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Teaching and Learning Strategies of Organic Reaction Mechanism in Pre-University Chemistry: A Scoping Review

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Teaching Organic Chemistry has always been viewed as difficult to teach, where learners are frequently repelled by the topic's high level of complexity, which appears to discriminate against the subject. Over the years, changes have been made from textbook-driven curriculum to activity-based learning for continuing meaningful learning provided in the Organic Chemistry classroom. This study aims to map the literature on teaching and learning strategies of Organic Reaction Mechanism (ORM) to be incorporated into a proposed module (ORM Module) between the year 2012 up to 2021. A computer-assisted literature search using Scopus, Google Scholar, EBSCOhost, and ProQuest was performed. Additionally, Arksey and O'Malley's (2005) five-stage framework guided the scoping review approach. The data extracted were respected to study characteristics, inclusion, and exclusion criteria of "organic reaction mechanisms" OR "mechanisms of reactions" keywords. Out of 784 records found in four databases, only 55 were suitable for full-text review, and 17 studies were finally included. Five key strategies for teaching ORM were identified: electron-pushing formalism (EPF), patterns of reactivity, technology integration, problem-solving, and self-regulated learning (SRL), along with six related teaching and learning activities. The findings of this study can be utilised for future development of the ORM Module. Further studies are recommended to investigate the interconnectedness of Organic Chemistry and other research areas.

Keywords: Organic chemistry; organic reaction mechanism; teaching and learning

I. INTRODUCTION

The content-laden curriculum of Organic Chemistry turns the students to experience a tough and challenging learning process. The students' population enrolled in Organic Chemistry either from high school, pre-university, or undergraduate need to be served by effective teaching strategies. Therefore, the pedagogical issue on teaching Organic Chemistry should be concerned. Regarding that matter, changes have occurred from textbook-driven, which is always considered traditional learning to become activity-based learning. However, one such issue in Organic Chemistry that plays a lot of controversy among teachers and learners, especially for the novice, is the volume of reaction mechanisms, which is difficult for students to learn meaningfully.

Historically, the fundamental mechanism and reactivity of organic chemistry were established initially by Ingold in 1926, when he interpreted the results in terms of electron movements, making extensive use of curly arrows, which Kermack and Robinson had introduced in 1922. Hence, a language for mechanistic studies eventually became acceptable in early 1930, whereas the first edition book entitled "Structure and Mechanism in Organic Chemistry" was released (Ridd, 2008). Moreover, since Morrison and Boyd published their revolutionary text in 1959, teaching organic chemistry using mechanisms has become widespread (Otter, 2020).

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Clearly, more studies of this nature have evolved since the forgotten history. Nevertheless, reaction mechanisms are foundational to the study of Organic Chemistry to understand why certain reactions occur and how they occur. Unfortunately, students seem to separate the reactions and mechanisms as two isolated phenomena, making it harder for them to learn yet frequently being provided with conceptual challenges (Evans, 2016; Otter, 2020). Even good students in general chemistry face difficulties in applying the knowledge to new contexts of the Organic Chemistry course, especially for reaction mechanisms. Nevertheless, Organic Chemistry educators have also reported the complexity of the reaction mechanism concept (Duis, 2011; O 'Dwyer & Childs, 2017).

In many cases, Organic Chemistry is taught through memorisation of reactions without providing an adequate understanding of reaction mechanisms. This approach may lead to a lack of conceptual understanding, making it difficult for students to apply their knowledge in novel situations (Grove & Lowery Bretz, 2012; Anzovino & Lowery Bretz, 2015; Dood & Watts, 2022). In a traditional classroom, the teacher generally discusses microscopically the stages of reaction mechanisms, followed by symbolic representation through a schematic reaction diagram. However, this chalk-and-talk method lacks the ability to visualise the exact events that occur during the reaction mechanisms (Shariman & Talib, 2017).

Lack of clarity and structure in the presentation of organic reaction mechanisms may lead students to struggle to understand the mechanisms involved in chemical reactions (Cruz-Ramírez De Arellano & Towns, 2014; Webber & Flynn, 2018). Therefore, presenting the material clearly and structured, with visual aids and step-by-step explanations, can help students better understand the concepts and mechanisms involved. According to Crandell *et al.*'s (2020) study, it is evident that repetition in watching the mechanistic arrow and reading the supporting reasoning is the only method to determine the students' coherent knowledge about reaction mechanisms. Students should be given a deeper understanding of the purpose of reaction mechanisms rather than thinking of those reactions as unrelated facts that they have to memorise for the exam.

Hence, this article intends to map the teaching and learning strategies implemented in the proposed module, which solely focuses on the organic reaction mechanism (ORM). This work also highlights the appropriate activities for teaching and learning ORM effectively. Introducing students to active strategies has been shown to be more effective in encouraging students to learn meaningfully (Shariman & Talib, 2017; Bhattacharyya, 2019; Lieber & Graulich, 2020; Schweiker, Griggs & Levonis, 2020).

1. *Scoping Review*

Scoping review is a comparably new approach to evidence synthesis. Since 2005, the scoping review has flourished substantially in identifying, analysing, and reporting on evidence, especially in the health area (Arksey & O'Malley, 2005). Scoping reviews, as opposed to typical systematic literature reviews, can be utilised to determine knowledge gaps, scope a literature body, answer various sorts of queries for systematic reviews, and map relevant material in a topic of interest (Tricco *et al.*, 2018; Khalil *et al.*, 2019, 2021; Munn *et al.*, 2019). Therefore, scoping reviews have sometimes been referred to as 'mapping' reviews (Arksey and O'Malley, 2005; Anderson *et al.*, 2008). Lately, scoping reviews have begun to incorporate features of systematic review, for instance, a priori protocol and a comprehensive search, into their conduct and report rigorously (Tricco *et al.*, 2018; Khalil *et al.*, 2019, 2021; Munn *et al.*, 2019).

Moreover, Arksey and O'Malley (2005) presented the first scoping review framework by detailing the purpose and methodology steps as guidance to researchers. With respect to Arksey and O'Malleys' framework, other researchers contributed for further recommendations related to the method. For each phase of Arksey and O'Malleys' framework, Levac, Colquhoun and O'Brien (2010) and Daudt *et al.* (2013) provided more methodological clarity and specifics. Consider the repercussions of the scoping review's outcomes within the wider study, policy, and practice context, as Levac, Colquhoun and O'Brien (2010) advocated in giving significance to the findings. They are putting together a team with the necessary content and methodological experience. Meanwhile, Daudt *et al.* (2013) advocate researchers to assemble a small suitable team to perform the task as well as to consider the benefits of a team like this, in which each member's abilities, for instance, depth and breadth of expertise, contribute to the investigation and save time.

According to Arksey and O'Malley (2005), the scoping reviews concentrate on four possible motivations for scholars to conduct such a review. The reasonings are (1) to assess the scope and character of research activity on a certain subject or area; (2) to determine if a systematic review is required; (3) to summarise and distribute research findings; and (4) to identify prospective research gaps in the current literature. Nonetheless, Arksey and O'Malley suggested those four purposes in two different roles of scoping study; firstly, the scoping review may be conducted as an ongoing process of reviewing by aiming to produce a full systematic review, and secondly, the study may serve as a stand-alone initiative (Arksey & O'Malley, 2005; Peterson *et al*., 2017).

II. METHODOLOGY

The methodology of this scoping review study was guided according to the five-stage framework by Arksey and O'Malley (2005) were among the first researchers to provide a framework for clarifying the utility and techniques of a scoping study. This scoping review approach is taken in the article for considering the findings of the study and drawing conclusions from the existing literature regarding studies related to teaching and learning of Organic Reaction Mechanism (ORM). Accordingly, the five stages of Arksey and O'Malley's framework comprise; (1) defining the research question, (2) locating relevant studies, (3) study selection, (4) charting the data, and (5) collecting, summing and reporting the findings.

A. Step 1: Identify the Research Question

This study aims at mapping the literature on teaching and learning strategies of ORM to be incorporated into the ORM Module. The primary question of the scoping review is "How did teaching and learning strategies of ORM were implemented in previous studies?'. The question is subdivided into two sub-research questions: (i) 'What are the suitable teaching and learning strategies of ORM for pre-university chemistry?'; (ii) 'What are the appropriate teaching and learning activities of ORM for pre-university chemistry?'.

B. Step 2: Identifying Relevant Studies

In this study, the search terms or keywords were chosen to capture literature related to organic reaction mechanisms at the students' level. Hence, four academic electronic databases were searched for the identified keywords and controlled vocabulary terms. The identified keywords contained organic reaction mechanisms and mechanisms of reactions. These terms were paired with the words of the target population of this study that were students and pupils. This is regarding Arksey and O'Malleys' suggestion that a broad definition of keywords is used for search queries in order to obtain a "broad coverage" of existing literature (Arksey & O'Malley, 2005). The advanced search techniques with Boolean, wildcards, and truncations, which are conceivably relevant to study, were also practiced to limit, widen and combine the literature search results. The specific search queries used were different for each database according to the limitation (refer to Table 1).

Table 1. Specific search queries, all databases

Database	Search Queries
Scopus	TITLE-ABS-KEY(((“organic reaction mechanisms” OR “Mechanisms Of Reactions”) AND (“student*” OR “pupil*”))) AND (LIMIT-TO (PUBYEAR,2021) OR LIMIT-TO (PUBYEAR,2020) OR LIMIT-TO (PUBYEAR,2019) OR LIMIT-TO (PUBYEAR,2018) OR LIMIT-TO (PUBYEAR,2017) OR LIMIT-TO (PUBYEAR,2016) OR LIMIT-TO (PUBYEAR,2015) OR LIMIT-TO (PUBYEAR,2014) OR LIMIT-TO (PUBYEAR,2013) OR LIMIT-TO (PUBYEAR,2012)) AND (LIMIT-TO (DOCTYPE,”ar”)) AND (LIMIT-TO (SRCTYPE,”j”)) AND (LIMIT-TO (LANGUAGE,”English”))
Google Scholar	(“Mechanisms Of Reactions” OR “organic reaction mechanism”) AND (“students” OR “pupils”)
EBSCOhost	(“Mechanisms Of Reactions” OR “organic reaction mechanism”) AND (“students” OR “pupils”)
ProQuest	(“organic reaction mechanisms” AND “students”) AND (20110605-20210605)

The databases decided were included Scopus, Google Scholar, EBSCOhost, and ProQuest since, with a comprehensive methodology, these four databases would be adequate to address the research questions (Arora *et al.*, 2021). Scopus is one of the world's largest multidisciplinary databases, containing research undertaken in a variety of fields. Google Scholar, on the other hand, is a useful tool for scholars seeing as it is free to use, seems to catalogue a large number of scholarly publications, and permits citations to be exported separately (Haddaway *et al.*, 2015). Meanwhile, EBSCOhost and ProQuest are the most prominent database providers available in many academic libraries, whereas the two are often used to pursue research and information seeking. The time period of this study was limited to ten years, from 2012 to 2021. Table 2 lists all of the criteria for inclusion and exclusion.

Table 2. Inclusion and exclusion criteria

Criterion	Inclusion	Exclusion
Time period	Last 10 years (2012-2021)	Studies outside these dates
Language	English	Non-english studies
Type of article	Original research and peer-reviewed	Articles that were not original research and peer-reviewed
Population and sample	High school or undergraduate students enrolled in Chemistry programme and lecturers who expert in Organic Chemistry	All other students not enrolled in chemistry high school or undergraduate study and lecturers who are experts outside of chemistry field
Literature focus	Studies related specifically to organic reaction mechanisms in classroom	Studies that do not relate to organic reaction mechanism in classroom environment

C. Step 3: Study Selection

The search results identified 784 articles after using the key search descriptors. The number of articles obtained in Scopus, Google Scholar, EBSCOhost, and ProQuest databases was 82, 559, 74, and 69, respectively. All articles were imported into a free web-based tool, namely Mendeley, to identify and remove the duplicate articles from the four databases selected. The identified article then proceeded to the screening process against the inclusion criteria. A review of the titles, abstracts, and keywords indicated a large number of papers that were unrelated to the population of interest, notably those connected to applied chemistry contexts utilising the organic mechanism reaction. Complete text versions of the 55 publications were collected and evaluated, as recommended by Arksey and O'Malley (2005), in order to make a final judgment on whether the investigation should be included in the review. By the guidance of inclusion and exclusion criteria, 17 articles that were the most relevant to the research question were identified, and several studies were excluded throughout the study selection process (Refer Figure 1).

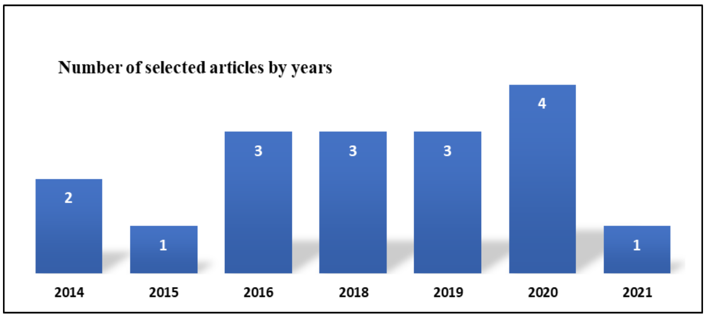

Figure 1. Total final selected of 17 articles

As indicated in Figure 2, the entire article selection procedure was guided by the Preferred Reporting of Items for Systematic Reviews and MetaAnalyses (PRISMA) 2020 Statement (Page *et al.*, 2021).

D. Step 4: Charting the Data

The charting of the final included articles is the fourth stage of Arksey and O'Malley's (2005) framework. The author, location, study participant and study design, activities, and strategies in ORM teaching and learning, and notes from each publication were presented in tabular form. The appropriateness of the charting form was debated with co-authors, and the chart data was checked by the second author. Table 3 outlines the investigations that were selected.

E. Step 5: Collating, Summarising, and Reporting the Results

Summarising and reporting findings is the fifth phase in Arksey and O'Malley's (2005) scoping review framework. The results were summarised according to the research questions and analysed using descriptive quantitative and qualitative thematic analyses.

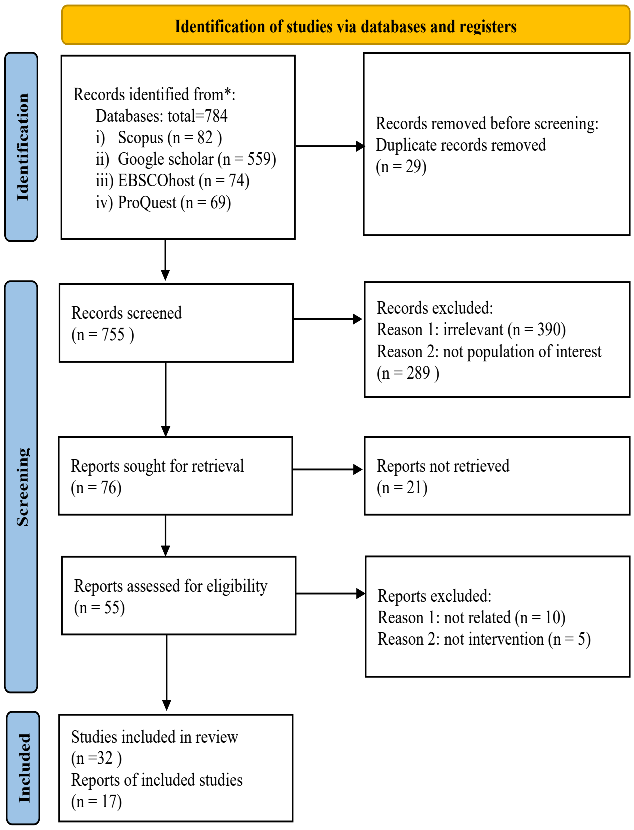

Figure 2. Flow diagram of the search strategy

Table 3. Summary of included studies (n=17)

	Author/ Location	**Study design/ Study participants**	**Strategies**	**Activities**
1)	(O'Brien-Tomory, 2016) United States	Mixed-method 21 high school students who took introductory chemistry courses for school nursing students	1) Online tutorials 2) Self-Directed Learning (SDL)	1) Lecture tutorial screencasts utilised the PowerPoints that accompanied the textbook with audio and written annotations to coincide 2) Review, screencasts designed to help students prepare for the upcoming exam
2)	(Bhattacharyya & Harris, 2018) United States	Qualitative 14 students who took Organic II at a university in the Midwest of the United States	1) An electron-pushing mechanism sample diagram (verbal → diagram tasks) 2)Mapping techniques and Geometric figures	1) The curved arrows' descriptions (a) The nucleophiles' specific atom(s) and/or electron source, bonding or nonbonding pair, were specifically identified, as were the electrophiles' equivalent positions. (b) The phrases had a nucleophile → active voice action verb → electrophile syntax with the nucleophile and electrophile serving as the subject and object, accordingly.
3)	(Bodé & Flynn, 2016) Canada	Qualitative 700 second-year undergraduate students.	Problem-solving strategies	1) The target molecule's newly generated bonds were detected 2) The target is formed by adding identified atoms to the starting molecule 3) Key regiochemical connections were discovered 4) The atoms from the starting material were mapped onto the target 5) A retrosynthetic analysis, either partial or total, was used
4)	(Bongers, Northoff & Flynn, 2019) Canada	Qualitative 7 undergraduate students.	Animated learning (Organic Chemware®)	Mental model in use: 1)Static – reasoning that is not based on a process 2) Static – a heuristic or symbolic pattern 3) Dynamic Process – a mechanism's connection between electrons and bonds 4) Dynamic Particles in Motion – pondering the mobility of molecules
5)	(Cruz-Ramírez De Arellano & Towns, 2014) United States	Qualitative 22 undergraduate students who registered in a three-credit non-majors organic	Toulmin's argumentation paradigm	1) Determining if a substance is a base and/or a nucleophile 2) Determining a substance's basic or nucleophilic strength 3) Detailing the electron movement of the stages that occur during alkyl halide reaction mechanisms with accuracy 4) Determining the feasibility of their hypothesised reactive intermediates and covalent bond breakdown

		chemistry course		5) Discussion in small groups
6)	(Caspari & Graulich, 2019) Germany	Qualitative 20 undergraduate chemistry and food chemistry majors	Problem-solving (Scaffolding)	1) Multivariate comparative mechanistic reasoning (stepwise reasoning) 2) Think aloud
7)	(Crandell *et al.*, 2018) United States	Mixed-method 301 general-chemistry and organic chemistry courses students	1) Mechanistic reasoning of an acid-base reaction 2) Mechanistic arrow	1) Online homework 2) Explain the polarity and electron transport using Lewis acid-base informal reasoning
8)	(Dood, 2020) United States	Quantitative 420 second-year organic chemistry courses students	Adaptive learning through Online tutorials (automated scoring)	1) Splitting up the instruction into manageable pieces 2) After each instructional unit, provide learners with multiple evaluation items 3) Quick "try-again" feedback, pushing learners to revisit wrong replies and reassess their solutions until they obtain the suitable answer
9)	(Flynn & Ogilvie, 2015) Canada	Review	Patterns of reactivity	1) Lewis structures, line structures, formal charge, and molecular orbital theory are all drawn i. Provided the initial materials and curved arrows, sketch the results of a reaction ii. Provided the basic materials and goods, insert curved arrows iii. Provided the starting materials, sketched the curved arrows, and anticipated the results of a new reaction 2) In the new curriculum, the reactions are reorganised: π Electrophiles, π Nucleophiles, E_1, E_2, S_N1, and S_N2, Enols and Enolates as π Nucleophiles, and π Electrophiles with a Leaving Group
10)	(Lieber & Graulich, 2020) Germany	Qualitative 29 students who were enrolled in a third-year organic chemistry course	Problem-solving approach (chemical concept of electrophilicity and nucleophilicity)	1) Requested to guess the outcome of a simple and familiar reaction. 2) Pupils were given five alternative product cards and asked to rate the plausibility and alternative molecular paths that led to these items
11)	(Moozeh *et al.*, 2020) Canada	Quantitative 127 undergraduate chemistry laboratory course	Web-based application	1) A video module that uses embedded movies to deliver information and concepts 2) A virtual laboratory module for doing experiments 3) A reaction mechanism module to practice sketching reaction mechanisms 4) A module for formative assessment with questions and explanatory feedback
12)	(O'Sullivan & Hargaden, 2014) Ireland	Quantitative 70 first-year pharmacy students	Online Tutorials with Automated Correction (MarvinSketch & LMS)	1) Open-access question bank 2) Individual assignments.
13)	(Sabitu *et al.*, 2021) Malaysia	Qualitative 5 experts lecturers who are specialists and professionals in chemistry education	1) Arrow pushing Formalism 2) Visualisation of the microscopic process (animation and video) 3) Cooperative and collaborative approach	1) Group learning task (assignment) 2) Teaching language symbolism before reaction 3) Mechanistic reasoning 4) Utilise Johnstone's Triangle as the framework
14)	(Webber & Flynn, 2018) Canada	Qualitative 11 undergraduate students	1) Interactive problem-solving (solving familiar and unfamiliar questions) 2) Flipped format	1) Identified Dipoles and Charges. 2) Expanding Mapping
15)	(Wilson & Varma-Nelson, 2019) United States	Mixed-method 64 first-semester organic chemistry students	1)Mechanistic problem-solving process (EPF) 2) Self-enrolled in Cyber peer-led team learning (cPLTL) and online peer-led team learning (PLTL)	1) Workshop-based (peer leader) 2) Instrumental learning 3) Relational learning
16)	(Winter *et al.*, 2020) United States	Quantitative	1) Mechanism Apps (a smart phone's touch screen interface) 2) Discovery-based learning	1) Guidelines on how to play 2) Each section's puzzles (Essentials, Substitution, and Elimination Reactions, Oxygen-containing Functional Groups, and Pi systems) 3) Scaffolding Features (provide a goal, hint, video, and immediate formative feedback)
17)	(Zurcher *et al.*, 2016) United States	Qualitative 201 first semester undergraduate students	1) E-homework platform 2) Feedback driven 3)Sapling Learning System	1) Questions on organic chemistry that are open-ended 2) By modifying past test problems, mechanistic and structural drawing capabilities 3) Teaching team

III. RESULT AND DISCUSSION

A. Study Characteristics

The study yielded 17 articles from five countries. The countries involved in this scoping review were the United States (n=8), Canada (n=5), Germany (n=2), Ireland (n=1), and Malaysia (n=1), as shown in Figure 3. The United States has been the most productive country in the number of publications. Plus, it was notable that the literature presented was only from continents of North America, Europe, and Asia. Meanwhile, the study designs were monopolised by qualitative study (n=9), followed by quantitative(n=4), mixed-method (n=3), and review paper (n=1). The study designs summary can be seen in Figure 4. The participants of this study were high school and undergraduate students taking organic chemistry courses. Experts who are lecturers in Organic Chemistry were also selected as participants because the content of the article meets the inclusion criteria of the study.

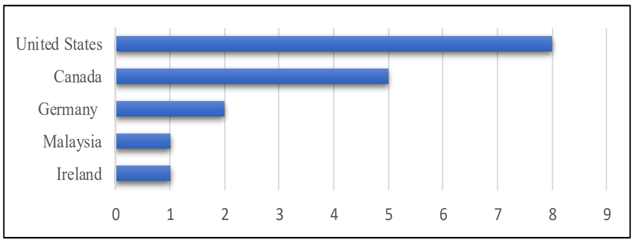

Figure 3. Country of origin of the studies

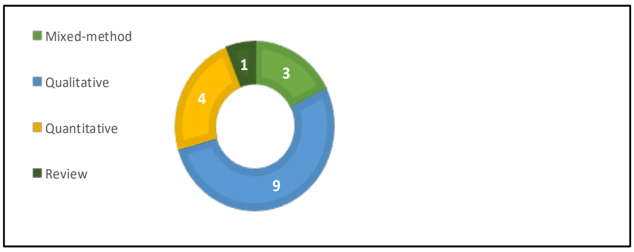

Figure 4. Study designs of the 17 selected articles

B. Literature Search

The database search had identified 784 records in total including Scopus (n=82), Google Scholar (n=559), EBSCOhost (n=74) and ProQuest (n=69). Figure 1 presented that 29 duplicate records were removed, which left 755 records to be screened. Due to irrelevant articles and such a population were not included in the interest of the study, 679 records were excluded. From 76 records left for retrieval, only 55 records were managed to assess for eligibility of full-text assessment. In the final screening process, 11 publications were deleted based on the exclusion and inclusion criteria, but 32 publications were included or reviewed. Finally, in agreement with other authors, 17 articles were identified to be analysed and reported in this study.

C. Qualitative Thematic Analysis

1. Teaching and learning strategies of ORM

Five key strategies for teaching and learning Organic Reaction Mechanism (ORM) were identified from the 17 selected articles (see Figure 5); (1) Electron Pushing Formalism (EPF); (2) Patterns of reactivity; (3) Technology Integration (4) Problem-solving; and (5) Self-regulated Learning (SRL). Through the scoping review, various methods of teaching and learning ORM have been found in different settings, study design, participants, and outcomes. However, the selected teaching and learning strategies will be further investigated, considering those in the study scope and suitable for implementation in the ORM module.

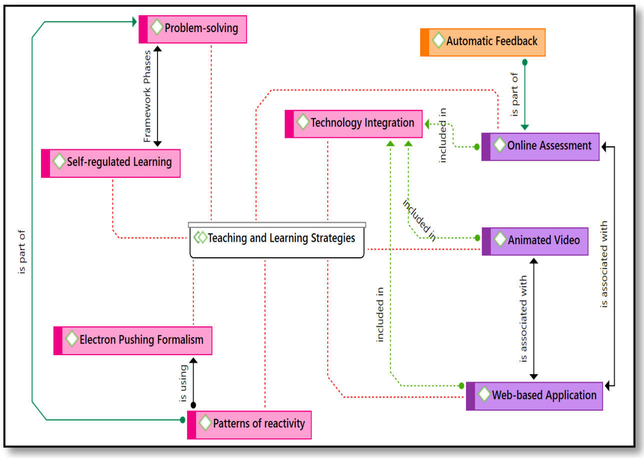

Figure 5. Five key strategies for teaching and learning ORM

The most frequent key method in teaching and learning ORM presented in previous studies is EPF, also known as Electron-pushing Arrow or Arrow-pushing Formalism. For example, 12 out of 17 articles had mentioned EPF as an arrow to depict the movement of electrons during chemical reactions (Flynn & Ogilvie, 2015; Bhattacharyya & Harris, 2018; Crandell *et al.*, 2018; Webber & Flynn, 2018; Bongers, Northoff & Flynn, 2019; Sabitu *et al.*, 2021). In Webber and Flynn (2018), they found that EPF is a useful tool for students in solving ORM problems, whereas they can determine plausible steps through EPF successfully. As Johnstone (2010) proposed in his Triangle Model for understanding chemistry content, students must be able to connect the three levels of representation which are macroscopic, submicroscopic, and symbolic. Hence, implementing EPF will help students in understanding language symbolism and mechanistic reasoning without fully depending on rote memorisation. However, learning the symbols seems like learning a foreign language for a novice (Talanquer, 2011; Taber, 2013). Therefore, the EPF, which is in the symbolism system, could be used to connect and communicate to the submicroscopic representation of electron movement in an organic reaction (Galloway, Stoyanovich & Flynn, 2017).

Alternatively, Flynn and Ogilvie (2015) have developed a pattern of mechanisms that totally differ from the functional group approach implemented in the entire organic chemistry curriculum from all over the world. Since 2011, the University of Ottawa has taught organic chemistry by emphasising mechanistic patterns. As Flynn and Ogilvie defined in their previous study, the mechanistic technique is quicker to comprehend and gives a more thorough understanding of chemical reactivity. Certainly, the goal of this approach is to help students identify and predict the mechanism patterns of organic reactions rather than memorise them. This strategy was also focused on the use of the EPF method. However, interestingly, the concept of mechanism as well as EPF will be taught before students learn any reaction. Hence, students are able to think mechanistically and can develop their EPF skills before they meet the chemical reactions.

The key method of 'technology integration' has been used in various terms among those selected papers whereby the integration is expected to assist students' learning process. Basically, technology may be divided into three categories: instructional preparation, instructional delivery, and technology as a learning aid (Inan & Lowther, 2010). Twelve papers had discussed technology integration into ORM learning. Throughout the papers, the frequently found terms regarding technology integration were online assessment, animated video, and web-based application. In classrooms, the integration of technology as a method for teaching ORM was reported as undoubtedly positive. In addition, 21st-century students can access technology comfortably as these generations are digital natives who have grown up with advanced technology. Moreover, Dood *et al.* (2020) stated that online systems would perform better on assessments as compared to the textbook, which provides a positive impact on students' mastery of the subject studied. Meanwhile, an animated video seem recommended by most authors because, through visualisation, the curve arrow in mechanism reaction shows the dynamic changes to how electrons and bonds are represented, yet the video can be viewed repeatedly at any time to point outs the correct steps of mechanisms (O'Brien-Tomory, 2016; Bongers, Northoff and Flynn, 2019; Winter *et al.*, 2019; Sabitu *et al.*, 2021). Furthermore, 11 from 17 studies had discussed automatic feedback or automated scoring as effective tools in supporting students' learning. By preparing automatic electronic feedback, students can use their level information to guide the learning in order to reach the depth explanation of the lesson. Also, Zurcher *et al.* (2016) stated that effective feedback is triggered by advising pupils on how to amend a faulty response.

Problem-solving is defined as a cognitive process that focuses on achieving an objective to reach the desired goal, which the students do not know the solution technique (Mayer, 1992, 2003; Mayer & Wittrock, 2006). Besides, nine out of 17 studies did mention problem-solving in Organic Chemistry. Meanwhile, two of the nine had initiated the term of mechanistic problem-solving. Likewise, Webber and Flynn (2018) reported in their study on solving students' unfamiliar and familiar organic chemistry questions through interactive problem-solving activities. For the reaction mechanism that had been clearly explained, a familiar question was defined. In contrast, an uncommon question was posed for a reaction mechanism that had not been specifically established. Even yet, the pupils were able to address it by combining a number of previously acquired mechanistic steps (Webber & Flynn, 2018). Moreover, Lieber and Graulich (2020) summarised that the problem-solving approach could help students apply chemical concepts and principles to make a judgment about the plausibility of reaction mechanisms. Thus, the problem-solving approach tends to challenge the Organic Chemistry students to shift from rote learning to meaningful learning yet practice problem-solving to predict the product of reactions (Wilson & Varma-Nelson, 2019; Lieber & Graulich, 2020).

Self-Regulated Learning (SRL) is a practical process which the learners are setting goals before they start the learning and probe to regulate even manage their cognitive, metacognitive, motivation, and learning preferences by their own learning regarding those goals' context (Ramdass & Zimmerman, 2013; Olakanmi & Gumbo, 2017; Alvi, 2020). Only two papers from the selected studies had stated the term SRL. Additionally, Dood (2020) recommended SRL as additional instruction in learning for preparing successful students without depending on memorisation. Meanwhile, O'Brien-Tomory (2016) has utilised online tutorials and lecture videos in which those approaches tend to be more self-directed learning (SDL). SDL will enhance students to become independent in control over their learning processes at their own pace (O'Brien-Tomory, 2016). However, this study is preferably discussing SRL rather than SDL due to several criteria and differences that better meet the study. In fact, previous literature had been discussed widely on the terminology of SRL that is regularly connected to SDL even termed both as the same concept (Loyens, Magda & Rikers, 2008; Saks & Leijen, 2014). Indubitably, both SRL and SDL include goal-directed and active engagement activity, but they vary in terms of whether the notion arises. Furthermore, SRL, which is an umbrella phrase encompassing a variety of processes, is derived from educational and cognitive psychology, whereas the study is mostly utilised in the school environment (Loyens, Magda & Rikers, 2008; Saks & Leijen, 2014; Linkous, 2021).

2. Teaching and learning activities of ORM

Based on the previous findings for strategies in teaching and learning ORM (Figure 6), there are six relevant activities that seem enticing for ORM module's development. The activities are; (1) students' goal, (2) a video module to introduce the ORM and information concepts, (3) mechanistic approach contents, (4) group activities, (5) formative assessment with scaffolding and automatic scoring, and (6) reflection on students' own learning.

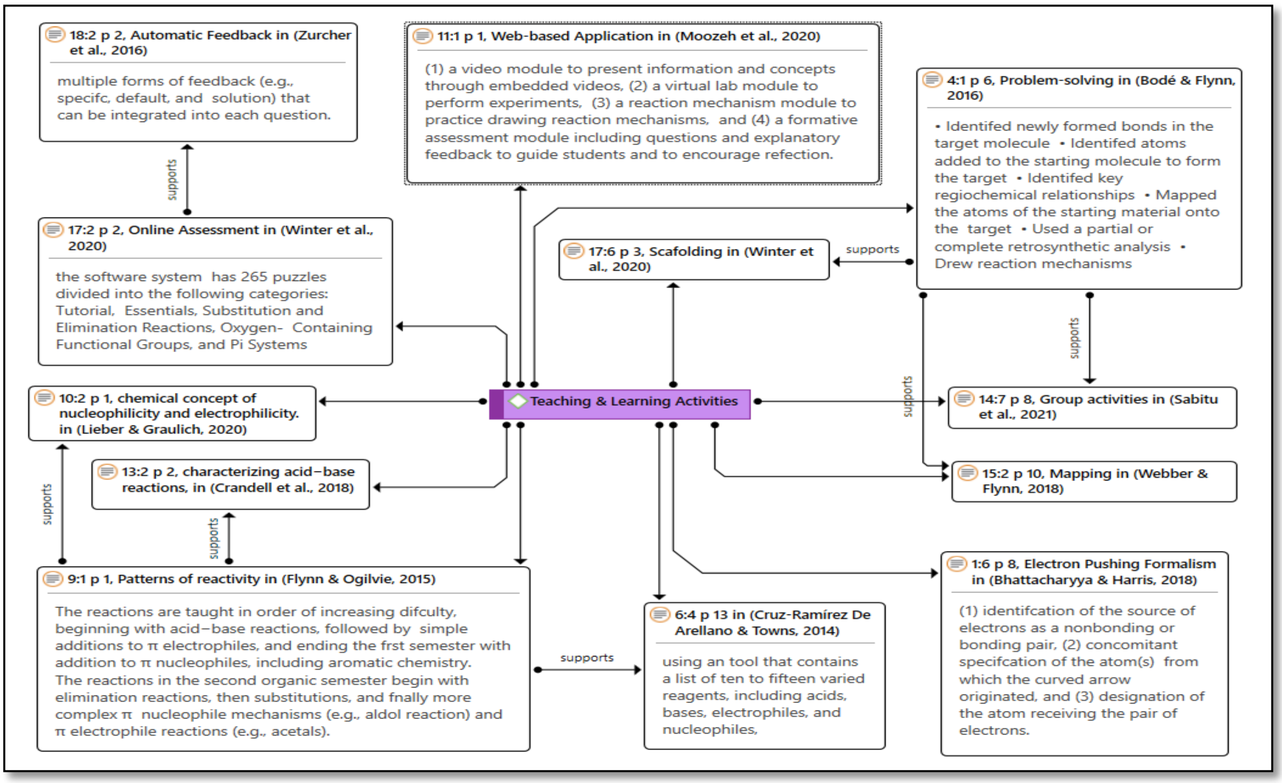

Figure 6. The emerging themes for teaching and learning activities of ORM

The activities of the ORM module start by determining the students' goals and end by writing a reflection. As Ramdass and Zimmerman (2013) defined, SRL is an active process when students learn preferences in the context of goals and motivation, regulate or control their cognition, and attempt to monitor and set goals for their learning. Setting a goal before learning will help students stay engaged in their learning by providing them with a clear sense of purpose and direction (Schmitz, Klug & Schmidt, 2017). Students can analyse their progress in achieving their goals to pinpoint the areas where they are succeeding and those where they require further improvement (Winne & Perry, 2000; Schmitz, Klug & Schmidt, 2017; Teng & Zhang, 2018). Through reflection, learners can identify their strengths and weaknesses, set new goals, and make informed decisions about approaching future learning tasks. Students will do a reflection on their own learning. Throughout the activity, students are to make self-reflection after the learning process, which is influenced by their reactions to that experience. This is due to the fact that people tend to pursue the action from the result for satisfaction and positive effect, otherwise avoiding any courses that give dissatisfaction and negative affect (Bandura, 1991; Zimmerman, 2000). This insight allows them to modify their learning techniques and adapt their approach accordingly. Winarti *et al.* (2022) revealed that the utilisation of SRL strategies enabled students to solve the problem independently by allowing them to monitor and rectify their own learning process.

Providing a video module to present the information about ORM concepts could be a very effective way to help students understand and retain the material. Videos can provide a more engaging and interactive learning experience than traditional lecture-based teaching methods, allowing students to visualise the reactions and mechanisms as they occur (Kazanidis *et al.*, 2018; Stewart & Dake, 2019). According to a study conducted by Gupta and Nikles (2019), the use of videos that demonstrate the process of an electron pushing arrow through step-by-step movements and accompanying descriptions can enhance students' comprehension of the mechanism. In the meantime, Fautch (2015) concluded that incorporating videos into their flipped classroom increased the students' ease of problem-solving.

As per Schmitt and Schween (2018), having a mechanistic approach is a crucial skill when it comes to problem-solving in the field of Organic Chemistry. Essentially, a mechanistic approach is universal, simpler to comprehend, and offers a superior means of thoroughly comprehending chemical reactivity since it drives the product (Flynn & Ogilvie, 2015; Caspari *et al.*, 2017). The traditional Organic Chemistry textbooks are typically structured by functional group, which involves grouping organic compounds according to their chemical properties and reaction behaviours. Hence, instead of categorising Organic Chemistry based on functional groups, the mechanistic approach organises it based on its mechanisms (Chaloner, 2015).

Developing an effective organic reaction mechanisms module for Malaysian pre-university students requires addressing potential gaps, such as unclear presentation of material and insufficient focus on problem-solving. By implementing the mechanistic approach, the next step will be taken to prepare and divide the ORM concepts into five parts; (i) Part A: Nucleophilicity and electrophilicity & acid-base concept (ii) Part B: Simple additions to π electrophiles and π nucleophiles (iii) Part C: σ electrophiles (E1, E2, S_N1 & S_N2) (iv) Part D: aromatic π nucleophiles with electrophiles. The module begins with the basics of Organic Chemistry, such as determining reagents as electrophiles or nucleophiles, identifying reactants as Lewis acidic or basic sites, and the concepts of electron movement in chemical reactions before moving on to the more complex concept of reaction mechanisms. Flynn and Ogilvie (2015) presented a revised sequence for the Organic Chemistry curriculum, which promotes students' familiarity with the subject matter. The reactions were organised into different categories based on their similar mechanisms: acid-base, π electrophiles, π nucleophiles, and σ electrophiles. Considering the cognitively complex to differentiate E1, E2, S_N1 & S_N2, this part must postpone after mastering π electrophiles (nucleophilic addition) until students have a better grasp of all the required concepts (Flynn & Ogilvie, 2015; Cooper *et al.*, 2019).

In order to grasp students' attention in learning ORM, Wilson and Varma-Nelson (2019) reported in their previous study that students become encouraged to solve a mechanistic problem when they take turns drawing the curve arrows on a small and portable whiteboard, hence, employing the group activities will encourage classroom interaction and propose students' problem-solving skills. Additionally, engaging in group activities resulted in better student perception of skills that can be applied in different settings and being provided with more enhanced opportunities to promote active learning (Canelas, Hill & Novicki, 2017; Martin & Bolliger, 2018). Martin and Bolliger (2018) revealed that group activities would enhance learner-to-learner engagement, especially in online courses, which prevents students from feeling isolated in the learning environment.

The activities should be followed by a formative assessment to engage students in their own learning. Providing formative assessment tools is appropriate for further evaluating students' understanding of ORM contents. For example, Andersson and Palm (2017) reported in their study that when formative assessment is given, students are encouraged to become more autonomous learners and are able to regulate their own learning process. Formative assessment entails offering students feedback while learning to help them recognise the aspects that require enhancement and motivate them to persevere in their learning journey. However, those assessments can be embedded together with scaffolding and automatic scoring as guidance and support students' learning for reflection in a timely manner. Meanwhile, Crandell *et al.* (2020) clearly stated that furnishing appropriate scaffolding is able to prompt students' reasoning and mechanistic explanation for organic reactions.

IV. CONCLUSION

The scoping review presents an overview of existing strategies and activities to develop the ORM module. Some limitations found in this study whereby our search did not include literature published before 2012 to enhance the timeliness of this study. Besides, the inclusion criteria used identified mainly high school or undergraduate students enrolled in the Chemistry program and Organic Chemistry expert lecturers who were involved in the classroom environment. However, this study employed the searching strategy to other bibliographic databases (Scopus, Google Scholar, EBSCOhost, and ProQuest), which yielded additional published scoping reviews.

At the commencement of the study, we employed Arksey and O'Malley's (2005) five-stage framework for scoping reviews and discovered that it was generally helpful in guiding study selection. Seventeen articles were finally identified to be analysed in answering the research questions of this study. The first research question was answered with five key strategies for teaching and learning ORM identified, whereas EPF was the most often key found in 12 articles. Meanwhile, six appropriate activities were detailed to be included in the ORM module. On the basis of our findings, we recommend that future research focus on identifying methods for teaching and learning ORM that incorporates as many research areas as possible. Nevertheless, the strategies and activities may be further analysed to fit the needs of organic module development for teaching and learning ORM across all levels of Organic Chemistry candidates. This is an opportunity for researchers to extract knowledge for teaching and learning in a meaningful way. They found it very useful for novice teachers who are starting to teach an Organic Chemistry course.

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VI. REFERENCES

Alvi, E 2020, 'Education sciences Teachers and the Teaching of Self-Regulated Learning (SRL): The Emergence of an Integrative, Ecological Model of SRL-in-Context'.

Anderson, S *et al.* 2008, 'Asking the right questions: Scoping studies in the commissioning of research on the organisation and delivery of health services', *Health Research Policy and Systems*, vol. 6, pp. 1–12. doi: 10.1186/1478-4505-6-7.

Andersson, C & Palm, T 2017, 'Characteristics of improved formative assessment practice', *Education Inquiry*, vol. 8, no. 2, pp. 104–122. doi: 10.1080/20004508.2016.1275185.

Annette Jean O'Brien-Tomory 2016, A Study On The Benefits For Nontraditional Commuter Students Of Supplemental Screencasts In A Traditional Chemistry Lecture Setting, Purdue University.

Anzovino, ME & Lowery Bretz, S 2015, 'Organic chemistry students' ideas about nucleophiles and electrophiles: The role of charges and mechanisms', *Chemistry Education Research and Practice*, vol. 16, no. 4, pp. 797–810. doi: 10.1039/c5rp00113g.

Arksey, H & O'Malley, L 2005, 'Scoping studies: Towards a methodological framework', *International Journal of Social Research Methodology: Theory and Practice*, vol. 8, no. 1, pp. 19–32. doi: 10.1080/1364557032000119616.

Arora, AK *et al.* 2021, 'Evaluating Usability in Blended Learning Programs Within Health Professions Education: a Scoping Review', *Medical Science Educator*, Springer US. doi: 10.1007/s40670-021-01295-x.

Bandura, A 1991, 'Human agency: The rhetoric and the reality', *American Psychologist*, vol. 46, no. 2, pp. 157–162.

Bhattacharyya, G 2019, 'Construction by De-construction', *Journal of Chemical Education*, pp. 8–11. doi: 10.1021/acs.jchemed.8b00579.

Bhattacharyya, G & Harris, MS 2018, 'Compromised Structures: Verbal Descriptions of Mechanism Diagrams', *Journal of Chemical Education*, vol. 95, no. 3, pp. 366–375. doi: 10.1021/acs.jchemed.7b00157.

Bodé, NE & Flynn, AB 2016, 'Strategies of Successful Synthesis Solutions: Mapping, Mechanisms, and More', *Journal of Chemical Education*, vol. 93, no. 4, pp. 593–604. doi: 10.1021/acs.jchemed.5b00900.

Bongers, A, Northoff, G & Flynn, AB 2019, 'Working with mental models to learn and visualize a new reaction mechanism', *Chemistry Education Research and Practice*, vol. 20, no. 3, pp. 554–569. doi: 10.1039/c9rp00060g.

Canelas, DA, Hill, L & Novicki, A 2017, 'Research and Practice Cooperative learning in organic chemistry increases student assessment of learning gains in key transferable skills †', *Chemistry Education Research and Practice*, vol. 18, pp. 441–456. doi: 10.1039/C7RP00014F.

Caspari, I *et al.* 2017, 'This mechanistic step is "productive": organic chemistry students' backward-oriented reasoning', *Chemistry Education Research and Practice*, vol. 19, no. 1, pp. 42–59. doi: 10.1039/c7rp00124j.

Caspari, I & Graulich, N 2019, 'Scaffolding the structure of organic chemistry students' multivariate comparative mechanistic reasoning', *International Journal of Physics and Chemistry Education*, vol. 11, no. 2, pp. 31–43.

Chaloner, P 2015, 'Organic Chemistry A Mechanistic Approach', CRC Press.

Cooper, MM *et al.* 2019, 'Organic Chemistry, Life, the Universe and Everything (OCLUE): A Transformed Organic Chemistry Curriculum', *Journal of Chemical Education*. doi: 10.1021/acs.jchemed.9b00401.

Crandell, OM *et al.* 2018, 'Reasoning about Reactions in Organic Chemistry: Starting It in General Chemistry', *Journal of Chemical Education*. doi: 10.1021/acs.jchemed.8b00784.

Crandell, OM, Lockhart, MA & Cooper, MM 2020, 'Arrows on the Page Are Not a Good Gauge: Evidence for the Importance of Causal Mechanistic Explanations about Nucleophilic Substitution in Organic Chemistry', *Journal of Chemical Education*, vol. 97, no. 2, pp. 313–327. doi: 10.1021/acs.jchemed.9b00815.

Cruz-Ramírez De Arellano, D & Towns, MH 2014, 'Students' understanding of alkyl halide reactions in undergraduate organic chemistry', *Chemistry Education Research and Practice*, vol. 15, no. 4, pp. 501–515. doi: 10.1039/c3rp00089c.

Daudt, HML, Van Mossel, C & Scott, SJ 2013, 'Enhancing the scoping study methodology: A large, inter-professional team's experience with Arksey and O'Malley's framework', *BMC Medical Research Methodology*, vol. 13, no. 1, pp. 1–9. doi: 10.1186/1471-2288-13-48.

Dood, AJ 2020, 'Scholar Commons Asking Why : Analyzing Students' Explanations of Organic Chemistry Reaction Mechanisms using Lexical Analysis and Predictive Logistic Regression Models'.

Dood, AJ *et al.* 2020, 'Using the Research Literature to Develop an Adaptive Intervention to Improve Student Explanations of an SN1 Reaction Mechanism', *Journal of Chemical Education*, vol. 97, no. 10, pp. 3551–3562. doi: 10.1021/acs.jchemed.0c00569.

Dood, AJ & Watts, FM 2022, 'Students' strategies, struggles, and successes with mechanism problem solving in organic chemistry: a scoping review of the research literature', *Journal of Chemical Education*, vol. 100, no. 1, pp. 53–68.

Duis, JM 2011, 'Organic chemistry educators' perspectives on fundamental concepts and misconceptions: An exploratory study', *Journal of Chemical Education*, vol. 88, no. 3, pp. 346–350. doi: 10.1021/ed1007266.

Evans, MJ 2016, 'Generalized Organic Chemistry: Teaching Chemistry Using a Framework Approach for a MOOC Audience', *ACS Symposium Series*, vol. 1217, pp. 21–36.

doi: 10.1021/bk-2016-1217.ch003.

Fautch, JM 2015, 'The flipped classroom for teaching organic chemistry in small classes: is it effective?', *Chemistry Education Research and Practice*, vol. 16, no. 1, pp. 179–186. doi: 10.1039/x0xx00000x.

Flynn, Alison B & Ogilvie, WW 2015, 'Mechanisms before Reactions: A Mechanistic Approach to the Organic Chemistry Curriculum Based on Patterns of Electron Flow', *Journal of Chemical Education*. doi: 10.1021/ed500284d.

Galloway, KR, Stoyanovich, C & Flynn, AB 2017, 'Students' interpretations of mechanistic language in organic chemistry before learning reactions', *Chemistry Education Research and Practice*, vol. 18, no. 2, pp. 353–374. doi: 10.1039/c6rp00231e.

Grove, NP & Lowery Bretz, S 2012, 'A continuum of learning: From rote memorization to meaningful learning in organic chemistry', *Chemistry Education Research and Practice*, vol. 13, no. 3, pp. 201–208. doi: 10.1039/c1rp90069b.

Gupta, N & Nikles, J 2019, 'Impact of Student-Created Mechanism Videos in Organic Chemistry 2 Labs', *ACS Symposium Series*, vol. 1325, pp. 107–117. doi: 10.1021/bk-2019-1325.ch008.

Haddaway, NR *et al.* 2015, 'The role of google scholar in evidence reviews and its applicability to grey literature searching', *PLoS ONE*, vol. 10, no. 9, pp. 1–17. doi: 10.1371/journal.pone.0138237.

Inan, FA & Lowther, DL 2010, 'Factors affecting technology integration in K-12 classrooms: A path model', *Educational Technology Research and Development*, vol. 58, no. 2, pp. 137–154. doi: 10.1007/s11423-009-9132-y.

Johnstone, AH 2010, 'Can't get there from here', *American Chemical Society and Division of Chemical Education, Inc.*, vol. 87, no. 1–2. doi: 10.1511/2008.70.169.

Kazanidis, I *et al.* 2018, 'Augmented Interactive Video: Enhancing Video Interactivity for the School Classroom', *Journal of Engineering Science and Technology Review*, vol. 11, no. 2, pp. 174–181. doi: 10.25103/jestr.112.23.

Kermack, WO & Robinson, R 1922, 'An explanation of the property of induced polarity of atoms and an interpretation of the theory of partial valencies on an electron basis', *J. Chem. Soc.*, vol. 121, pp. 427–440.

Khalil, H *et al.* 2019, 'Evaluation of the JBI scoping reviews methodology by current users', *International Journal of Evidence-Based Healthcare*, pp. 1–6. doi: 10.1097/XEB.0000000000000202.

Khalil, H *et al.* 2021, 'Conducting high quality scoping reviews-challenges and solutions', *Journal of Clinical Epidemiology*, vol. 130, pp. 156–160. doi: 10.1016/j.jclinepi.2020.10.009.

Levac, D, Colquhoun, H & O'Brien, KK 2010, 'Scoping studies: Advancing the methodology', *Implementation Science*, vol. 5, no. 1, pp. 1–9. doi: 10.1186/1748-5908-5-69.

Lieber, L & Graulich, N 2020, 'Thinking in Alternatives - A Task Design for Challenging Students' Problem-Solving Approaches in Organic Chemistry', *Journal of Chemical Education*, vol. 97, no. 10, pp. 3731–3738. doi: 10.1021/acs.jchemed.0c00248.

Linkous, HM 2021, 'Self-directed learning and self-regulated learning: What's the difference? A literature analysis', *American Association for Adult and Continuing Education*, pp. 118–122.

Loyens, SMM, Magda, J & Rikers, RMJP 2008, 'Self-directed learning in problem-based learning and its relationships with self-regulated learning', *Educational Psychology Review*, vol. 20, no. 4, pp. 411–427. doi: 10.1007/s10648-008-9082-7.

Martin, F & Bolliger, DU 2018, 'Engagement Matters : Student Perceptions on the Importance of Engagement Strategies in the Online Learning Environment', *Online Learning*, vol. 22, no. 1, pp. 205–222. doi: 10.24059/olj.v22i1.1092.

Mayer, RE 1992, *Thinking, problem solving, cognition*, 2nd Edition, New York: Freeman.

Mayer, RE 2003, *Learning and instruction*, Prentice Hall.

Mayer, RE & Wittrock, MC 2006, 'Problem Solving from: Handbook of Educational Psychology Routledge. Accessed', in *Handbook of Educational Psychology*, pp. 287–303. doi: 10.4324/9780203053874.

Moozeh, K *et al.* 2020, 'Learning beyond the Laboratory: A Web Application Framework for Development of Interactive Postlaboratory Exercises', *Journal of Chemical Education*, vol. 97, no. 5, pp. 1481–1486. doi: 10.1021/acs.jchemed.9b00756.

Morrison, RT & Boyd, RN 1959, *Organic Chemistry*, Boston: Allyn and Bacon.

Munn, Z *et al.* 2019, 'The development of software to support multiple systematic review types: The Joanna Briggs Institute System for the Unified Management, Assessment and Review of Information (JBI SUMARI)', *International Journal of Evidence-Based Healthcare*, vol. 17, no. 1, pp. 36–43. doi: 10.1097/XEB.0000000000000152.

O'Sullivan, TP & Hargaden, GC 2014, 'Using structure-based organic chemistry online tutorials with automated correction for student practice and review', *Journal of Chemical Education*, vol. 91, no. 11, pp. 1851–1854. doi: 10.1021/ed500140n.

O 'Dwyer, A & Childs, PE 2017, 'Who says Organic Chemistry is Difficult ? Exploring Perspectives and Perceptions', vol. 13, no. 7, pp. 3599–3620. doi: 10.12973/eurasia.2017.00748a.

Olakanmi, EE & Gumbo, MT 2017, 'The effects of self-regulated learning training on students' metacognition and achievement in chemistry', *International Journal of Innovation in Science and Mathematics Education*, vol. 25, no. 2, pp. 34–48.

Otter, CA 2020, 'The Use of Drama in A Level Chemistry: A study into the effects of simulation-role-play on the quality of, and student attitudes towards, learning of organic reaction mechanisms', <http://etheses.whiterose.ac.uk/27163/>.

Page, MJ *et al.* 2021, 'The PRISMA 2020 statement: An updated guideline for reporting systematic reviews', *The BMJ*, vol. 372. doi: 10.1136/bmj.n71.

Peterson, J *et al.* 2017, 'Understanding scoping reviews: Definition, purpose, and process', *Journal of the American Association of Nurse Practitioners*, vol. 29, no. 1, pp. 12–16. doi: 10.1002/2327-6924.12380.

Ramdass, D & Zimmerman, BJ 2013, 'Journal of Advanced Academics'. doi: 10.1177/1932202X1102200202.

Ridd, JH 2008, 'Organic pioneer', *Chemistry World*, vol. 5, no. 12, pp. 50–53.

Sabitu, A *et al.* 2021, 'Exploring the Needs for the Development of Organic Reaction Teaching Model: Experts' Collective Opinion', *Malaysian Journal of Social Sciences and Humanities (MJSSH)*, vol. 6, no. 4, pp. 191–201. doi: 10.47405/mjssh.v6i4.728.

Saks, K & Leijen, Ä 2014, 'Distinguishing Self-directed and Self-regulated Learning and Measuring them in the E-learning Context', *Procedia - Social and Behavioral Sciences*, vol. 112(Iceepsy 2013), pp. 190–198. doi: 10.1016/j.sbspro.2014.01.1155.

Schmitt, C & Schween, M 2018, 'Using Trityl Carbocations to Introduce Mechanistic Thinking to German High School Students', *World Journal of Chemical Education*, vol. 6, no. 1, pp. 18–23. doi: 10.12691/wjce-6-1-4.

Schmitz, B, Klug, J & Schmidt, M 2017, 'Assessing Self-Regulated Learning Using Diary Measures with University Students', *Handbook of Self-Regulation of Learning and Performance*, no. 13109. doi: 10.4324/9780203839010.ch16.

Schweiker, SS, Griggs, BK & Levonis, SM 2020, 'Engaging Health Student in Learning Organic Chemistry Reaction Mechanisms Using Short and Snappy Lightboard Videos', *Journal of Chemical Education*, vol. 97, no. 10, pp. 3867–3871. doi: 10.1021/acs.jchemed.0c00619.

Shariman, TPNT & Talib, O 2017, 'OCRA, A Mobile Learning Prototype For Understanding Chemistry Concepts', *14th International Conference on Cognition and Exploratory Learning in Digital Age*, 2015(Celda), pp. 181–188.

Stewart, JJ & Dake, GR 2019, 'Activating Students' Prior Knowledge Using a Bridge Activity as an Initial Interactive Discussion in a Flipped Organic Chemistry Course', *Journal of Chemical Education*, vol. 96, no. 11, pp. 2426–2431. doi: 10.1021/acs.jchemed.9b00370.

Taber, KS 2013, 'Revisiting the chemistry triplet: Drawing upon the nature of chemical knowledge and the psychology of learning to inform chemistry education', *Chemistry Education Research and Practice*. doi: 10.1039/c3rp00012e.

Talanquer, V 2011, 'Macro, submicro, and symbolic: The many faces of the chemistry "triplet"', *International Journal of Science Education*, vol. 33, no. 2, pp. 179–195. doi: 10.1080/09500690903386435.

Teng, LS & Zhang, LJ 2018, 'Effects of motivational regulation strategies on writing performance : a mediation model of self-regulated learning of writing in English as a second / foreign language Effects of motivational regulation strategies on writing performance : a mediation model of self-regulated learning of writing in English as a second / foreign language', (August). doi: 10.1007/s11409-017-9171-4.

Tricco, AC *et al.* 2018, 'PRISMA extension for scoping reviews (PRISMA-ScR): Checklist and explanation', *Annals of Internal Medicine*, vol. 169, no. 7, pp. 467–473. doi: 10.7326/M18-0850.

Webber, DM & Flynn, AB 2018, 'How Are Students Solving Familiar and Unfamiliar Organic Chemistry Mechanism Questions in a New Curriculum?', *Journal of Chemical Education*, vol. 95, no. 9, pp. 1451–1467. doi: 10.1021/acs.jchemed.8b00158.

Wilson, SB & Varma-Nelson, P 2019, 'Characterization of First-Semester Organic Chemistry Peer-Led Team Learning and Cyber Peer-Led Team Learning Students' Use and Explanation of Electron-Pushing Formalism', *Journal of Chemical Education*, vol. 96, no. 1, pp. 25–34. doi: 10.1021/acs.jchemed.8b00387.

Winarti, Ambaryani, SE & Putranta, H 2022, 'Improving

Learners' Metacognitive Skills with Self -Regulated Learning based Problem-Solving', *International Journal of Instruction*, vol. 15, no. 1, pp. 139–154.

Winne, PH & Perry, NE 2000, 'Measuring Self-Regulated Learning', *Handbook of Self-Regulation*. doi: 10.1016/b978-012109890-2/50045-7.

Winter, J *et al.* 2020, 'The Mechanisms App: Electron-Pushing Formalism as a Software System', pp. 1–18. doi: 10.26434/chemrxiv.11936244.

Winter, JE *et al.* 2019, 'The Mechanisms App and Platform: A New Game-Based Product for Learning Curved Arrow Notation', *ACS Symposium Series*, vol. 1336, pp. 99–115. doi: 10.1021/bk-2019-1336.ch007.

Zimmerman, BJ 2000, 'Self-Efficacy: An Essential Motive to Learn', *Contemporary Educational Psychology*, vol. 25, no. 1, pp. 82–91. doi: 10.1006/ceps.1999.1016.

Zurcher, DM *et al.* 2016, 'Using Student-Generated Instructional Materials in an e-Homework Platform', *Journal of Chemical Education*, vol. 93, no. 11, pp. 1871–1878. doi: 10.1021/acs.jchemed.6b00384.