Examining Challenges that Students Face in Learning Organic Chemistry Synthesis

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ABSTRACT: Organic chemistry course is usually offered after general chemistry and is the course that many students find challenging and difficult. Synthesis is first introduced in first organic chemistry course and is widely considered as one of the topics in which students struggle with and is evident in their performance. Our method of data collection is a Likert-type and open-ended questionnaire that was distributed to students at the end organic chemistry course in an anonymous fashion. The collected data enabled us to examine the challenges students face in learning organic chemistry synthesis. Our findings support the notion that students have many difficulties with multistep organic chemistry synthesis including challenges recalling all of the varied required reactions, the amount of content and topics covered in organic chemistry, conceptual understanding of needed important topics such as mechanisms, acids and bases, nucleophiles and electrophiles, and stereochemistry, and problem-solving competency. Students view organic chemistry synthesis as challenging because of their reliance on memorization of a large number of reactions, reagents, and rules, poor conceptual understanding of the topics, ineffective teaching methods which lacks active learning and student engagement, and the myriad number of possible pathways to solve synthesis problems. Our participants suggest that memorization and rote-learning plays an important role in the learning of multistep organic synthesis, which might cause a hindrance to the process of learning and can impede students' problem-solving ability.

Keywords: second year-undergraduate, chemistry education research, organic chemistry, synthesis

INTRODUCTION

Organic chemistry is the course the usually follows the general chemistry sequence for most students and is the course that many of its students struggle to succeed in due to its rigorous curriculum and demanding work-load. Organic chemistry is required as rite of passage for most science majors, engineers, and pre-health fields. Learning organic chemistry synthesis requires understanding of several organic chemistry concepts including functional groups, acidity and basicity, electrophiles and nucleophiles, mechanisms, stereochemistry, reactions, and problem-solving skills. The organic chemistry curriculum covers a wide array of topics, with a few topics extending from general chemistry curriculum that students may be familiar with such as acid-base reactions [1]. But beyond acid-base reactions, most of organic chemistry is a whole new world to the students in which they are introduced to topics such as functional groups, stereochemistry, conjugated systems, and spectroscopy [2]. All the topics discussed throughout the course serve as the knowledge required for students to understand the constructed mechanisms for various reactions that lead them to the world of organic chemistry synthesis.

A synthesis is a series of two or more reactions designed to obtain a specific final product from a specific starting material. Therefore, the number of synthetic steps is equal to the number of reactions performed to create the sequence that leads to the desired product. Solving a synthesis problem involves a student designing a series of reactions, on paper, in which they combine molecules to give a specific, more complex molecule. Students are expected to choose form dozens of reactions they have learnt in previous and current organic chemistry courses, making sure that their strategies account for regiochemistry, stereochemistry, and that their reactions maximizes yield, and safety, while also minimizing cost and waste [3].

Synthesis is first introduced in organic chemistry I where students are expected to propose a full synthesis without being taught to integrate their knowledge and skills [4]. Therefore, students struggle with synthesis problems due to shortcomings in effective problem-solving methods, an incorrect approach to produce successful mechanisms, and a lack of sound understanding of organic chemistry concepts [5]. In one recent study, the author identified two recurring themes as limitations of students in organic synthesis which are: students are unable to transfer much of their general chemistry knowledge into organic chemistry courses and they often do not have the implicit knowledge required to understand how to apply concepts and models to various tasks [6].

Mechanisms play a key role in predicting the selectivity of synthetic transformations, and therefore, how well a student draws these curved arrows is highly indicative of their success in solving synthesis problems [7]. Reaction mechanisms, electron-pushing formalism, are crucial to an organic chemist's problem-solving processes. The electron-pushing formalism is a convention used by organic chemists to describe the step-by-step mechanism at the molecular level by which reactions occur. It was found that graduate students who became more acquainted with using reaction mechanisms as backbone to their synthesis problem-solving have improved drastically and have found mechanisms even more useful now than in their undergraduate years because mechanisms allowed them to troubleshoot unexpected problems [8]. A disturbing trend has been documented in which when students are asked to generate mechanisms in the course of predicting the products of a series of reactions. Students were able to predict product without supplying a mechanism, or producing a mechanism as an afterthought to the product [9].

A philosophy that is very common when writing these arrows is the "it-gets-me-to-the-product" philosophy, in which students use these arrows to bring them closer to a product by forcing the movement of electrons anywhere they can instead of allowing the arrows to guide them through any intermediate steps that will lead them to the product [10]. Additionally, some researchers argue that curved arrows held no physical meaning for their research participants [7]. The majority of their participants focused more on the starting material, intermediates, and products rather than the physical process involved in the transformation of starting materials into products [7].

It is beneficial to students to incorporate verbal and external representations of electron-pushing mechanisms which would cause a synergistic benefit to the learners [11]. The ability to translate between these representations is the underlying skill needed to succeed in mechanisms and ultimately, organic synthesis [12]. In one study where researchers investigated "mechanistic language descriptions" as students worked on different types of electron-pushing formalism tasks [13]. They noticed that students treated charges like objects instead of using electron movement as the reasoning to their existence. Students were also found overwhelmed with trying to consistently use curved arrows to keep track of electron and atom movement [13].

Another problem related to synthesis that students face are acid-base reactions. Acid and base reactions are important concepts in organic synthesis because they involve numerous proton transfers. In order to correctly solve a mechanism, one must understand the terms: protonate, deprotonate, acid, base, conjugate acid, and conjugate base. Therefore, before an understanding of these acid-base reactions can be achieved, students must learn to differentiate between an acid and a base and its functions. The three most relevant acid/base theories are the Arrhenius, Brønsted-Lowry, and Lewis definitions. The Arrhenius theory is mostly useful in identifying acids, bases and explaining neutralization. Brønsted-Lowry's proton theory also provides a simple way of explaining neutralization and is preferred by many chemists since most reactions involve proton transfers. While the Arrhenius and Brønsted-Lowry theories are specific at what they provide, the Lewis theory is the most inclusive in its definitions of acids and bases out of the three.

These three theories are all taught to every general chemistry student, but remains to be a highly overlooked topic, posing a big problem because the deeper students dive into chemistry, one will find that acid-base reactions are involved in the formation a variety of organic reactions [14]. Acidity and basicity is an important concept to master in organic chemistry to ensure students' learning and success in the course [3]. In terms of acid strength, researchers reported that students have the conception that functional groups determine acid strength, although acid is in fact independent from isolated functional groups [15]. Students fail to understand that acid strength in Brønsted-Lowry and Lewis models depends on the structure of the entire molecule, as well as any surrounding molecules present within the solution. In a recent report, students' challenges in learning acidity/basicity theory are related to rote-learning and memorization which do not serve students well in organic chemistry [16].

An area in which acid-base reactions are prevalent in is elimination and substitution reactions involving

acids and bases, and electrophile and nucleophiles, which are both defined using the Lewis theory. Lacking the skill of choosing the correct reaction based on acid/base character can hinder students' success when solving synthesis problems. A nucleophile is a Lewis base, and an electrophile is a Lewis acid. Cartrette and Mayo (2011) found this to be the cause of students' difficulties in distinguishing between a nucleophile and electrophile because they are unable to relate nucleophilic and electrophilic functionality to the appropriate acid/base model – the Lewis model [17]. Considering that the majority of reactions in organic chemistry involve nucleophiles and electrophiles, the Brønsted-Lowry theory is deemed less applicable in the course compared to the Lewis theory, which is far more useful in organic chemistry problem-solving. It was reported that although students' acid-base knowledge is correct despite basing them off of declarative knowledge, stemming from what they learned from past introductory chemistry courses, they are unable to use their knowledge when solving problems concerning acid-base and electrophilic-nucleophilic reactions [17].

Additional challenges students face in learning organic chemistry synthesis is the ability to convert a two-dimensional image into its three-dimensional equivalent [18]. This is typically achieved, without using a physical model, by drawing wedges and dashes to symbolize bonds moving in front or behind a molecule [19]. Chirality is a geometric property of molecules that are non-superimposable on their mirror images, and are therefore, non-superimposable enantiomers of one another [20] and cannot match its mirror image by any sort of translation and rotation [21]. Stereochemistry is the baseline of the three-dimensional challenges that all organic chemistry students face, and failure to master these concepts can handicap a student throughout an entire course, especially when approaching synthesis problems. Chirality and stereochemistry are two major concepts that commonly bombard students simultaneously in most organic chemistry courses causing students to overlook both topics and pass on without thorough understanding of either one [22]. Developing a sound understanding of stereochemistry can play an important role in learning and performance in organic chemistry [23].

The use of mechanisms causes a wide gap between novices and experts in organic problem-solving because molecules that are dynamic in the minds of experts remain static in the minds of novices. Rather than solving problems, novices play with them like puzzles, making it clear that they often reproduce memorize sequences of events when approaching synthesis problems rather than using mechanisms to serve as the explanation to their process [7]. Students' understanding of chemical principles and processes greatly impacts their problem-solving abilities. As Strickland and co-researchers (2010) investigated graduate students' abilities of conceptualizing the terms used to describe chemical reactivity - such as functional groups, acid-base, electrophile and nucleophile - and had them express mental models of the images used to depict organic reactions and mechanisms, the study showed that the participants' conceptualizations only demonstrated a surface-level understanding of the given concepts because of their lack of solid foundational knowledge [24]. Students have also been found to successfully produce correct answers to mechanisms without having an understanding of the chemical concepts behind their responses, hindering them from successfully moving forward in the organic chemistry curriculum [10]. Therefore, a sound understanding of organic chemistry concepts will ultimately lead to a successful synthesis problem-solving [3].

Problem-solving is what you do when you don't know what to do [25] and to overcome obstacles and barriers by bridging the gap using information and reasoning [26]. Using these two terms, it can be understood that the only difference between exercises and problems is not a difference in complexity, but only of familiarity. The distinction between the two is important because it can be the root of miscommunication between an instructor and the students. Students lack the important skill of properly organizing their thought process when approaching synthesis problems, adhering to simple, algorithmic rules without questioning their intention and justification [26]. Regardless of the problem-solving method used, a key phase in the entire process is the very beginning in which the given information is disassembled and the problem is restructured. All of this information must also be understood by students to successfully answer any synthesis problems, and they must know how to relate the new knowledge to old knowledge rather than perceiving them as separate concepts. A prominant chemistry education researcher proposed an anarchist model of problem solving in which a student is taught to solve a problem in a non-linear, trial-and-error process [27].

The research questions that guided this study are:

1. What are the students' views on the challenges they face in learning organic chemistry synthesis?
2. What are the students' views on approaches to improve learning and overcome obstacles they face in learning organic synthesis?

The overarching goal of our research is to examine challenges that students face in learning organic synthesis. Our students' population are those enrolled in first semester organic chemistry at the City College of New York, an urban, minority serving commuter institute. A total of 184 students (N = 184) were available and willing to participate in the optional survey. Students include those majoring in science, engineering, and health fields. In order to properly examine the challenges that students face in learning organic chemistry synthesis, data were collected using a Likert-type questionnaire, composed of eight questions, a short answer questionnaire, composed of five questions, and student interviews. The students' interviews were conducted to elicit information and clarifications on some of the answers that students provided on the short answer questions. The information we obtained from the student interviews helped in categorizing some of the answers used to make pie charts. The study participants were approached individually after organic chemistry course and were asked to participated in the study. Students were recruited anonymously and were informed of their rights as human subjects. All data were collected, stored, and analyzed in accordance with the Institutional Review Board. The survey started with multistep organic synthesis problem that is challenging and can be seen in Figure 1. The surveys were optional and anonymous and the interviewees selected at the completion of organic chemistry I course.

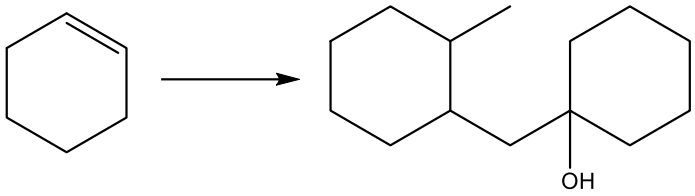

FIGURE 1. A question about synthesis that was asked to participants in this research project which involves the seen transformation.

The Likert-type questions were scored on a five-point scale, where (1) Strongly Disagree, (2) Disagree, (3) Neutral, (4) Agree, (5) Strongly Agree. For the open-ended questions, answers that fell into similar categories were compiled and their percentages were calculated. A pie chart was used to graphically represent the data.

RESULTS AND DISCUSSION

Graphical depiction of the Likert-type questions and the average answer from respondents are shown in Figure 2.

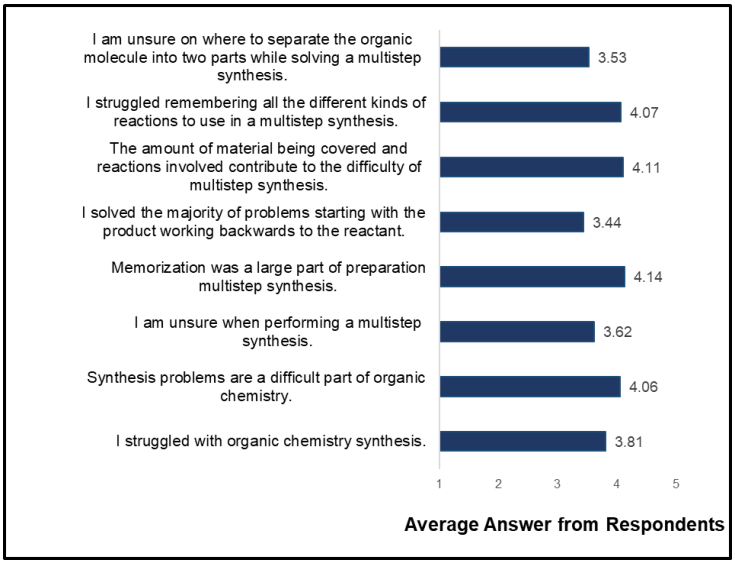

FIGURE 2. Likert-scale questions and averages of students' responses

Based on the results from the Likert-type questionnaire, the data suggests that students struggle with

multistep organic synthesis and face uncertainties in their abilities to complete synthesis problems successfully. Students are unsure where to separate the molecule into synthons while working backwards. Students struggle remembering the different types of reactions needed to solve an organic synthesis. The amount of material covered seems to be overwhelming to the students and their learning. The data also seem to suggest that students think that memorization is a large part of organic synthesis. Additionally, the data suggest that students might indicate that students do not always rely on retrosynthesis to solve and try to solve synthesis problems by starting at the reactant and going to product which makes the task arduous. Overall, the data suggests that students struggle with learning about synthesis in organic chemistry.

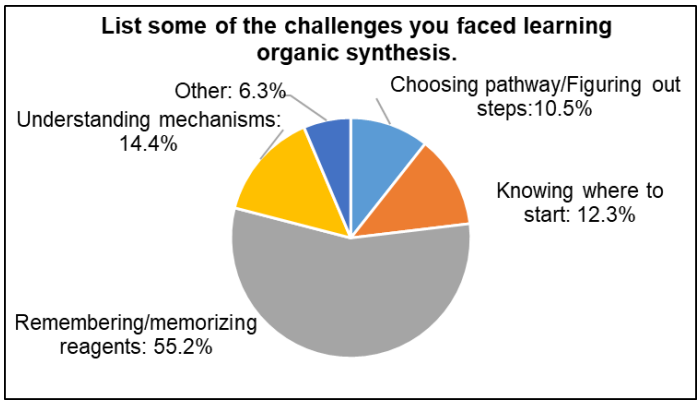

FIGURE 3. A pie chart that shows the percentages of the list of challenges, based on short answer questions, students have with organic synthesis

Figure 3 is a pie chart, based on short answer questions, displaying the challenges student face in learning organic synthesis. Majority of the students, 55.2%, indicated that remembering and memorizing reagents and reactants poses the biggest challenge to organic synthesis. Some of our research participants, 14.4%, report that they struggle with organic synthesis because they lack a deep understanding of mechanisms and electron-pushing formalism. 12.3% of participant struggle with organic synthesis because they do not know where to start, as going from the reactant to product, instead of working a retrosynthetic procedure. Another group of participants, 10.5%, struggle choosing a pathway and figuring out the steps, which might be related to problem-solving ability. The 6.3% that we listed as other reported that poor knowledge of stereochemistry, acidity, basicity, nucleophilicity, and electrophilicity were part of the obstacle for learning multistep organic chemistry synthesis. A small fraction of students commented on poor instruction as a hindrance to their learning of organic synthesis. A sample response from one of our participants: "*The amount of mechanisms makes it difficult to organize when trying to complete a synthesis.*"

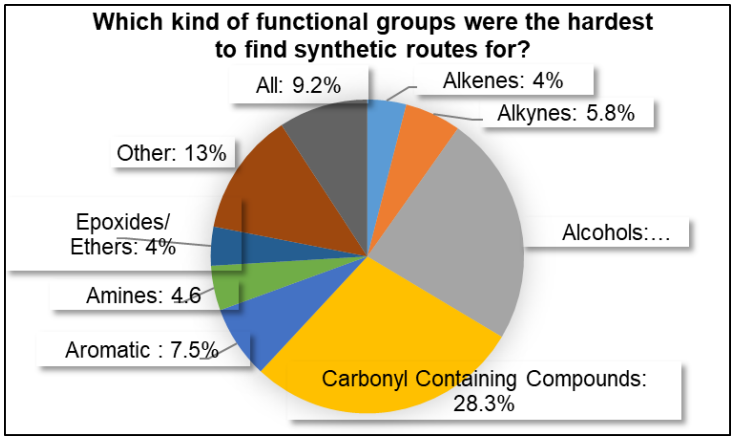

FIGURE 4. A pie chart that shows the different functional groups, based on short answer questions, that students struggle with in an organic synthesis

We were able to compile a list of functional groups that students find challenging when attempting an organic synthesis problem. A significant number of students struggled with carbonyl containing compounds, 28.3%, which includes ketones, aldehydes, carboxylic acids, esters, and amides. Alcohols were the second more common groups that students struggle with producing a value of 23.7%. Also to make the list are amines, alkenes, alkynes, and epoxides.

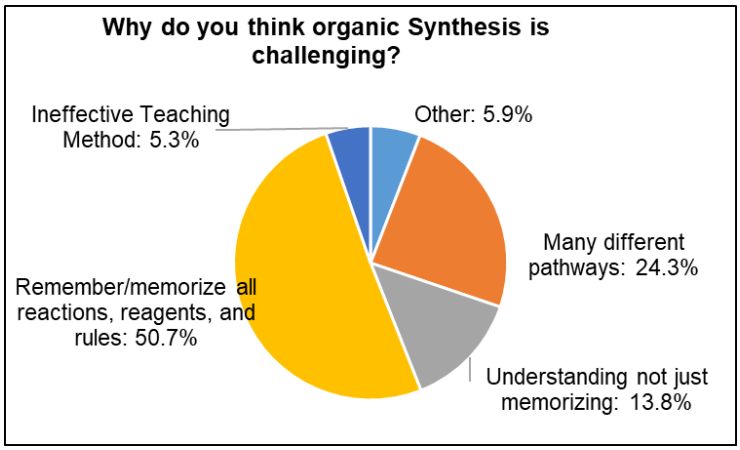

FIGURE 5. A pie chart, based on short answer questions, that shows some of the challenges that students encounter when learning organic synthesis

Figure 5 is a pie chart, based on short answer questions, illustrating the reasons that organic chemistry synthesis is challenging. Our data shows that 50.7% of students think that recollection and memorization of all the reactions, reagents, and rules needed for synthesis problems are challenging. Participants of this research project, 24.3%, report that organic chemistry synthesis is challenging because of the myriad pathways that one can use. Some participants, 13.8%, present the belief that organic synthesis require understanding of reactions and mechanisms and not just memorization. They also claim that they lack this understanding. A small fraction of participants, 5.3%, claim that ineffective teaching method or instructor poses a challenge to learning of organic synthesis. The 5.9% other answers include: Organic synthesis is not challenging, hard to visualize, and other classes take time away from studying for organic chemistry. Some typical responses from the short answer questions are:

Student 1. "*Because there are so many different pathways to approach one problem and then too many reagents to remember*."

Student 2. "*It requires you to recall every reaction you have learned in a meaningful manner*."

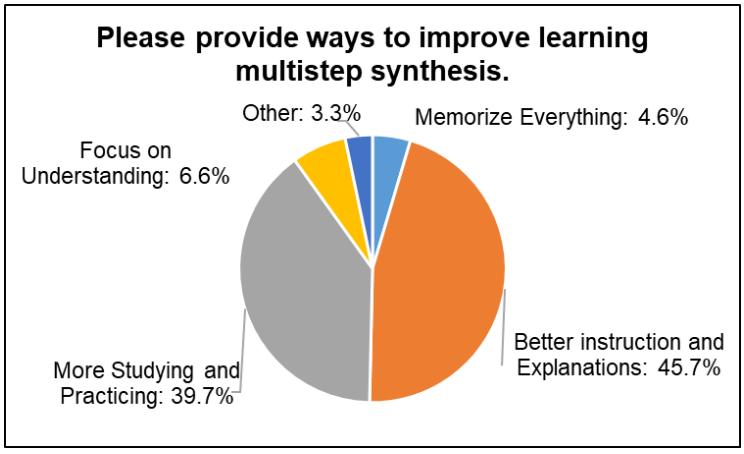

FIGURE 6. A pie chart, based on short answer questions, that shows the different ways to improve learning of organic synthesis

We wanted to know how to improve learning of organic chemistry and asked the students about the ways that can be accomplished. The results, based on short answer questions, are presented as a pie

chart in Figure 6. A significant number of students, 45.7%, think that the problem is with instruction and ask for improvement of instruction and better explanation from instructors. Many of the participants referred to active learning as opposed to lecture format. The interesting results for us is that numerous students hold themselves accountable for the learning process. This is attested by the 39.7% of the participants that suggest more studying and practicing would improve learning of organic synthesis. 6.6% say that instructors should focus on understanding and development of deeper knowledge. Whereas, 4.6%, think that memorizing everything is the solution to improvement in organic chemistry synthesis. The 3.3% of other include: cover less material, emphasize practice of mechanisms first, use visual aids, and ask for help. A typical response from a participant is: “Doing as many practice problems during a lecture would help a lot. Additionally, professor walking through those problems while offering tips.”

In terms of synthesis, if one cannot successfully identify a base from an acid, an electrophile from a nucleophile, and somewhat form a plausible mechanism with the substrate and reagent at hand, nothing in synthesis will make sense because all that occurs in a student’s brain is memorization without conceptualization. Students rely on rote-learning when examining nucleophiles and electrophiles instead of deep understanding of the relationship between the function and structure [28]. Therefore, one will have a harder time at predicting the steps that lead you to the final product given in a synthesis problem. Students give priority to structure over function when dealing with electrophiles and nucleophiles and they claim to know the mechanism of the organic reaction before determining whether the reactions involves nucleophiles or electrophiles [28]. This might influence students’ ability to successfully complete a synthesis problem.

One in seven students listed understanding mechanisms as one of the challenges that students face in learning organic synthesis. Electron-pushing formalism depicted during an organic chemistry mechanism is one of the most considerable symbolic conventions in the curriculum and students can benefit when involved in mechanism use [29]. Relying on electron-pushing formalism engages students in an efficient and organized method to solving organic chemistry problems [29]. Our data seems to be supported by other research in the field. Flynn and Ogilivie (2015) recommend that instructors teach mechanisms, electron-pushing formalism, in depth before teaching reactions, the reaction in organic chemistry should be arranged based on their mechanisms and not functional group, and arrow pushing and electron movement are emphasized for conceptual learning [30].

Based on the results presented in Figure 5, about 14 percent of participants refer developing better understanding rather than memorization as challenges in learning organic synthesis. Developing a conceptual understanding and mastery of acid-base reactions is needed for students to learn related concepts [31]. In learning organic chemistry, students should understand and see the connections between different topics instead of thinking about them as disparate pieces of information that they should memorize for the exam [32]. As students’ ability to recognize patterns and see connections in reactions and mechanisms improve, then they are less likely to rely on memorization [33]. Understanding content and relationships between reactions, mechanisms, functional groups, stereochemistry, acidity and basicity, nucleophilic and electrophilic character leads to improved problem-solving and performance in organic chemistry synthesis.

A significant number of student involved in our research study suggest that studying and practicing enhances their learning of organic synthesis. This is consistent with constructivism, that is “Knowledge is constructed in the mind of the learner” [25]. Relying on learning strategies that is consistent with constructivism and student-centered is effective in improving performance and learning in organic chemistry [34].

Our research participants place instruction and teaching as the number one method to improve learning of multistep organic synthesis. This is consistent with research in the field that suggests students should be given ample opportunities and provided with engaging instruction to develop their skills and competencies in solving reaction problems mechanistically [33]. We think that student should move from recall and comprehension into evaluation, analysis and synthesis. The more actively involved in the learning process, the better the students will perform on synthesis problems. One example of active learning is POGIL method for teaching and learning organic chemistry which resulted in greater understanding of content and positively impacted student performance on the standardized ACS organic chemistry exam when compared to traditional lecture format [35].

Our data suggests that students struggle with organic chemistry and they view the topic as challenging, which leaves them with uncertainty and anxiety. Research has demonstrated that graduate chemistry students struggle with predicting products of organic reactions [36]. Furthermore, our participants suggest

that memorization and rote-learning plays a significant part of multistep organic synthesis. This might be an obstacle to learning and it can negatively impact their problem-solving ability. We think that students use memorization and pattern recognition to as organic chemistry learning strategies which is detested by instructors. When students rely on memorization and rote-learning, it hinders their proficiency to incorporate new information into existing knowledge structure and limits their problem-solving ability [37].

CONCLUSION

Students view several difficulties with multistep organic chemistry synthesis which includes: challenges in working backwards (retrosynthesis), difficulties remembering all of the required different reactions needed for solving a synthesis problem, overwhelmed with the amount of material covered, development of conceptual understanding of mechanisms, understanding acids and bases, nucleophiles and electrophiles, difficulties in choosing proper pathway and lack of a well-developed problem-solving competency, and incomplete knowledge about stereochemistry. Participants in our research study list some of the reasons that organic synthesis is challenging and these include: reliance on memorization of a large number of reactions, reagents, and rules, poor conceptual understanding of the topics, infective teaching methods which lacks active learning and student engagement, and the myriad number of possible pathways to solve synthesis problems.

Research data underscores the need for improvement of instruction and enhanced instructional methods to overcome obstacles of learning organic synthesis. Active learning and student-centered teaching methods can provide an avenue to improve learning in organic chemistry and to enhance students' understanding and performance in organic chemistry synthesis. Electron-pushing formalism can play a dominant role for learning and experts to visualizing the order of steps that causes the conversion of a reactant to a product and thus student should be engaged in learning methods that nurtures the development of these competencies [9]. Development of conceptual understanding of structure, function, mechanisms, reactions, and the relationship between these key concepts can enhance problem-solving and performance in organic chemistry synthesis.

Students take responsibility and accountability as part of the solution to learning organic chemistry synthesis. This is significant since research supports the notion that knowledge in constructed in the mind of the learner [25]. Furthermore, our participants suggest that memorization and rote-learning plays an important role in the learning of multistep organic synthesis, which might cause a hindrance to their learning and can impede their problem-solving ability. Further work is needed to understand the challenges that students face in learning multistep organic synthesis and identifying solutions based on teaching and learning theories to overcome the challenges students face in learning organic chemistry synthesis. We think that active learning methods should be employed to enhance learning, improve conceptual understanding, and nurture problem-solving competencies of multistep organic chemistry synthesis.

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