for curriculum development, learning development, and learning evaluation. One of the chemistry subjects studied at the secondary and tertiary education levels is acid-base chemistry. Many studies have been conducted on learners' understanding of acid-base chemistry concepts. At the tertiary level, it is reported that 78% of second-semester students experienced partial understanding, misconception, and did not understand acid-base chemistry concepts. Another study with the same material conducted by Elvinawati et al. (2022) showed that 53.85% of students experienced partial understanding and misconception. Meanwhile, at the secondary education level, Amala et al. (2022) reported that students' understanding of salt hydrolysis concepts was relatively low with an average percentage of 43.95%. However, these studies were conducted separately between secondary education and higher education levels. There has been no research that examines the student learning progression from lower to higher levels of education. In other words, in Indonesia, curriculum development and learning development and evaluation have not paid attention to student learning progression. Therefore, it is very important to carry out studies on learning progression.

Learning progression is "a description of the learner's way of thinking logically and systematically about a topic" (Alonzo et al., 2022; Park et al., 2019; Reed & Wolfson, 2021; Scott et al., 2019; Yang et al., 2023). Learning progressions describe the changing of students' understanding on a topic over time (Jiménez-Liso et al., 2020). When starting to learn a new topic, a learner may already have an initial, non-scientific understanding. If he gets good guidance, he matches his understanding with the new knowledge being studied, collects new evidence, carries out critical analysis, and finally replaces his non-scientific understanding with scientific understanding. Armed with this new scientific understanding, he can learn new knowledge related to that knowledge more easily so that his understanding becomes deeper and broader. This illustration depicts a learning progression of a learner from initial non-scientific understanding /misconceptions, turning into scientific understanding, and being able to use it to build new, deeper and broader scientific knowledge.

Learning progression can be organized in both vertical and horizontal formats (Reed & Wolfson, 2019, 2021). Vertical alignment refers to the progression of concepts from foundational to more advanced levels of education. Horizontal alignment, on the other hand, focuses on the growth of concepts within subjects at the same education level. This article adopts a vertical approach, encompassing education levels ranging from primary school to university.

A chemistry topic that gives rise to a lot of non-scientific understanding in students' minds is acid-base chemistry (Arocena, 2022; M. Cooper et al., 2016; Cyril et al., 2022; Demirdöğen et al., 2023; Dood & Watts, 2023; Frost et al., 2023; Gültepe, 2021; Krebs et al., 2022, 2023; Mubarokah et al., 2018; Muntholib et al., 2018; Net et al., 2024; Romine et al., 2016; Salame et al., 2022). These studies have yielded valuable insights into students' explanations of acid and base behaviour, their utilization of the Arrhenius, Brønsted-Lowry, and Lewis models, acid base titration, their comprehension of acid strength, and their capacity to forecast reactions involving these molecules. These findings serve as a reference for tracking the progress of acid-base understanding. The fundamental framework for the notion of acid-base chemistry progression was formulated by incorporating insights from previous literature on acid-base comprehension, while also considering the constraints imposed by the lower and higher limits. The lower bound pertains to the minimum level of prior information possessed by students. Conversely, the higher limit pertains to the extent of knowledge attained by college students studying advanced chemistry. Nevertheless, the advancement of concepts is also impacted by many elements of student learning, including instructional techniques and educational resources (Jin et al., 2019). The accuracy and depth of a learner's understanding can be represented in the form of a mental model.

Mental models are internal representations of external reality that individuals use to interact with their environment (Jones et al., 2011). These models are constructed from life experiences, perceptions, and understanding of nature, serving as tools for reasoning, decision-making, and behavior. They act as mechanisms for critical thinking in working memory, filtering and integrating new information (Jones et al., 2011). The quality of mental models depends on the effectiveness of learning experiences, which enhance reasoning and deepen understanding.

In acid-base chemistry, Lin and Chiu (2007) identified four levels of students' mental models: the Phenomenon Model, where acids and bases are understood based on macroscopic characteristics like toxicity or taste; the Character-Symbol Model, associating acids and bases with chemical symbols (e.g., H groups for acids, OH groups for bases); the Inference Model, showing partial scientific understanding but errors in concept connections, such as misinterpreting neutralization reactions; and the Scientific Model, representing accurate, scientific comprehension.

Romine et al. (2016) streamlined these categories into three levels: the Phenomenon Model, the Inference Model, and the Scientific Model, combining the Character-Symbol Model with the Phenomenon Model. This simplified framework highlights the progression from basic to advanced understanding, offering a basis for improving instructional strategies and fostering students' scientific reasoning in chemistry education.

The participants of this study were introduced to the 2013 Indonesian Curriculum, which incorporated inquiry-based learning. This approach involved engaging in activities such as observing, inquiring, experimenting, associating, and communicating (Permendikbud, 2016). The process of "associating" in learning allows learners to construct new information by utilizing evidence obtained from "investigating" learning events and their preexisting knowledge. This learning experience applies to the concept of learning progression, which refers to the advancement of an individual's knowledge through the utilization of their cognitive capacities to construct new knowledge using both fresh evidence and preexisting knowledge. The introduction of a distinct curriculum between secondary school and university levels can impede the cognitive development of individuals. Therefore, our objective is to analyze the development of the acid-base idea by investigating the cognitive frameworks maintained by students and college students. This analysis will offer valuable insights into the depth and breadth of their comprehension of the concept, which can subsequently be applied in the creation of learning progressions about acid-base. Therefore, the questions we want to answer through this research are:

1. What is the mental model of the acid-base concepts of eleven graders, 2nd semester chemistry undergraduate students, and 4th semester chemistry undergraduate students?
2. How do the learners' learning progression of acid-base concepts in line with their level of education?

METHOD

This research applies a cross-sectional research design with a survey method. The research subjects were 153 eleventh graders (71 men and 82 women), 30 second semester students (21 men and 9 women), and 40 fourth semester students (25 men and 15 women). Data collection was carried out using test and interview methods. Tests were carried out on all research subjects, while interviews were carried out on research respondents taken proportionally from research subjects in the high, middle and lowest groups at each level of education. Interviews were conducted to determine the development of the acid-base concepts and the characteristics of the respondents' mental models.

Instrument Development for Assessing Acid-Base Concepts

This research instrument was developed by own with procedures: (1) Literature review, (2) Development of items, (3) Expert validation, (4) Pilot study, and (5) Finalization (Muntholib et al., 2020; Wattanakasiwich et al., 2013). Questions were developed based on Anderson and Krathwol's Taxonomic Framework (Anderson et al., 2001; Krathwohl, 2002) cognitive levels of understanding, applying, analyzing and evaluating. The scope and complexity of the questions are in line with the acid-base chemistry subject matter of the 2013 High School Indonesian Curriculum and the Chemistry Undergraduate Program Curriculum. Validation involved 2 experts who have knowledge and experience in the field of chemistry learning. The final form of the instrument is 9 valid open ended question items (Aiken kappa validity of 0.61) with Cronbach's Alpha reliability (KR-20) 0.75.

Data Analysis

The data sources of this research are students' answers to the open ended test and interview transcripts of respondents conducted after they took the test. Each respondent's answer is read carefully, analyzed and compared with one another, and tentatively included in one of the categories of mental models of acid-based concepts that have been determined, namely: The Phenomenon Model, The Inference Model, and The Scientific Model (Romine et al., 2016). Responses that were difficult to categorize were discussed with all researchers until consensus was reached. To increase inter-rater reliability, before carrying out the assessment, the assessors shared their perceptions regarding the criteria for each mental model of the acid-base concepts examined in this research. The assessors of student responses in this study were one of the researchers and a high school chemistry teacher.

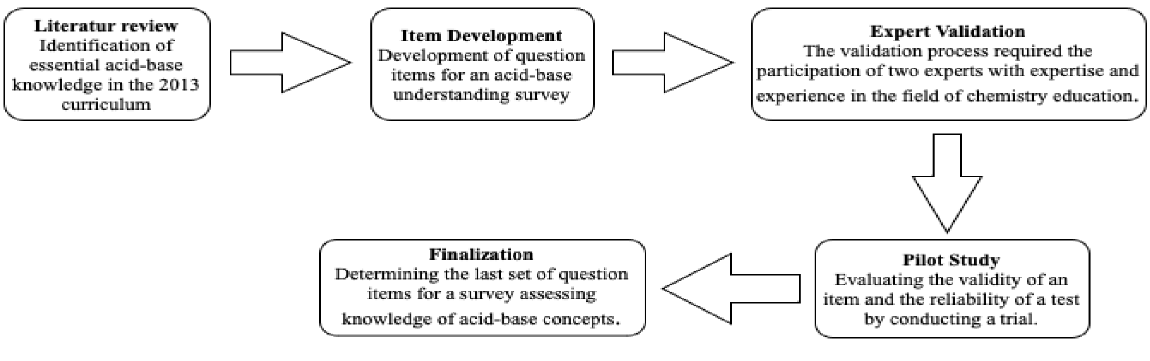

Figure 1. Stages of Acid-Base Instrument Development.

RESULT AND DISCUSSION

A learning progression is very important for the implementation of effective and efficient learning. With a good understanding of learning progression, instructors can design, develop strategies, and choose appropriate learning methods, especially in carrying out learning of complex concepts such as solution pH, acid-base titration, and buffer solutions. This research identified three levels of learners' mental models of acid-based concepts, namely Phenomenon Model.

Inference Model and Scientific Model (J. W. Lin & Chiu, 2007; Romine et al., 2016) at different educational levels, namely eleventh grade students, 2nd semester chemistry undergraduate students, and 4th semester chemistry undergraduate students. Table 1 presents the mental models of acid-base concepts of 11th grade students, 2nd semester of chemistry undergraduate students, and 4th semester of chemistry undergraduate students of the respondents of this study.

Table 1. Average Learners' Mental Model of Acid-Base Concepts.

Sub Consepts	Average Learners' Metal Model (Maximum Score = 100)								
	11th Graders			2nd Semester at University Students			4nd Semester at University Students		
	Pheno-menon	Inference	Scientific	Pheno-menon	Inference	Scientific	Pheno-menon	Inference	Scientific
pH Solutions	43.79	39.54	7.19	23.33	51.67	25.00	8.75	65.00	26.25
Acid-Base Titration	16.50	44.28	23.86	13.33	22.50	64.17	3.75	18.75	83.75
Buffer Solution	38.56	58.82	0.65	23.33	26.67	50.00	0.00	37.50	62.50
Average	**32.95**	**47.54**	**10.57**	**19.99**	**33.62**	**46.39**	**4.17**	**40.42**	**57.50**

Table 1 shows that the progression of learners' mental models is in line with the level of education, the higher the level of education, the better their mental models. However, if you look closely you can see several interesting learning progressions to discuss, both at the Phenomenon Model level, the Inference Model level, and the Scientific Model level.

Learning Progression of Phenomenon Mental Model of Learners

The average score of learners' Phenomenon Mental Model decreases drastically as the level of education increases. The acid-base sub-concept where the learners' Phenomenon Mental Model is still high is the pH of solution with an average score of 43.79 (from maximum score of 100), 23.33, and 8.75 respectively for eleventh graders, 2nd semester of university students, and 4th semester of university students.

The findings regarding the decline in students' understanding of the Mental Model of Phenomena as their education progresses align with the trends observed in previous studies. Our findings also show similar results where a significant decline in the mean score of 43.79 for eleventh graders, 23.33 for second-semester students, and 8.75 for fourth-semester students have shown the same pattern that understanding of chemistry concepts develops as students progress in their studies. Similar findings have been reported by Wan (2014). He reported that second and fourth semester students also often have difficulty in understanding abstract concepts that can lead to misunderstandings in basic chemistry courses. This result is also in line with the findings of Jensen, (2013), which shows that students often memorize facts without developing a deep understanding, which can explain the persistence of the mental model phenomenon that we found in semester 2 and 4 students.

In addition, a study by Tümay, (2016) also supports our findings, showing that traditional teaching methods often cannot address students' misconceptions and their difficulties in understanding complex topics. This study shows that as students progress in their education, their ability to connect and apply basic concepts gets stronger. This is in line with the observation that understanding of acid-base concepts increases over time.

Learning Progress of the Inference Model Mental of Learners.

Over the past decade, research has consistently emphasized students' difficulties understanding chemistry concepts, especially in pH, buffer solutions, and salt hydrolysis. This broader trend is consistent with the research results. The pH scale and acid-base chemistry are challenging for students of all educational levels, especially when understanding logarithmic relationships and acid dissociation constants (Bretz & McClary, 2015; M. M. Cooper et al., 2016). This is consistent with the anomalies observed in the data, which show improvement from eleventh graders to university students, but challenges remain. The gradual improvement in this study, from a mean score of 39.54 among eleventh graders to 65.00 at the fourth-semester university level, is consistent with previous research emphasizing the need for improved instructional strategies to address the challenges.

Similarly, the patterns from this research identified in your research regarding buffer solutions and salt hydrolysis are consistent with those found in previous studies. Research by Orgill & Sutherland, (2008) and Arocena, (2022) demonstrated that students encounter difficulties with these concepts due to their abstract nature, frequently prioritizing memorization over comprehension of the underlying mechanisms. This is consistent with the performance anomaly observed in our study, in which second-semester university students achieved an average score of 26.67 on buffer and hydrolysis concepts, which only improved to 37.50 by the fourth semester. This is due to the most recent research conducted by Adadan & Savasci, (2012), who found that buffer solutions continue to be a complex subject for students at the college level.

As observed in our study, the broader literature is consistent with the overall progression in students' mental models. J.-W. Lin et al., (2016); Amalia et al., (2018) and Sodanango et al., (2021) underscore that even as students' mental models develop over time, misconceptions frequently endure, particularly in intricate subjects such as chemistry. This pattern is consistent with the data provided, demonstrating a nonlinear progression and anomalies between second- and fourth-semester university students. These results indicate that, although exposure to advanced material does result in improvement, more profound misconceptions may remain unresolved.

Moreover, Jiménez-Liso et al., (2020) and López-Banet et al., (2021) research suggests that conventional instructional methods frequently must adequately address these misconceptions, particularly in abstract concepts such as buffer systems and acid-base equilibria. The enhancement in data may be attributable to increased practice; however, as previous research indicates, procedural learning is only achievable with conceptual comprehension. Our findings and earlier research demonstrate the persistence of these challenges across various levels of education, which underscores the necessity of more focused, concept-based instructional strategies to assist students in surmounting these obstacles.

Learning Progression of the Scientific Mental Model of the Learner

The learners' Scientific Model of acid-based concepts improves as the level of education increases. The average scores of the Scientific Model of eleventh graders, 2nd semester of university students, and 4th semester of university students were 10.57, 46.39, and 57.50 respectively. However, their achievement on the concept of pH of solution is very low, namely 7.19 for eleventh graders, 25.00 for semester 2 of university students, and 26.25 for semester 4 of university students. This is quite worrying because the concept of pH of solutions is very important for the social life of students.

This research also elaborates on how learners represent their mental models, both the Phenomenon Model, the Inference Model, and the Scientific Model. The representation of the learners' mental model in describing the concepts of pH of acid-base solutions, acid-base titration, and buffer solutions is shown in Table 2.

Table 2. Learners' Mental Models about pH of Solutions, Acid-Base Titrations, and Buffer Solutions.

Concepts	Mental Models	Submental Models	Description
All	-	-	Students do not have any idea about acid-base concepts or they cannot remember anything that can be used to describe their mental model.
pH of acid-base solutions	Inference	Mathematical equations	Interpret $[H]^+$ in the equation of $pH = -\log [H]^+$ as concentration of acid solution.
		Concentration	Calculate the pH of a solution based on concentration only, do not pay attention to the strength of the acid-base.
Acid-base titration and indicators	Phenomenon		Use color changes (macroscopic characteristics) to determine the end point of the titration as well as the reaction equivalence point.
	Inference	Concentration	Determine the acid-base properties of a mixture is only based on the concentration of the solution being mixed, the acid or base solution with a higher concentration determines the acidity or basicity of the resulting mixture, both weak acid/base and strong acid/base.
		Neutralization Reaction	Assume that neutralization reactions only occur in strong acids and bases solutions, weak acids and bases cannot change the color of litmus paper.
		Laboratory activities	Never use acid-base titration indicators other than PP.
		Chemical Composition	Assume a change of color in a solution, for example in a titration, is caused by the excess of H^+ or OH^- ions.
Buffers and salt hydrolysis	Phenomenon	Definition	Have an understanding that a buffer solution is a mixture of a weak acid or base and its salt alone.
	Inference	Chemical species	Have an understanding that hydrogen halides are strong acids so that the equimolar reaction HF + NaOH produces a neutral salt.

Table 2 shows that there are learners who have no conceptual understanding, there are those who have the phenomenon model, and there are those who have the inference model, of course in addition to those who have the scientific model. However, most of learners' non-scientific understanding comes from incomplete, incoherent and fragmented understanding. These problems can come from the choosing of inappropriate subject matter, instructors not being able to differentiate between the essential concepts and non-essential concepts, and the choosing of inappropriate learning strategies so that the learners cannot understand the essential concepts. Below we describe some of the non-scientific models that students held that were revealed in this research.

Description of Learners' Model Mental of Acid-Base Concepts

There were respondents who had the understanding that the pH of an acid solution is determined by its concentration because pH = -log [H+]. This is revealed in the following written answer:

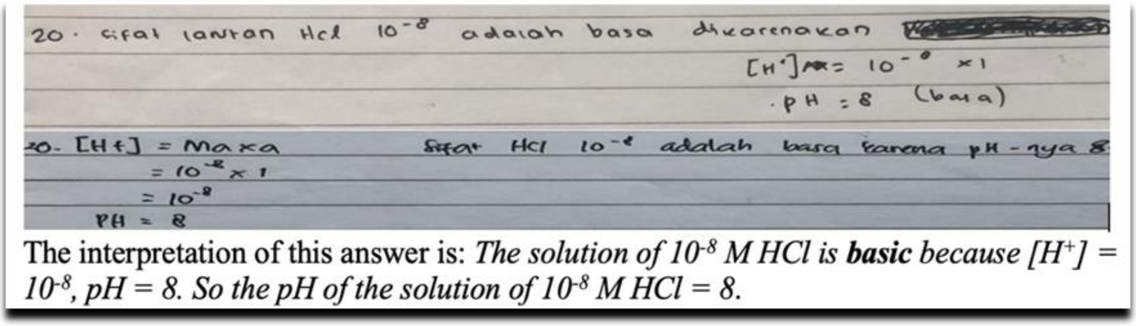

Figure 2. Examples of Interpretation Question.

Table 3. Interview Results.

No	Interviewer	Interviewee
1	What is the pH of a 10-8 M HCl solution?	8 (eight)
2	Why 8? How do you know 8?	Because pH = -log [H+]; pH = -log[10-8] = 8.

Some respondents also had the understanding that the pH of an acid solution would increase (perhaps what is meant is decrease?) 2X if the concentration of the solution was increased 2X. This was revealed in following written answer.

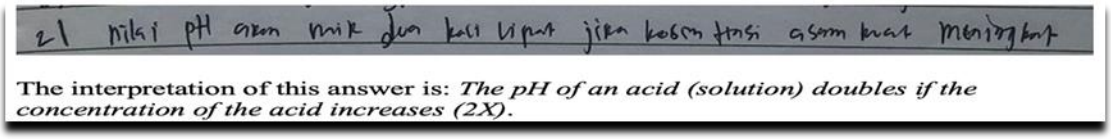

Figure 3. Examples of Interpretation Question.

Table 4. Interview Results.

No	Interviewer	Interviewee
1	What if I increase the HCl concentration to 2X the original concentration?	The pH of the acid will increase 2X.
2	Why is that? Can you explain?	Because pH = -log $[H^+]$, if the acid concentration increases then the pH also increases (it means may decrease?) as much as the concentration increases or another respondent's answer "pH is directly proportional to concentration, so if the acid concentration increases the pH will definitely also increase.

This description shows that the respondent's understanding is fragmented, his understanding of H+ ion concentration is separate from water ionization and acid-base strength. This understanding falls into the category of The Inference Model. Figure 1 shows the learners' mental model in understanding the pH of an acid solution. The figure shows that the learner equates the concentration of H+ ions in a solution to the concentration of an acid solution.

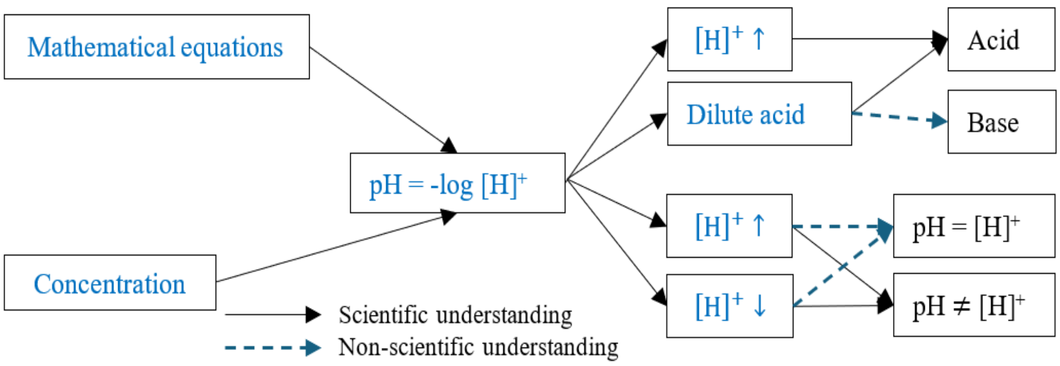

Figure 4. Learners' Understanding of the pH of Acid-base Solutions; Represent the Inference Model.

There were also respondents in this study who were biased in understanding the concept of buffer solutions. They interpret the absolute definition of buffer solutions, both as a process and as a product. For them, a buffer solution is a mixture of a weak acid or weak base and its salt. They did not classify the mixture of excess HF solution with limited NaOH solution as a buffer because NaOH is not a salt derived from HF. This interpretation captured in the following answer:

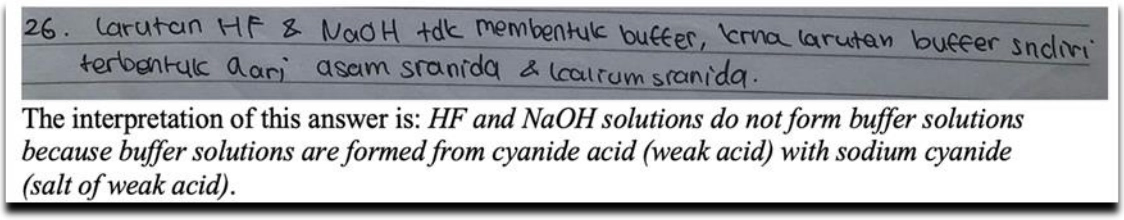

Figure 5. Examples of Interpretation Question.

Table 5. Interview Results.

No	Interviewer	Interviewee
1	Why can't a mixture of HF solution and NaOH solution form a buffer solution?	Because there is a strong base, namely NaOH, so it is definitely not a buffer solution.
2	What's wrong with NaOH?	Buffers should not contain strong bases, they should be weak bases.

This interview shows that the respondents have an understanding that buffer solutions are only formed from solutions of weak acids and salts of the weak acid. This understanding clearly contains truth (in a buffer there is a weak acid and its salt) and error (a buffer is only formed from a mixture of a weak acid and its salt). This kind of understanding is classified as Inference Mental Model.

CONCLUSION

The concepts of pH of solutions, acid-base titration, buffer solutions, and salt hydrolysis are complex and require an understanding of foundational chemical concepts such as acid-base theory, chemical properties, atomic structure, chemical formulas, reaction equations, stoichiometry, particulate properties of matter, solution chemistry, chemical equilibrium, and bonding. This study reveals that students' understanding of these concepts generally improves with educational level; however, anomalies were identified in the understanding of pH solutions, buffer solutions, and salt hydrolysis. Specifically, the inference model among learners showed fragmentation and incoherence, even at higher educational levels, indicating incomplete or inconsistent learning. These issues may stem from inappropriate curriculum content, ineffective learning strategies, or extrinsic factors, as knowledge of these concepts often intersects with non-scientific, everyday contexts. The study highlights the need for curriculum development and the careful selection and implementation of learning strategies that enable structured, gradual, and coherent learning. For instance, high school instruction should prioritize fundamental concepts such as the pH of strong and weak acids and bases, while college-level learning should expand to cover acid-base neutralization and the pH of salt solutions. Moreover, to provide a comprehensive understanding of Indonesian students' learning conditions, future research should broaden the scope to include all regions of Indonesia.

REFERENCES

Adadan, E., & Savasci, F. (2012). An analysis of 16-17-year-old students' understanding of solution chemistry concepts using a two-tier diagnostic instrument. *International Journal of Science Education*, *34*(4), 513–544. https://doi.org/10.1080/09500693.2011.636084

Alonzo, A. C., Wooten, M. M., & Christensen, J. (2022). Learning progressions as a simplified model: Examining teachers' reported uses to inform classroom assessment practices. *Science Education*, *106*(4), 852–889. https://doi.org/10.1002/sce.21713

Amala, F., & Habiddin, H. (2022). Pemahaman konsep dalam topik sifat asam basa larutan garam: studi pada siswa SMA di Blitar. *Jurnal Zarah*, *10*(2), 91–100.

Amalia, F. R., Ibnu, S., Widarti, H. R., & Wuni, H. (2018). Students' mental models of acid and base concepts taught using the cognitive apprenticeship learning model. *Jurnal Pendidikan IPA Indonesia*, *7*(2), 187–192. https://doi.org/10.15294/jpii.v7i2.14264

Anderson, L. W., Krathwohl Peter W Airasian, D. R., Cruikshank, K. A., Mayer, R. E., Pintrich, P. R., Raths, J., & Wittrock, M. C. (2001). *A Taxonomy for Learning, Teaching, And Assessing. A Revision 0f Bloom's Taxonomy Of Educational Objectives*. Longman. https://www.uky.edu/~rsand1/china2018/texts/Anderson-Krathwohl - A taxonomy for learning teaching and assessing.pdf

Arocena, M. (2022). A simple theoretical, quantitative approach to help understand the titration of weak acids and bases. *Chemistry Teacher International*, *4*(1), 47–54. https://doi.org/10.1515/cti-2021-0021

Bretz, S. L., & McClary, L. (2015). Students' understandings of acid strength: How meaningful is reliability when measuring alternative conceptions? *Journal of Chemical Education*, *92*(2), 212–219. https://doi.org/10.1021/ed5005195

Cooper, M., Kouyoumdjian, H., & Underwood, S. M. (2016). Investigating students' reasoning about acid–base reactions. *Journal of Chemical Education*, *93*, 1703–1712. https://doi.org/10.1021/ACS.JCHEMED.6B00417

Cooper, M. M., Kouyoumdjian, H., & Underwood, S. M. (2016). Investigating students' reasoning about acid-base reactions. *Journal of Chemical Education*, *93*(10). https://doi.org/10.1021/acs.jchemed.6b00417

Cyril, N., Coll, S., Ketpichainarong, W., & Rajoo, M. (2022). Blended learning in acids and bases: an alternative to science teaching for lower secondary schools. *SN Social Sciences*, *2*. https://doi.org/10.1007/s43545-022-00447-z

Demirdöğen, B., Nelsen, I., & Lewis, S. E. (2023). Organic chemistry students' use of stability in mental models on acid and base strength. *Chemistry Education Research and Practice*, *24*, 1127–1141. https://doi.org/10.1039/d3rp00049d

Dood, A. J., & Watts, F. M. (2023). Students' strategies, struggles, and successes with mechanism problem solving in organic chemistry: A scoping review of the research literature. *Journal of Chemical Education*, *100*(1), 53–68. https://doi.org/10.1021/acs.jchemed.2c00572

Elvinawati, E., Rohiat, S., & Solikhin, F. (2022). Identifikasi miskonsepsi mahasiswa dalam mata kuliah kimia sekolah II Pada materi asam basa. *alotrop*, *6*(1), 10–14. https://doi.org/10.33369/atp.v6i1.20303

Frost, S. J. H., Yik, B. J., Dood, A. J., de Arellano, D. C.-R., Fields, K. B., & Raker, J. (2023). Evaluating electrophile and nucleophile understanding: a large-scale study of learners' explanations of reaction mechanisms. *Chemistry Education Research and Practice*, *24*, 706–722. https://doi.org/10.1039/d2rp00327a

Gültepe, N. (2021). Pre-service chemistry teachers' understanding about equilibria in acid-base solutions. *Pedagogical Research*, *6*(4), 1–11. https://doi.org/10.29333/pr/11349

Hikaya, N., Lukum, & Botutihe. (2018). Studi komparasi kemampuan pemahaman konseptual, algoritmik, dan grafis mahasiswa jurusan kimia pada materi asam basa. *Jurnal Entropi*, *1*(441412007), 95–102.

Jensen, J. D. (2013). *Students' understandings of acid-base reactions investigated through their classification schemes and the acid-base reactions concept inventory*. 1–209. https://etd.ohiolink.edu/pg_10?0::NO:10:P10_ACCESSION_NUM:miami1365611297

Jiménez-Liso, M. R., López-Banet, L., & Dillon, J. (2020). Changing how we teach acid-base chemistry. *Science & Education*, *29*(5), 1291–1315. https://doi.org/10.1007/s11191-020-00142-6

Jin, H., Mikeska, J. N., Hokayem, H., & Mavronikolas, E. (2019). Toward coherence in curriculum, instruction, and assessment: A review of learning progression literature. *Science Education*, *103*(5), 1206–1234. https://doi.org/10.1002/sce.21525

Jones, N. A., Ross, H., Lynam, T., Perez, P., & Leitch, A. (2011). Mental models: An interdisciplinary synthesis of theory and methods. *Ecology and Society*, *16*(1). https://doi.org/10.5751/ES-03802-160146

Krathwohl, A. and. (2002). A revision of bloom ' s taxonomy : An overview. *Theory into Practice*, *41*(4), 212–219.

Krebs, R. E., Rost, M., & Lembens, A. (2022). „Protons as the main drivers of a chemical reaction?" – educational reconstruction of the Brønsted-Lowry acid-base concept for upper secondary school. *CHEMKON*, *30*(8), 334–340. https://doi.org/10.1002/ckon.202200045

Krebs, R. E., Rost, M., & Lembens, A. (2023). Developing and evaluating a multiple-choice knowledge test about Brønsted-Lowry acid-base reactions for upper secondary school students. *Chemistry Teacher International*, *5*, 177–188.

https://doi.org/10.1515/cti-2022-0038

Lin, J.-W., Chiu, M.-H., & Liang, J.-C. (2016). Exploring mental models and causes of students' misconceptions in acids and bases. *National Taiwan Normal University*, *January*, 1–12. https://medium.com/@arifwicaksanaa/pengertian-use-case-a7e576e1b6bf

Lin, J. W., & Chiu, M. H. (2007). Exploring the characteristics and diverse sources of students' mental models of acids and bases. *International Journal of Science Education*, *29*(6), 771–803. https://doi.org/10.1080/09500690600855559

López-Banet, L., Aguilera, D., Jiménez-Liso, M. R., & Perales-Palacios, F. J. (2021). Emotional and cognitive preservice science teachers' engagement while living a model-based inquiry science technology engineering mathematics sequence about acid-base. *Frontiers in Psychology*, *12*(October). https://doi.org/10.3389/fpsyg.2021.719648

Mubarokah, F. D., Mulyani, S., & Indriyanti, N. Y. (2018). Identifying students' misconceptions of acid-base concepts using a three-tier diagnostic test: A case of Indonesia and Thailand. *Journal of Turkish Science Education*, *15*(Special Issue), 51–58. https://doi.org/10.12973/tused.10256a

Muntholib, D., Mayangsari, J., Pratiwi, Y. N., Muchson, D., Joharmawan, R., Yahmin, D., & Rahayu, S. (2018). *Development of simple multiple-choice diagnostic test of acid-base concepts to identify studentsr alternative conceptions*. *218*(ICoMSE 2017), 251–268. https://doi.org/10.2991/icomse-17.2018.45

Muntholib, Mauliya, A. H., Utomo, Y., & Ibnu, M. S. (2020). Assessing high school student's chemical literacy on salt hydrolysis. *IOP Conference Series: Earth and Environmental Science*, *456*(1). https://doi.org/10.1088/1755-1315/456/1/012065

Net, W. W. W. P., Suparman, A. R., Rohaeti, E., Wening, S., Gunung, J., & Amban, S. (2024). Student misconception in chemistry: A systematic literature review. *Pegem Journal of Education and Instruction*, *14*(2), 238–252. https://doi.org/10.47750/pegegog.14.02.28

Orgill, M. K., & Sutherland, A. (2008). Undergraduate chemistry students' perceptions of and misconceptions about buffers and buffer problems. *Chemistry Education Research and Practice*, *9*(2), 131–143. https://doi.org/10.1039/b806229n

Park, C., Sungki, K., Choi, H., & Seounghey, P. (2019). Exploring learning progression of logical thinking in acid and base chemical reactions. *Journal of The Korean Chemical Society*, *63*, 376–386. https://doi.org/10.5012/JKCS.2019.63.5.376

Permendikbud. (2016). Permendikbud RI Nomor 21 Tahun 2016 Tentang Standar Isi Pendidikan Dasar dan Menengah. *JDIH Kemendikbud*, 1–168.

Reed, C. R., & Wolfson, A. J. (2019). Learning progressions as a pedagogical tool for instructors. *The FASEB Journal*, *33*(S1), 32–40. https://doi.org/10.1096/fasebj.2019.33.1_supplement.456.7

Reed, C. R., & Wolfson, A. J. (2021). Are Learning progressions a useful pedagogical tool for instructors? *Journal of College Science Teaching*, *51*(2), 32–40. https://doi.org/10.1080/0047231X.2021.12290546

Romine, W. L., Todd, A. N., & Clark, T. B. (2016). How do undergraduate students conceptualize acid–base chemistry? Measurement of a concept progression. *Science Education*, *100*(6), 1150–1183. https://doi.org/10.1002/sce.21240

Salame, I. I., Montero, A., & Eschweiler, D. (2022). Examining some of the students' challenges and alternative conceptions in learning about acid-base titrations. *International Journal of Chemistry Education Research*, *6*, 1–10. https://doi.org/10.20885/ijcer.vol6.iss1.art1

Scott, E. E., Wenderoth, M. P., & Doherty, J. H. (2019). Learning progressions: An empirically grounded, learner-centered framework to guide biology instruction. *CBE Life Sciences Education*, *18*(4), 1–11. https://doi.org/10.1187/cbe.19-03-0059

Sodanango, P. Y., Munzil, M., & Sumari, S. (2021). Analisis model mental peserta didik SMA dalam memahami konsep laju reaksi. *Jurnal Pendidikan: Teori, Penelitian, Dan Pengembangan*, *6*(10), 1543. https://doi.org/10.17977/jptpp.v6i10.15048

Tümay, H. (2016). Emergence, learning difficulties, and misconceptions in chemistry undergraduate students' conceptualizations of acid strength. *Science and Education*, *25*(1–2), 21–46. https://doi.org/10.1007/s11191-015-9799-x

Wan, Y. (2014). Assessing college students understanding of acid base chemistry concept [Clemson University]. In *All Dissertations*. https://tigerprints.clemson.edu/all_dissertations/1394

Wattanakasiwich, P., Taleab, P., Sharma, M. D., & Johnston, I. D. (2013). Development and implementation of a conceptual survey in thermodynamics. *International Journal of Innovation in Science and Mathematics Education*, *21*(1), 29–53.

Yang, Y., Liu, Y.-X., Song, X.-H., Yao, J.-X., & Guo, Y.-Y. (2023). A tale of two progressions: students' learning progression of the particle nature of matter and teachers' perception on the progression. *Disciplinary and Interdisciplinary Science Education Research*, *5*(1). https://doi.org/10.1186/s43031-023-00085-2