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Examining some of the Students' Challenges and Alternative Conceptions in Learning about Acid-base Titrations

Issa I. Salame[a,*], Adrianny Montero[a], Dani Eschweiler[a]

[a]*Department of Chemistry and Biochemistry, The City College of New York of the City University of New York, 160 Convent Avenue, New York, NY 10031*

**Corresponding Author: isalame@ccny.cuny.ed*

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ABSTRACT: Chemical equilibria, including acid-base equilibria, play a significant role in the learning of general chemistry. Acid-base reactions as well as acidity and basicity concepts and their relationship to titrations are an important part of any general chemistry course, and students have difficulties understanding these concepts. The purpose of this research project is to examine some of the challenges and alternative conceptions that students face in learning about acid-base titrations. A Likert-type survey with open-ended questions were used to assess the understanding of 110 participants. The investigation took place at a public, urban, and minority-serving institute. Our data suggest that students struggle with learning about acid-base titration problems and concepts. They rely on algorithmic problem solving, rote-learning, plugging into equations, and calculator use when approaching acid-base titration problems instead of developing their conceptual understanding and meaningful learning of the concepts. Additionally, our data support the notion that development of conceptual understanding of acid-base titration is important for students' learning. Furthermore, our research data suggest that students have difficulties with understanding and visualizing what is taking place at the microscopic level during acid-base titration reactions. Instructors should consider teaching strategies that include leaning about and interrelating the symbolic, macroscopic, and microscopic levels of representations which can promote learning and deeper understanding of abstract chemical concepts. We recommend that instructors explicitly address and relate the three levels of representation in their teaching of chemistry concepts.

Keywords: chemistry education research, acid-base titration, challenges

INTRODUCTION

Acid-base reactions play important roles in many chemical processes, biological systems, our bodies, and in the environment. The majority of students find chemistry to be a difficult subject to learn due to its abstract nature, complex calculations, and dependence on the different levels of representation. Those systems are described using equations and reactions between substances at the phenomenological level and as proton-transfer reactions at an abstract level using ionic equations according to the Brønsted model [1]. Moreover, acid-base systems are a major component of chemistry in general. According to chemistry education researchers, if students fully understand the process of acid-base reactions in all its form, they are able to analyze, predict, and explain the outcomes of a wide range of unrelated reactions and concepts [2]. Nonetheless, there are many well-recognized difficulties that students face while learning about acid-base reaction systems and titration curves [3].

The concepts of acid-base reactions are major components of the chemistry curricula and the study of these may require a combined understanding of different areas of introductory chemistry courses [4]. Acid-base theory has been known since the years of the Ancient Greeks, where copies of the Greek manuscripts were found [5]. The understanding of acids through the Greek and Arabic periods were only limited to fruits, juices, and some salts (hydrolyzed salts). Acidic substances were found to taste sour and to change the color of litmus paper and corrode metals, whereas basic substances were generally described and studied because of their ability to neutralize acids [6]. The work of Svante Arrehenius was vital to broaden experts’ understanding of acid and base reactions. By 1890, rapid changes in acid and base theories were obtained, and those theories were re-defined depending on their abilities to furnish hydrogen.

The most frequent model used in the classroom is the Brønsted-Lowry model. The Brønsted-Lowry definition of acid-base behavior has two possible sources that are used by students according to Cheung [7]. The first source is known to be the main theory explained by instructors in general chemistry classrooms at the university level. This theory is also presented to the exclusion of other theories in secondary science classrooms. The second source states that students are more exposed to the Brønsted-Lowry theory than the Lewis theory, and they consequently have far more experience with the learning and application of this model. This is because the Brønsted-Lowry model lends itself well for the studying of equilibrium, acid/base behaviors, and a host of other topics [7]. Also, the Lewis theory of acid and base concepts is more widely applicable in courses like organic chemistry, where students can obtain a solid foundation of mechanistic prediction and draw direct correlations between Lewis acid-base reactions [8].

Titration curves have traditionally been used by instructors to provide a assess students’ learning and understanding of concepts of acid-base equilibrium in both theoretical and practical approaches [9]. Titration methods, also known as titrimetric procedures, comprise a huge set of quantitative techniques based on measuring the amount of a reagent with a known concentration, which is then depleted by the analyte used in a chemical reaction [10]. Titration curves are usually taught and studied by dividing them into different regions. Understanding the chemical process and reactions aking place in each of the titration curve regions is important for a better comprehension [11].

Acid-base titration reactions are also used in laboratory activities that are carried out in high school and university chemistry courses. An acid-base titration is a technique used in laboratories to find out the total concentration of an acid or a base by neutralizing them with standard solutions [12]. The titration plot can be used to find out the ionization constant of the substances in the samples or the total unknown concentration of the samples used [4]. In addition, the neutralization of strong acids with strong bases is the most regularly conducted titration, in which students, lab instructors, or experts are required to calculate the total concentration of unknown substances [13].

Understanding key fundamental principles is vital to learning about acid and base reactions and titrations. For instance, acid-base titration curves allow the prediction of protonation states and isoelectric points of molecules, which is very helpful for undergraduate biochemistry students [7]. Additionally, a common undergraduate laboratory experiment for biochemistry students is the creation of a titration curve for weak acids such as phosphoric acid or an amino acid. Students are able to identify the unknown amino acids provided by the lab instructors based on the shape of the obtained titration curve [14].

The calculations that are involved in acid and base concepts and titration curves can cause many students difficulties. Additionally, they even hold many alternative conceptions about the processes involved. Students find difficulties identifying species of ions involved in the titration process (before, during, and after the endpoint of titration), titration curves, equations, and stoichiometry [12]. The procedures of the buffer solutions can be easier understood through titration curves according to Harris [15]. This researcher explained that a simple look at acid-base titration curves would allow students to locate the maximum buffer capacity of a given buffer, and this may be because buffer systems could be acknowledged like the variation of pH with the volume of titrant.

According to Dreschesler and Schmidt [16], students face challenges in comprehending and differentiating between different acid and base models. Students struggle with developing basic knowledge of acid/base substances as well as understanding that water can be or act as an acid or a base depending on the reaction conditions that are being carried out [17]. Other studies have shown that students also struggle relating acid strength and concentration [13], understanding the logarithmic nature of the pH scale and its value change during the titration process [13]; comprehending the actual meaning behind the neutralization processes [18]; and differentiating the concepts between ‘equivalence point’ and ‘neutral point’ (when pH=7) in acid-base titration process [16].

One study suggested that students hold onto their alternative conceptions about acid-base solutions based due to the lack of developed understanding of the three levels of representations [19]. In addition, Zoller stated that in freshman chemistry, there may be many abstract ideas and many non-intuitive ideas or concepts that are not derived or logically interrelated with one another, and thus a huge number of students face the difficulties in understanding the acid-base chemistry concepts [20]. Chemistry education researchers have tried to investigate the reasons why a huge number of students face so many difficulties in successfully developing a deep comprehension of chemical equilibrium [21]. Because of those research projects, experts have identified educational experiences and teaching approaches that may help to eliminate some of the obstacles and help the students to get meaningful learning of fundamental concepts regarding chemical equilibrium. Özmen explained that understanding and having adequate conceptualizations of chemical equilibria and reaction mixtures are required to resolve acid-base reactions and titration curve problems [3].

Students tend to focus on memorizing facts and formulas used rather than making the effort to truly understand the concepts behind the topic of acids and bases and develop their problem-solving skills [22]. Also, some of the challenges identified in some studies on acid-base systems suggested that students should develop proper understandings of the properties of acid-base reactions, strength, and clear comprehension of pH as well as its function [23].

According to some studies, learning difficulties can result if students are unable to relate the newly learned concepts to prior concepts [24]. Additionally, it is understood that getting deep comprehension of the chemical equilibrium can be hard because of the difficult concepts that it involves, especially when students are dealing with the disturbance of equilibrium or just the direction of a reaction [25]. Sheppard also stated that those students who struggle in deeply comprehending acid-base chemistry are probably not able to explain or describe precisely the concepts that are related to acid-base reactions such as acid-base strength, pH changes, or neutralization [13].

Researchers have tried to focus their investigations on understanding how students usually get the definition or properties of acid-base systems [26] as well as how they conceptualize related acid-base topics including equilibrium [27], pH changes during titration [28], and neutralization [29]. The problem with possessing alternative conceptions about acid-base reactions and their related topics is that it may have certain influences over the correct learning of acid-base conceptions as well as the understanding in solving problems or laboratory situations [28].

One of the challenges presented in teaching acid-base chemistry and titration concepts is that many students prefer learning the algorithmic problems solving approach instead of developing conceptual understanding of the topic [30]. However, sometimes the use of other models during the process of the concept explanation may be needed to fully comprehend the processes involved in acid-base chemistry and titration curves [31]. In addition, the students' perceptions about the difficulty of acid-base reactions and titration curves play an important role in their capacity and disposition to learn and fully understand those concepts. Having students gain meaningful learning of the concepts is important for understanding and future learning [32]. Usually, when students are learning new scientific concepts, they most likely need to have a conceptual change of the deeply rooted misunderstanding that often interferes with their new conceptual learnings.

Other studies suggest that if students do the problems related to the concepts they are learning without any external aids, they can gain practice problem-solving skills that will be useful on exams [22]. According to Cooper and colleagues, there are just a few studies that focus on how students describe what happens during acid-base systems and how and why those chemical reactions occur [2]. Nonetheless, the student can successfully get the answer to the problem if he/she is taught how to shift his/her way of seeing the problem and move from lower-levels to higher-levels of thinking without any problem [32]. The research project aims to examine some of the challenges and learning difficulties related to acid-base titration to improve instruction and students' performance.

METHODS

Guiding Research Questions

Our research was structured to address the following specific questions:

1. What are some of the challenges and alternative conceptions that students possess about acid-base titration?
2. What approaches do students use when solving acid-base titration related problems?
3. What role does rote learning play in acid-base titrations and its impact on impeding students' learning?

Method of Quantitative Analysis

The purpose of this research project is to examine some of the challenges and difficulties students face in learning about acid-base titrations. The research project took place at the City College of New York, a public, commuter, urban, and minority-serving institute. The participants' population represents a diverse number of majors including those in the sciences, engineering, and liberal arts, as well as post-baccalaureate students. The project took place during the period of Spring 2020 to Spring 2021. The research was conducted in accordance with the Internal Review Board of the City College of New York.

For this research project, we administered a survey that contained an acid-base titration problem, Likert-type questions, and open-ended questions. The research survey was administered and collected from 110 students (n = 110) of the City College of New York. The survey was examined by two experts who agree that the questions adequately capture the investigation about acid-base titration. We relied on face validity which involves the experts looking at the items in the questionnaire and agreeing that the test is a valid measure of the concept which is being measured just on the face of it. The reliability coefficient was assessed to be 0.82 through the use of test-retest reliability method. For the Likert-type questions that were collected as part of the survey, the students' answers were converted to values as follow: Strongly disagree = 1, Disagree = 2, Neutral = 3, Agree = 4, and Strongly Agree = 5. A single factor ANOVA method was performed on the Likert-type questions part of the survey and found that $P<0.05$ which indicates evidence against the null hypothesis, and that reveals a strong relationship between variables. The numerical values were then entered into an Excel sheet and the average value was calculated for each of the questions. A bar chart was created using this data.

For the open-ended questions part of the survey, we coded the data and created figures. For two of the questions, we created a rubric using a scale from 1 to 5. The two researchers independently examined the answers using the rubric. The researchers then met and compared their results which were about 96% in agreement. Values that were not in agreement were no more than one point of difference. The researcher discussed the answers using the rubric until consensus were achieved. The data obtained were entered into an Excel sheet and a bar chart was created. For the rest of the open-ended questions, we created categories based on the responses and converted them to percentages and created pie charts. The approach for this part of the project, was to compile all of the answers and create categories based on the responses and place similar responses into the same categories.

RESULTS AND DISCUSSION

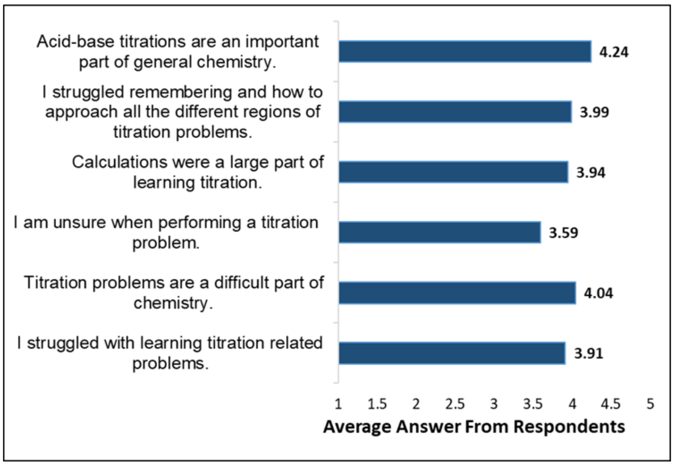

FIGURE 1. Average responses of students to Likert-type questions in our survey. The range of answers was strongly disagree (1), disagree (2), neutral (3), agree (4), and strongly agree (5).

Figure 1 is a bar graph representing the Likert-type questions that were part of the survey. Our data show that the students agree that they struggle with learning about titration problems, and that they are unsure when performing titration problems. Additionally, the students agree that titration problems are a difficult part of chemistry. Students also agree that calculations are a large part of learning about titrations and that titrations are an important part of general chemistry. Furthermore, the data collected suggest that students agree that they struggle remembering and approaching the different regions of a titration curve.

Our data suggest that students struggle with acid-base titrations— which they also consider difficult— and rely on multistep calculations to solve titration-related problems. This is consistent with research in science education reports: pH calculations during an acid-base titration can be an arduous process for students because it involves knowledge and competency of properties and nature of acids/bases, stoichiometric calculations, the ability to differentiate between moles changes and molarity changes, and the competence to perform mathematical manipulations involving algebraic and logarithmic ones [33-34].

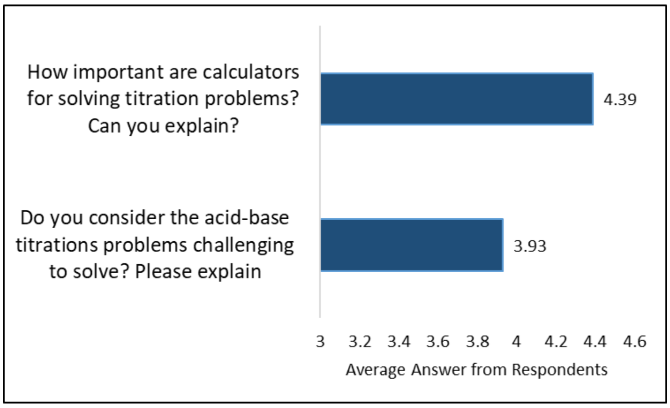

FIGURE 2. Short-answer questions and average answer from respondents based on rubric. While the questions were open-ended, our rubric scored the student responses on the same scale as the Likert-type questions: a higher score reflects greater agreement with 1 as the lowest value (minimum disagreement) and 5 as the highest value (maximum agreement).

An example for the first question that yields a value of five based on the rubric would be:” Calculations are very important due to the amount of meticulous calculation involved in solving titration problems”. For the second questions, here is an example of an answer that received four points based on the rubric: “In some cases, it may be difficult when worked a certain way. It confuses me when similar problems have different approaches.”

Figure 2 represents a bar chart of two open-ended questions and the average answer from respondents based on the rubric used. The figure shows that students find acid-base titration problems challenging to solve and that they rely heavily on calculator use in solving titration problems. Research has shown that pH determination during an acid base titration requires understanding and knowledge about strong and weak acids and bases, salt hydrolysis, buffer solutions, and the connection between them [35]. This makes the concept of acid-base titration a challenging one which supports our findings.

Acid-base concepts and titration curves are two important and, at the same time, complicated concepts in both primary and secondary curricula. Dechesler and Schmidth (2005) explained in their paper that both chemistry instructors and students agree that freshman chemistry is one of the most problematic science disciplines during the first year of college, and students’ learning difficulties and alternative conceptions are issues of concern for many experts [16]. Students underscore the importance of calculators, and that might have to do with that fact that instructors assess students’ learning with examinations that rely on algorithmic problem-solving and calculations, and they assign grades based on performance and achievement on these examinations. This might lead the students and instructor to believe that algorithmic problem-solving translates to learning and conceptual understanding. This is consistent with research in chemistry education that finds that instructors correlate students’ mathematical ability with academic achievement in undergraduate chemistry courses [36].

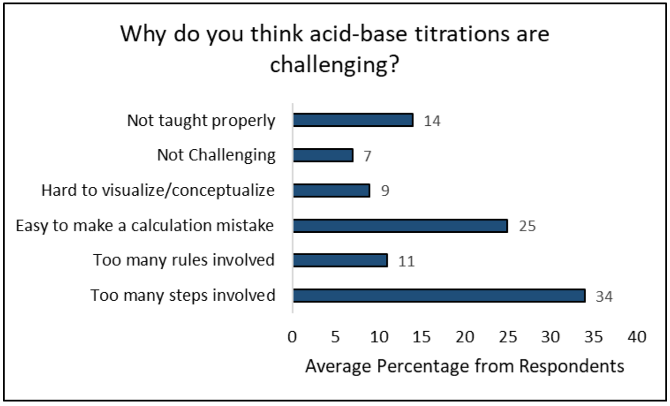

FIGURE 3. Student responses to an open-ended question about students' perceptions of what makes titration problems challenging were broken down into six principal categories. The distribution of these responses was fairly uniform, but the number of steps involved and the ease of making a calculation mistake were dominant responses.

Figure 3 is a bar chart depicting students' perceptions of the reasons that solving acid-base titration problems are challenging. Our data shows that 34% of students' perceptions refer to the multitude of steps involved in solving acid-base titration problems as an impediment to learning. Further, 25% of students suggest that acid-base titration problems are challenging due to the easiness of making a calculation error. Some of the students, 11%, suggest that acid-base titration problems involve many rules. Furthermore, 9% of the participants refer to the difficulty of visualization and conceptualization of acid-base titration as a deterrent to learning. We should note that 7% of the student participants report that acid-base titration problems as not challenging and easy to solve. Lastly, 14% of the students who participated in this research report that acid-base titration concepts are not properly taught by the instructors.

The data suggest that students rely on rules, rote learning, algorithmic approaches, and mathematical calculations when approaching acid-base titrations. For effective teaching methodologies, instructors should promote meaningful learning and discourage rote learning [37]. It is noteworthy that some students suggest that traditional teaching methods including lecture format are not effective in learning about acid-base titration concepts and calculations. Visualization and conceptualization of acid-base titration is important for students' learning of the concepts. This might be related to teaching approaches that emphasize symbolic and macroscopic levels of chemistry and do not try to relate it to the microscopic level. It is important for students learning acid-base titrations to be able to interrelate and think about what is happening at the symbolic, macroscopic, and microscopic levels.

In the process of teaching sciences, new instructional strategies must be implemented in the classroom to help students to gain new acid-base and titration knowledge, hold it, and process it through the development of the link between concepts and sub-concepts. The lack of students' understanding in the chemical sciences at all levels constitutes crucial issues which concern not only students but also science instructors and researchers [38].

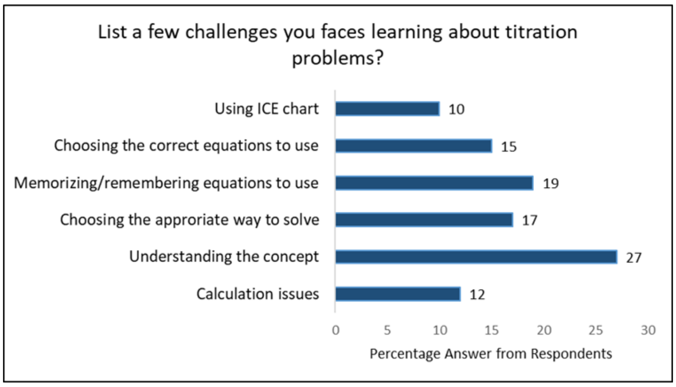

FIGURE 4. Student responses to an open-ended question about the challenges they faced while learning about titration problems were broken down into six principal categories. The distribution of

these responses was fairly uniform but understanding the concepts and remembering equations to solve were dominant responses.

Figure 4 is a bar chart of challenges that students faced in learning about acid-base titrations. The data obtained show that 27% of students list not understanding the concepts as hindrance to learning; 19% of the students struggle with memorization and remembering the needed equations to use; 17% of the participants report that choosing the appropriate method to solve titration related problems as an obstacle to learning; 15% of the students suggest that they have problems choosing the correct equations to use; 12% of the students struggle with calculation related issues; and 10% of the participants face difficulties with ICE charts.

The data suggest that students view acid-base titrations as some algorithmic problems with several calculation steps with many equations and approaches to solve. This might cause difficulties in learning about acid-base titration concepts. We think that instructors should consider the effect of algorithmic problem-solving teaching methods on students' meaningful learning and development of conceptual understanding. Students tend to solve acid-base titration problems by relying on rote learning, plugging into equations, using calculators, and building ICE charts. Students should approach acid-base titrations with conceptual knowledge of what is taking place in the solution and at the molecular level before delving into calculations and plugging into equations. Development of conceptual understanding and understanding what is happening in solution during the titration process are important for the instructors to consider when teaching these challenging concepts.

External representations such as molecular representations, graphs, and symbols can lead to meaningful learning can be used as learning tools to relate observable concepts with the underlying submicroscopic causes [39]. Additionally, in one recent article, the author's results showed that combining guided inquiry-based learning with multiple representations led an increase in conceptual knowledge and learning [40].

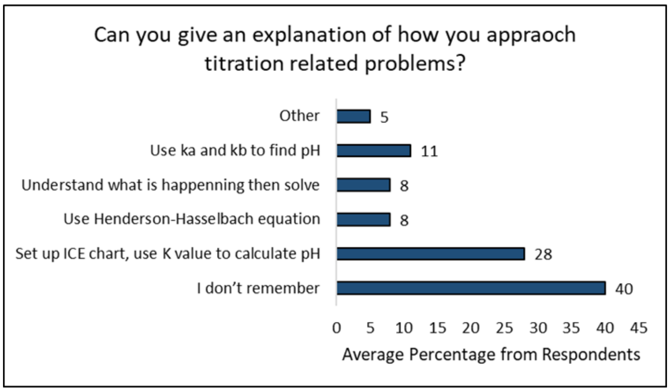

FIGURE 5. Student responses to an open-ended question about the approaches they use to solve titration problems. Using ICE charts and "I don't remember [how to solve]" were dominant responses.

Figure 5 is a bar chart that presents approaches that students use in solving acid-base titration problems. The data obtained show that 40% of students say they do not recall how to solve titration problems; 28% of the participants prefer to set up an ICE chart and use equilibrium constants to calculate pH and solve titration problems; 11% of students prefer to use acid and base equilibrium constants to find pH; 8% suggest using Henderson-Hasselbalch equation to solve titration related problems; and 8% of the participants suggest that they need to understand what is happening in the solution and reaction in order to solve.

The data above suggest that majority of students depend on algorithmic problem-solving in approaching acid-base titration problems. Additionally, the data suggest that students rely on "chug-and-plug" methods in solving titration related problems. Only a small fraction of our student participants suggested that understanding the solution composition, reactions involved, and what is happening in the solution were preferred approaches to solving acid-base titration problems. In one study, researchers related the understanding and learning of acid-base chemistry to four level of related understandings which include phenomena such as the description of acids as sour, character-symbols such as pH, inference, and scientific models [41].

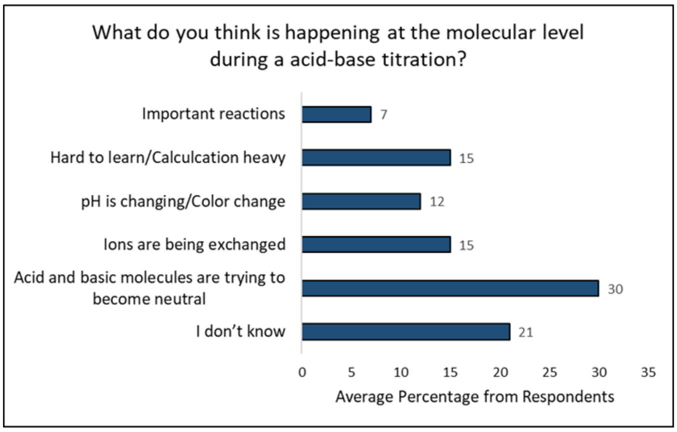

FIGURE 6. Student responses to an open-ended question about what is happening at the molecular level during an acid-base titration. “Acid and base molecules are trying to become neutral” and “I don’t know” were dominant responses.

Figure 6 is a bar chart depicting students’ perceptions of what is happening at the molecular level in acid-base titrations. The data show that 30% of students’ understanding of what is happening at the molecular level is that acid and base molecules are trying to become neutral; 21% of participants say they do not know what is taking place between molecules during the titration process; 15% of the participants suggest that ions are being exchanged during the titration process; 12% of students refer to color change or pH change as the processes taking place at the molecular level; and 15% of participants say that titration is hard to learn and that it is difficult to understand what is taking place at the molecular level because it is calculation-heavy.

Our research data suggest that students struggle with understanding and visualizing what is taking place at the molecular, microscopic level during an acid-base titration reaction. This is supported by other research in the field that suggests students struggle learning acid-base phenomena due to lack of understanding of particulate nature of matter and the nature of chemical change [13]. Chemistry courses taught in a traditional lecture format are often presented at the symbolic and macroscopic levels and therefore neglect students’ learning of chemistry at the microscopic level; further, these courses neglect the need to underscore the interrelationship between the three levels. Chemistry is challenging for students to learn because students need to understand it on the three representational levels: the macroscopic, which refers to tangible, observable phenomena; the submicroscopic, which includes atoms, molecules and structures; and the symbolic, which contains formulae, equations, symbols, and mathematics [38]. Finding connections and relating the three levels of representation play a significant role in the learning of chemical concepts [42]. Thus, alternative teaching strategies that make the students acquire meaningful learning should be developed and implemented in the classroom. One of the solutions to overcome those issues is that a lecturer is expected to provide macroscopic, submicroscopic, and symbolic representations when giving an explanation [12].

Instructors might consider active learning teaching methods that immerse students in investigative activities, as these lead to the development of scientific knowledge and conceptual understanding. Also, teaching students about the three levels of representation in chemistry and relating the three levels for each concept covered has the potential to improve students’ learning and conceptual understanding of acid-base chemistry. Finally, involving students in metacognitive exercises could improve learning. Some experts have also postulated that metacognition may be a key component in students’ efforts to achieve profound comprehensions of acid-base reactions, titrations, and the processes of chemistry as a whole; with this technique, they can become problem-solving experts [43].

CONCLUSION

The data obtained from this research project suggest that students face difficulties in learning about acid-base titrations concepts and problems. Students struggle while learning about titration concepts and rely on algorithmic problem-solving and calculation methods to solve titration-related problems instead of developing a conceptual understanding of the topic. Students emphasize the role of calculators in approaching acid-base titration concepts and problems, which might have to do with assessment methods used by instructors that depend heavily on algorithmic problem solving to assess learning and achievement. Algorithmic problem-solving ability should not be equated with meaningful learning and the development of conceptual understanding. However, our research data also suggest that students have difficulties with understanding and visualizing what is taking place at the microscopic level during acid-base titration reactions. Students rely on rote learning, plugging into equations, using calculators, building ICE charts, and using mathematical calculations when approaching acid-base titrations instead of counting on meaningful learning and conceptual understanding. Our data also suggest that visualization and conceptualization of acid-base titration are important for students' learning of the concepts. This is a major indication that instructors should explicitly address and relate the three levels of representation in their teachings of different chemistry concepts. Teaching strategies that include learning about the symbolic, macroscopic, and microscopic levels of representation promote effective learning and deeper understanding of chemistry concepts. Chemistry instructors have to reconsider the traditional lecture format and consider adopting teaching strategies that can increase students' conceptual comprehension of acid-base reactions and related topics. For example, immersing students in an inquiry-based activity can enhance their conceptual understanding and lead to meaningful learning of chemistry concepts—including acid-base titrations. Additionally, instructors are encouraged to implement learning strategies that identify and address students' alternative conceptions in learning about acid-base titrations. We also suggest that instructors be aware of their students' inadequate understanding of chemical concepts at the three levels of representation and make an effort to address these issues during their teaching sessions. Something that may increase students' learning abilities is group study, such as peer-led team learning.

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