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Improving students' achievement in organic chemistry: A systematic review of experimental studies

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ABSTRACT
Organic chemistry is a cognitively demanding subject with persistently low student achievement. This review aimed to identify instructional strategies and educational technologies used to improve learning outcomes in organic chemistry across educational levels and learning environments. A systematic review of 40 experimental studies (2014–2023) was conducted using PRISMA guidelines. The analysis revealed that group-based learning, such as cooperative and problem-based learning, is the most frequently used instructional approach to enhance academic performance and retention. Task-based and individual learning strategies were also reported but less common. E-learning technologies were most widely used in high school and classroom settings, while multimedia tools were more prevalent in higher education and laboratory contexts. Representational competence was primarily supported through the use of models. The findings suggest that instructional methods and technologies should be aligned with students' learning needs, content complexity, and context. These results offer practical guidance for improving cognitive outcomes in organic chemistry education.

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Introduction

Organic chemistry is a challenging subject with notable attrition, failure rates and low performance (Childs & Sheehan, 2009; Eastwood, 2013; Flynn, 2015; Johnstone, 2006; O'Dwyer & Childs, 2017; Ratcliffe M, 2002; Teixeira & Holman, 2008). Organic chemistry is a discipline that necessitates substantial cognitive effort and demands during the learning process (Akaygun & Jones, 2013; Ahmad & Samara, 2016; McCollum et al., 2014; Seery & McDonnell, 2013). To facilitate this, instructors may employ active learning methods or approaches (Crouch & Mazur, 2001; Prince, 2004; Lasry et al., 2008). Various studies reveal that chemistry learning is best conducted by applying models or approaches that can facilitate student to think at a high level (Fensham & Bellocchi, 2013). Hermanns and Schmidt (2019) revealed that the integration of various methods or approaches can increase student participation as well as be one of the solutions to address heterogeneous class problems. Research examining the implementation of methods or approaches in organic chemistry and learning has yielded beneficial outcomes. These including an application of active learning methods through multiple strategies (e.g., cooperative, class discussion, conceptual maps, and lectures) which improve student participation (Houseknecht et al., 2019) and academic achievement; (Christiansen et al., 2017; Dai et al., 2021; Iyamuremye et al., 2023; Shattuck, 2016a; Wenzel & Pichler, 2005; Wilson & Varma-Nelson, 2019). Instructors play a key role in applying active learning strategies effectively, especially when they are aware of appropriate teaching methods and set clear learning objectives. (Hermanns & Schmidt, 2019). Therefore, it is necessary to advise teachers on choosing the appropriate learning method or approach. A review of previous researchers' work on the application of instructional approaches can serve as a guide for educators in selecting the appropriate instructional approaches.

The incorporation of technology into education is a type of educational advancement. Empirical research examining the incorporation of technology into organic chemistry instruction has demonstrated beneficial effects. These investigations have found that digital technology (e.g. virtual simulations, animations, multimedia tutorials, and online platforms) can help student visualize complex organic structures and reactions, predict the properties of organic compounds (Hoover et al., 2021; McCollum et al., 2014; Seery & McDonnell, 2013; Soong et al., 2020), improve conceptual understanding, motivation and involvement (Akpokiere et al., 2020; Chekour et al., 2022; Miller et al., 2021; Nadelson et al., 2015; Shoesmith et al., 2020), support independent and stress-free learning (Mistry & Shahid, 2021), and correct misconceptions (Srisawasdi & Panjaburee, 2019). These outcomes ultimately contribute to improved performance in learning chemistry (Ryoo et al., 2018). Despite these advantages, Barak (2007 noted that many chemistry teachers remain hesitant to integrate technology due to insufficient knowledge about how to effectively use appropriate tools in classroom instruction. This cause can be attributed to their failure to find technology that can have a positive impact on their teaching and learning (Rutten et al., 2012). Hence, it is crucial to provide guidance to educators in selecting appropriate and efficient technology. Researchers have demonstrated that employing effective technology-based learning methods can inspire instructors to enhance their research and teaching. (Halverson et al., 2014). A review is needed to encourage educators to implement appropriate learning innovations to enhance quality of education and achieve the desired goals (Zhang et al., 2012). Examining and elucidating technologies and instructional methods that can improve the effectiveness of teaching and learning can aid educators and researchers in creating successful learning activities, as suggested by certain researchers (Agwuudu & Udu, 2017; Alegre et al., 2020; Campbell & Mayer, 2009; Chung et al., 2019; Febliza et al., 2023; Valcazar et al., 2023).

Four review papers have explored organic chemistry learning, each with specific but limited scopes. First, Dood & Watts (2022) conducted a scoping review focused on how students describe and explain reaction mechanisms. However, the study did not address instructional methods or evaluate their effects on learning outcomes. Second, Dood & Watts (2023) expanded their review on the mechanisms of organic reactions at the college level. While conceptually rich, this paper lacks attention to how these topics are taught or supported through teaching strategies or technologies. Third, (Sukmawati, 2020) reviewed instructional techniques for undergraduate organic chemistry but did not specify the types of research designs employed, nor did it assess the impact of these techniques on student achievement. Fourth, (Sibomana et al., 2020) reviewed learning strategies from a Rwandan educational context but omitted crucial methodological details such as article inclusion criteria, participant types, or measurable learning indicators. These four reviews, although informative, do not systematically analyze how instructional approaches and technologies affect measurable learning outcomes—particularly in terms of academic achievement, retention, and problem-solving ability.

Therefore, this present review offers novelty by synthesizing experimental studies that evaluate the effectiveness of instructional approaches and learning technologies in organic chemistry education. This approach provides empirical evidence useful for chemistry educators, curriculum developers, and decision-makers to implement evidence-based strategies that enhance student learning.

Thus, this study offers valuable contributions for curriculum developers, chemistry educators, and policy-makers by presenting evidence of the effectiveness of instructional interventions in organic chemistry through experimental research. Prior studies have demonstrated measurable links between specific teaching interventions and improvements in student learning outcomes, such as achievement, retention, and engagement (Lavi et al., 2019). Furthermore, experimental analysis serves as a powerful tool to identify and refine instructional strategies, providing educators with evidence-based insights for successful implementation in formal educational settings (Baye et al., 2019; Finlayson & Mccrudden, 2019).

The Purpose and Research Questions

The objective of this study is to analyse and evaluate published experimental research conducted between 2014 and 2023 that focuses specifically on the use of instructional approaches and technologies to improve student academic achievement in organic chemistry. The selection of this time frame reflects the increased integration of digital tools and student-centred pedagogies during the last decade, which are highly relevant to current educational practices.

This study aims to explore how various instructional methods and emerging technologies have been applied to enhance organic chemistry learning, particularly in addressing underperformance in cognitive achievement. The following research questions have been formulated to investigate instructional approaches and technologies within the context of organic chemistry:

1. What are the instructional approaches used to enhance student cognitive achievement on topics of organic chemistry learning?
2. What are the technologies used to improve cognitive achievement of students on the topics of organic chemistry learning?
3. What are the appropriate types of instructional approaches and technology used for formal and laboratory classes?
4. What are the types of instructional approaches and technology suitable for different levels of education?

Methods

In order to accomplish the goals of this study, the researchers identified and integrated relevant research related to interventions in instructional approaches and technologies toward student academic achievement in organic chemistry. The researchers conducted a methodical and structured analysis to see whether treatments involving free variables (e.g., cooperative learning) had a positive impact on bound variables (e.g., academic achievement in organic chemistry (Agwuudu & Udu, 2017). Papers with insignificant effects are also used as samples (e.g., performance course or grades of Peer-Led Team Learning (PLTL) and cyber Peer-Led Team Learning (cPLTL) students on the exam for Organic Chemistry in the First Semester of the American Chemical Society (ACS) (Wilson & Varma-Nelson, 2019) to provide a balanced view.

Selection Criteria

The research was conducted through a comprehensive and systematic search using relevant keywords across multiple reputable databases, including Taylor & Francis Online, Springer Link, ERIC, Wiley Online Library Full Collection, Scopus, Web of Science, IEEE Explore, Sage, Emerald, ProQuest Dissertations & Theses Global, Open Access Theses & Dissertations, and Google Scholar. The search was limited to publications from 2014 to 2023 to capture the most recent decade of experimental research, reflecting current trends in the use of instructional approaches and educational technologies in chemistry education. This 10-year time frame was selected to ensure the relevance and applicability of the findings to today's educational practices. The final search was completed on December 31, 2023. The latest search was conducted on December 31, 2023, to ensure that all relevant studies published before 2023 have been included. One of the purposes of systematic surveys is to diagnose academic production over a period of time. The decision to limit the review to a 10-year period is supported by several factors, including the scope of the manuscript, the depth of analysis applied to the selected publications, and the intention to highlight recent developments that reflect current trends in chemistry education (Bernardi & Pazinato, 2022). Additionally, the study did not apply indexing restrictions when selecting databases. Limiting the search to specific indexing services could have excluded relevant research and introduced selection bias. By broadening the scope, this review aims to include a more representative sample of recent literature.

The determination of coding and inclusion criteria was conducted by measuring the agreement level between two raters specializing in the field of organic chemistry education. The agreement between these two raters was calculated using Cohen's Kappa, where the result for both coding and inclusion criteria was $\kappa = 0.95$. This value indicates an interpretation of "almost perfect" agreement (McHugh, 2012).

The author use the following keyword patterns in each database and search engine mentioned above:

Pattern 1: organic chemistry, educational technology, model, experimental, science education, or chemical education

Pattern 2: organic chemistry, educational technology, model, treatment, science education, or chemical education

Pattern 3: organic chemistry, educational technology, model, intervention, science education, or chemical education

Pattern 4: organic chemistry, educational technology, teaching method, experimental science education, or chemical education

Pattern 5: organic chemistry, educational technology, teaching method, treatment, science education, or chemical education

Pattern 6: organic chemistry, educational technology, teaching method, intervention, science education, or chemical education

Pattern 7: organic chemistry, teaching aids, models, experiments, science education, or chemical education

Pattern 8: organic chemistry, teaching aids, models, treatments, science education, or chemical education

Pattern 9: organic chemistry, teaching aids, model, intervention, science education, or chemical education

Pattern 10: organic chemistry, teaching aids, teacher's method, experimental, science education, or chemical education

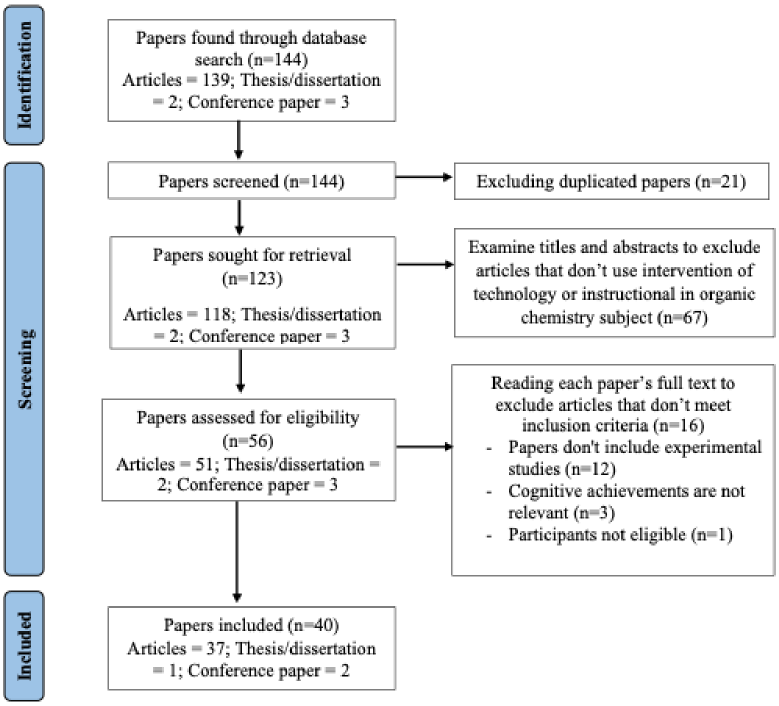
Pattern 11: organic chemistry, teaching aids, teacher's method, treatment, science education, or chemical education

Pattern 12: organic chemistry, teaching aids, teacher's method, intervention, science education, or chemical education

The authors identified 144 potential studies for analysis from the search results. All papers were in English. The subsequent phase involves scrutinising the paper to ensure its alignment with the study objectives. Refer to Figure 1 for the flow diagram illustrating the selecting procedure and screening process based on PRISMA flow diagram.

Figure 1

Flow chart of the selection process and screening process based on PRISMA flow diagram



From the initial search across multiple databases, a total of 144 papers were retrieved. To ensure the accuracy of the review, all entries were cross-checked for duplication, since many papers appeared in more than one database (e.g., the same study listed in both Scopus and ERIC). Each study was labelled consistently within the text to track its origin and avoid double-counting. As a result of this screening process, 21 duplicate papers were identified and excluded from the final dataset, leaving 123 studies for analysis.

A total of 67 articles that did not focus on instructional technology in organic chemistry were excluded. Authors assessed eligibility of the papers by reading the full text carefully and applying the inclusion criteria (experimental design: pre-, quasi-, and true-experiential designs; cognitive achievement: achieving, representational competence, and retention; and participant = students). As a result, 16 articles were excluded for not meeting these criteria. These exclusions included studies that employed only survey methods(e.g., Cha et al., 2021; Dixson et al., 2022; Popova & Jones, 2021), cross-sectional study (e.g., Austin et al., 2018), applied development research without experimental validation (e.g., Akpokiere et al., 2020), measured non-cognitive outcomes such as attitudes and perceptions (e.g. Collini et al., 2023; Gallardo-Williams, 2021; Knudtson, 2015), or participants: instructors (Leontyev et al., 2019). Articles employing mixed-methods designs were included only if they contained a clear experimental component, (e.g., (Iyamuremye et al., 2021). The inclusion assessment also involved verifying whether each intervention had an observable impact on cognitive achievement, based on reported quantitative data such as means, standard deviations, t-values, and p-values. To address potential publication bias, studies reporting statistically insignificant or negative results were also included in the review (e.g. De Gale, 2016; Wilson & Varma-Nelson, 2019). This ensured a more balanced and objective synthesis of evidence regarding the effectiveness of instructional approaches and technologies in organic chemistry learning.

Study Sample

The selection process yielded a total of 40 papers, all of which focused on evaluating the effectiveness of instructional technologies and teaching approaches in improving academic performance. The final sample consists of 37 research articles, two conference proceedings and a thesis/dissertation. Among the 37 research articles, 17 discuss the effectiveness of specific instructional approaches, while the remaining 20 evaluate the impact of technology on student learning outcomes.

Coding Procedure

Encoding is the method of extracting clear and study-appropriate data from the material gathered during research (Karadag, 2020). The primary goal of this technique is to create a specialized encoding system that encompasses both general and specific aspects, ensuring that no elements of any form of research are overlooked. In order to retrieve data from the manuscript, the author implemented an encoding technique utilising the subsequent parameters: research article reference, conference proceeding, thesis or dissertation, type of intervention (instructional approach and technology), cognitive achievement, level of education, and learning environment. The explanation of the parameter is as follows:

1. Research References

The references included in this review comprise experimental studies published as journal articles, conference proceedings, and dissertations. Each study examined the effectiveness of an instructional intervention, either in the form of a teaching approach or the use of technology, on students' cognitive achievement. The results were evaluated using quantitative data, including descriptive statistics such as mean scores and standard deviations, as well as inferential statistics such as t-values and p-values that indicate statistical significance (Çalik et al., 2024).

2. Type of Intervention

This review focuses on two categories of intervention: instructional approaches and instructional technologies. Instructional approaches refer to pedagogical frameworks or teaching methods, such as problem-based learning or peer-led team learning. Instructional technologies refer to the tools or platforms that support instruction, such as computer simulations, digital learning environments, or learning management systems. Although there may be some overlap between the two categories, the classification in this review is based on the stated emphasis of each study. A study was categorized as focusing on instructional approach if it emphasized the teaching method as the main factor. It was classified as technology-based if the primary intervention involved the use of a technological tool or platform to enhance learning.

3. Cognitive Achievement

This study categorizes cognitive achievement into three indicators: academic performance (e.g., scores from examinations and tests), representational competence, and retention. These indicators are consistently used across the selected studies to measure student learning outcomes. In one study that measured generic science skills, the data were classified under academic performance, as it involved assessment of conceptual understanding and application. Overall, cognitive achievement serves as a key parameter for determining the effectiveness of instructional interventions.

4. Education Level

The included studies involve participants from two levels of education: high school and higher education. High school refers to students in grades 9 through 12, which are also known as senior secondary levels (Iyamuremye et al., 2023). Higher education refers to students enrolled in university-level programs. If a paper identified participants as coming from senior secondary schools, they were classified under the high school category for consistency.

5. Learning Environment

Organic chemistry is studied in two distinct learning environments: classroom (theoretical learning) and laboratory (practical learning). Both environments are essential and often complementary. In this review, the learning environment is considered a contextual parameter for analysis, particularly in relation to how instructional technologies and approaches are applied. Studies that explicitly referenced either classroom-based or laboratory-based interventions were coded accordingly. In cases where both settings were involved, the study was marked as addressing dual learning environments.

Data Analysis

The mapping of each paper is determined by the following parameters: research article reference, conference proceeding, thesis or dissertation, type of intervention (instructional approach and technology), cognitive achievement, level of education, and learning environment. After the mapping, we perform a thematic analysis to formulate answers to each research question. If there is ambiguity or the author disagrees with whether an article contains findings on a particular topic, the entire author discusses (Dood & Watts, 2023) consensus (Dood & Watts, 2023).

Analysis Methods for RQ1

The initial phase of data extraction and analysis addressed Research Question 1 (RQ1). Data were categorized according to the following parameters: (1) instructional strategy, (2) category of instructional approach, (3) topic or theme related to organic chemistry, and (4) cognitive achievement. These categories were recorded systematically in a spreadsheet for subsequent analysis. To accurately identify and classify the instructional strategies described in each study, the research team extracted descriptive information directly from the articles. These descriptions were used to determine how instructional approaches were implemented. Across the reviewed studies, instructional approaches were grouped into several recurring types, including group-based learning, individual learning, and task-based instruction. At present, there is no universal agreement about how instructional approaches should be classified. Therefore, the research team established a grouping instructional approach by analyzing each description and applying the focus method to each paper. If researchers conduct learning activities with an emphasis on group learning (e.g., cooperative, collaborative, flipped classroom with peer-led team learning, problem-based learning with group work, etc.), then they categorize instructional approaches into group-based learning. If the paper does not mention the implementation of learning activities in groups (e.g., adaptive learning, analogy instructional strategy, etc.), then the instructional approach is classified as individual learning. If the paper the implementation of assignment, the instructional approach is classified as task-based instruction.

Analysis Methods for RQ2

The extraction and analysis of RQ2 were technology-oriented. The parameters used to categorize data are: (1) technology; (2) technology categories; (3) organic chemistry topics; and (4) cognitive achievement. The categorisation is documented in the spreadsheet for further analysis. Based on the analysis of the language used in the paper, the researchers conducted a technology categorization. The researchers found several terms: multimedia used for video; models used for molecular models, concrete models, physical models, animation, etc.; immersive learning for augmented reality, virtual reality, etc.; e-learning for online learning tools, web-based learning management systems, games hosted on a website, etc. Finally, we group technologies such as multimedia, models, immersive learning, and e-learning.

Analysis Methods for RQ3

The researchers grouped learning environments into formal learning classes that are coded classrooms and learning in laboratories that are code labs. The classroom is defined as the place where learning activities take place, whereas the laboratory is the environment in which students conduct scientific research and experiments (S. H. Wu et al., 2021). Further, the researchers mapped every type of instructional approach and technology to each learning environment, including topics of organic chemistry and cognitive achievement. Each article is analyzed to find out the characteristics of the instructional approach and the technology applied to each learning environment.

Analysis Methods for RQ4

We classify education levels into two categories: high school and higher education s. Then the researchers mapped the types of instructional approaches and technologies at each educational level, topics of organic chemistry, and cognitive achievement. Each article is analyzed to find out the characteristics of the instructional approach and the technology applied to each learning environment.

Data Distribution

Based on the 40 papers obtained, the distribution of data is based on the type of intervention given in each year, as shown in Figure 2.

Figure 2

Distribution of studies on instructional approaches and technology in organic chemistry (2014–2023)

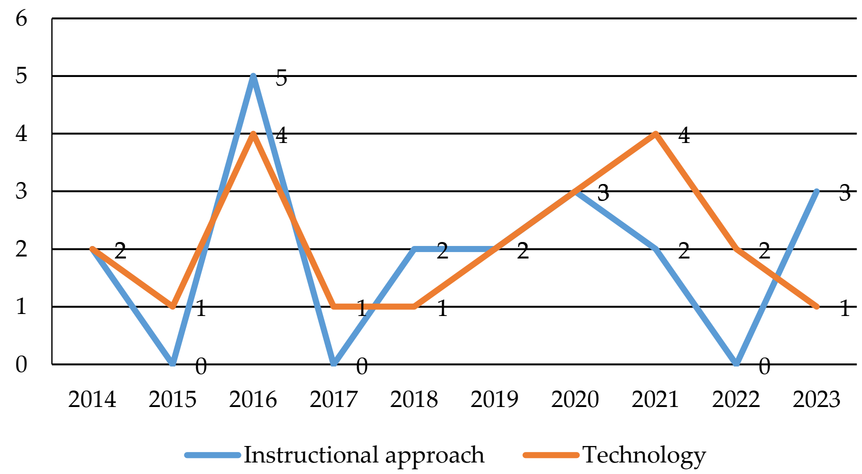


Figure 2 illustrates the annual number of studies focusing on instructional approaches and instructional technologies in the context of organic chemistry education between 2014 and 2023. The graph shows that publications related to technology use reached their highest points in 2016 and 2021, with four studies reported in each of those years. Studies on instructional approaches peaked in 2016 with five publications.While instructional technologies were used in 21 of the reviewed studies, instructional approaches were implemented in 19. These categories are not mutually exclusive, as several studies employed both instructional approaches and technological tools in combination. Overall, the frequency of technology-related studies increased between 2018 and 2021, reflecting growing interest in the integration of digital tools within chemistry instruction. The data do not show a consistent year-over-year increase, so no definitive prediction about future trends can be made based solely on this dataset. The distribution of data based on the country where the research was conducted can be seen in Figure 3.

Figure 3

Country distribution of studies on instructional approaches and technology in organic chemistry

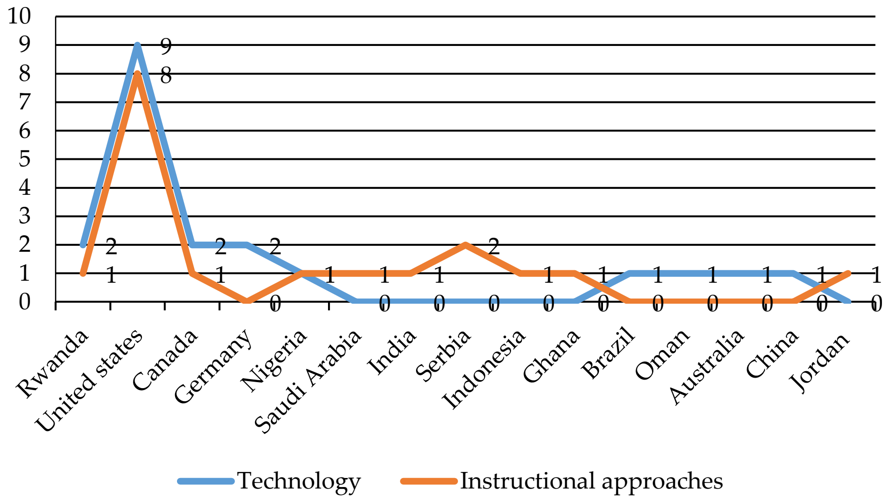


Figure 3 presents the distribution of reviewed studies based on the country in which the research was conducted. The United States appears most frequently in the dataset, indicating a higher volume of research originating from U.S.-based institutions. However, this observation should be interpreted with caution, as no statistical test was conducted to assess the significance of this distribution, and the presence of studies from a particular country does not necessarily imply a higher level of technological or instructional advancement. Both instructional technologies and teaching strategies were represented in studies from a range of countries. It is important to clearly define the distinction between "instructional approach" and "technology" throughout the analysis, as the two often overlap but are not conceptually identical.

Findings

The results of the data analysis were done to answer the research questions that have been set. There are four research questions in this study.

What Are the Instructional Approaches Used to Enhance Student Cognitive Achievement on Topics of Organic Chemistry Learning?

The first research question explores the types of instructional approaches applied to enhance students' cognitive achievement in organic chemistry learning. Table 1 presents a synthesis of the instructional approach categories, the specific methods employed, the related organic chemistry topics, and the cognitive outcomes reported. There are 17 papers on the application of instructional approaches to improving the cognitive achievement of students in organic chemistry learning. However, there are two articles that do not show significant results in improving student achievement. These two papers are the implementation of POGIL and Peer-Led Team Learning & Cyber Peer-Led Team Learning.

Table 1

Categorization of ınstructional approaches to enhance cognitive achievement in organic chemistry

Instructional approach category	Instructional approach	Reviewed studies	Topic	Cognitive achievement
Group-based learning	Cooperative learning, Flipped classroom, PLTL, Collaborative approaches, Problem based learning	(Angawi, 2014; Birundha, 2020; Pilcher et al., 2023; Dibyantini et al., 2018)	NMR spectroscopy, hydrocarbon, isomerism, Alkanes, alkenes, and alkynes; alkyl halides, Hybridisation, Functional group structures, resonance, organic chemistry reaction	Academic performance, Retention
Individual learning	Adaptive intervention, Analogy instructional strategy	(Dood et al., 2020; Samara, 2016)	Organic chemistry reactions, Functional group	Academic performance
Task-based instruction	Online homework, Writing-to-learn (WTL), Online categorization task, Systemic synthesis questions [SSynQs]	(Malik et al., 2014; Schmidt-Mccormack et al., 2019; Lapierre & Flynn, 2020; Hrin, Fahmy, et al., 2016; Hrin, Milenković, et al., 2016)	Organic chemistry reaction, Acid-base, Hydrocarbons	Academic performance

Based on Table 1, group-based learning was the most frequently implemented instructional category in the reviewed studies. This category includes cooperative learning, flipped classrooms, peer-led team learning, and problem-based instructional methods. These approaches were commonly used to improve students' academic performance and retention, particularly in topics such as spectroscopy, functional groups, and organic reaction mechanisms.

Two studies reported that the application of group-based strategies, specifically peer-led team learning (PLTL) and Process-Oriented Guided Inquiry Learning (POGIL), did not result in significant learning gains. This suggests that the effectiveness of instructional approaches may depend on how they are implemented and on contextual factors such as the learner's background. Previous research has shown that variables like prior academic achievement and student demographics can influence learning outcomes, as demonstrated by Alyahyan & Düşteaör (2020). Rather than attributing effectiveness solely to the instructional strategy, it is essential to consider how such strategies are implemented, and how learners interact with the materials and peers within each learning environment.

Task-based instruction appeared in several studies and typically involved structured activities such as online homework, writing-to-learn exercises, or categorization tasks. These strategies were designed to support conceptual understanding and improve academic performance (Ole & Gallos, 2023). Individual learning was the least represented category. It was implemented through approaches such as analogy-based instruction and adaptive interventions. These methods aim to enhance student understanding through personalized or independent learning experiences. Regarding content coverage, reaction mechanisms in organic chemistry, including electron pushing formalism (EPF), emerged as a recurrent topic across studies. Nonetheless, given the modest size of the dataset, no definitive claims about topic prevalence can be made. Notably, several studies have identified persistent challenges in students' interpretation of symbolic representations in reaction mechanisms (Bhattacharyya, 2013; Grove et al., 2012). This difficulty reflects a broader issue in science education: the cognitive demand of integrating macroscopic, sub-microscopic, and symbolic domains of understanding (Bhattacharyya & Bodner, 2005; Gilbert & Treagust, 2009; Johnstone, 1991).

What Are the Technologies Used to Improve Cognitive Achievement of Students on the Topics of Organic Chemistry Learning?

Numerous researchers have used technology to address the issue of learning organic chemistry. The distribution of the application of technology in improving student learning achievement in organic chemistry courses is presented in Table 2. 20 papers examine the effectiveness of the use of technology to improve student performance in organics courses.

Table 2

Types of technology to improve students' performance

Technology category	Technology	Reviewed studies	Topic	Cognitive achievement
Multimedia	Lightboard video, Tutorial video, Student-generated videos, Video-based demonstrations	(Schweiker et al., 2020) (Rodemer et al., 2021) (Box et al., 2017) (Nadelson et al., 2015) (Jordan et al., 2016) (Pölloth et al., 2020)	Organic reaction mechanisms, separation and purification, infrared spectroscopy (IR)	Academic performance
Models	Animation with concrete model, Computer model, Molecular model, Computer-based simulation	(Al-Balushi & Al-Hajri, 2014; Springer, 2014; Stull et al., 2016; Casselman et al., 2021; Stull & Hegarty, 2016; Nsabayezu et al., 2023)	Characteristics of organic molecules, stereochemistry, Molecular diagrams	Academic performance, Representational competence

Immersive learning	Augmanted Reality, Immersive virtual reality	(Ling et al., 2021; Miller et al., 2021)	Molecular structure	Academic performance
e-learning	Self-Directed Primer E-Book, e-module, Computer Game, Web-based discussion, Online-preparatory course	(Ali, 2019; Carle et al., 2020; Bodé et al., 2016; Da Silva Júnior et al., 2018; Iyamuremye et al., 2023; Iyamuremye et al., 2021; Fischer et al., 2019)	Nomenclature of organic compounds, functional group, resonance struvture	Academic performance

Table 2 presents the types of instructional technologies reported in the reviewed studies aimed at improving students' cognitive achievement in organic chemistry. These technologies are grouped into four main categories: multimedia, models, immersive learning, and e-learning platforms. Among these categories, e-learning was the most frequently reported. E-learning tools included digital modules, computer games, web-based discussions, and online preparatory materials. These were primarily applied to topics such as nomenclature, functional groups, and resonance structures. Multimedia tools, such as lightboard videos and video-based tutorials, were also widely implemented to enhance understanding of reaction mechanisms and spectroscopic methods.

Model-based technologies were often used to improve representational competence and conceptual understanding. These included animations, molecular models, and computer simulations, which were applied to topics such as molecular structures and stereochemistry. Although immersive learning technologies, such as augmented and virtual reality, appeared less frequently, they were used to improve spatial understanding of molecular concepts. Most of the studies in this review measured academic performance as the primary cognitive outcome. Only studies involving models explicitly assessed representational competence in addition to academic performance.

What Are the Appropriate Types of Instructional Approaches and Technology Used for Formal and Laboratory Classes?

As an inherently experimental discipline, organic chemistry is taught through both theoretical instruction and laboratory-based learning. This dual-context approach is reflected in several studies that investigate the application of instructional strategies and technologies across classroom and laboratory environmentsThe distribution of data-type instructional approaches and technologies applied in learning environments in classrooms and laboratories is presented in Table 3.

Table 3

Distribution of data types, instructional approaches, and technologies applied in classrooms and laboratories

Learning environment	Intervention	Intervention category	Reviewed studies	Cognitive achievement
Classroom	Instructional approach	Group-based learning	(Abukari et al., 2023; Agwuudu & Udu, 2017; Angawi, 2014; Birundha, 2020; Dibyantini et al., 2018; Mooring et al., 2016; Pilcher et al., 2023; Shattuck, 2016; Sibomana et al., 2021, 2023)	Academic performance and retention
		Individual learning	(Dood et al., 2020; Samara, 2016)	Academic performance
		Task-based instruction	(Hrin, Fahmy, et al., 2016; Hrin, Milenković, et al., 2016; Lapierre & Flynn, 2020; Malik et al., 2014; Schmidt-Mccormack et al., 2019)	Academic performance
	Technology	Multimedia	(Rodemer et al., 2021; Schweiker et al., 2020)	Academic performance
		Models	(Al-Balushi & Al-Hajri, 2014; Nsabayezu et al., 2023; Schweiker et al., 2020; Springer, 2014; Stull et al., 2016; Stull & Hegarty, 2016)	Academic performance and representational competence
		Immersive learning	(Ling et al., 2021; Miller et al., 2021)	Academic performance
		e-learning	(Ali, 2019; Bodé et al., 2016; Carle et al., 2020; Da Silva Júnior et al., 2018; Iyamuremye et al., 2021, 2023)	Academic performance
Laboratory	Instructional approach	-	-	-
	Technology	Multimedia	(Box et al., 2017; Jordan et al., 2016; Nadelson et al., 2015; Pölloth et al., 2020)	Academic performance
		e-learning	(Fischer et al., 2019)	

Table 3 summarizes the instructional approaches and technologies used in two learning environments: classroom and laboratory settings. The majority of the reviewed studies were conducted in classroom environments. Within these settings, group-based learning was the most frequently reported instructional approach, often aimed at improving academic performance and retention. Technology tools applied in the classroom included multimedia resources, models, immersive learning environments, and e-learning.

Studies in this category showed varied outcomes, with some reporting improvements in both academic performance and representational competence, particularly when models were used. Fewer studies were conducted in laboratory settings. Among those, multimedia and e-learning technologies were applied to support laboratory instruction. Instructional approaches in the laboratory were not specifically identified in the included studies. Although the number of laboratory-based studies was limited, the available data suggest that digital technologies were used to supplement hands-on experiences and to provide pre-laboratory instruction or virtual engagement.

What Are the Types of Instructional Approaches and Technology Suitable for Different Levels of Education?

Organic chemistry is studied at different levels of education: high school and higher education. The distribution of data on the application of instructional approaches and technologies at each educational level is presented in Table 4.

Table 4

Distribution of data types, instructional approaches, and technologies applied to each of the different levels of education

Levels of education	Intervention	Category	Reviewed studies	Cognitive achievement
High school	Instructional approach	Group-based learning	(Abukari et al., 2023; Birundha, 2020; Sibomana et al., 2021)	Academic performance and retention
		Task-based instruction	(Hrin, Fahmy, et al., 2016) (Hrin, Milenković, et al., 2016)	Academic performance
	Technology	Immersive learning	(Ling et al., 2021)	Academic performance
		e-learning	(Da Silva Júnior et al., 2018; Iyamuremye et al., 2021, 2023)	Academic performance
		Models	(Nsabayezu et al., 2023)	Academic performance
Higher education	Instructional approach	Group-based learning	(Agwuudu & Udu, 2017; Angawi, 2014; Dibyantini et al., 2018; Mooring et al., 2016; Pilcher et al., 2023; Shattuck, 2016; Sibomana et al., 2023)	Academic performance and retention
		Individual learning	(Dood et al., 2020; Samara, 2016)	Academic performance
		Task-based instruction	(Lapierre & Flynn, 2020; Malik et al., 2014; Schmidt-Mccormack et al., 2019)	Academic performance
	Technology	Multimedia	(Box et al., 2017; Jordan et al., 2016; Nadelson et al., 2015; Pölloth et al., 2020; Rodemer et al., 2021; Schweiker et al., 2020)	Academic performance
		Models	(Al-Balushi & Al-Hajri, 2014; Casselman et al., 2021; Springer, 2014; Stull et al., 2016; Stull & Hegarty, 2016)	Academic performance and representational competence
		Immersive learning	(Miller et al., 2021)	Academic performance
		e-learning	(Ali, 2019; Bodé et al., 2016; Carle et al., 2020; Fischer et al., 2019)	Academic performance

Table 4 presents the distribution of instructional approaches and technologies according to educational level, categorized into high school and higher education. Most of the reviewed studies were conducted at the higher education level, focusing primarily on university students. At the university level, group-based learning was the most frequently applied instructional approach. This method was associated with improvements in both academic performance and retention. Technologies commonly used in higher education included multimedia tools, e-learning platforms, and modeling technologies. These tools were employed across a range of topics, from reaction mechanisms to symbolic representations.

At the high school level, group-based learning was also used to improve academic achievement and retention. In addition, immersive learning and e-learning technologies were applied to support conceptual understanding. However, fewer studies were conducted at this level compared to higher education. Because of the limited number of studies reviewed in this synthesis, no definitive claims can be made about the broader prevalence of these interventions across educational systems. The findings reflect the distribution and content focus of the sampled research, rather than the full spectrum of instructional practices in organic chemistry education.

Discussion

What Are the Instructional Approaches Used to Enhance Student Cognitive Achievement on Topics of Organic Chemistry Learning?

Most papers apply learning with an emphasis on group-based learning. The conclusions of this analysis are consistent with previous research demonstrating that group learning enhances students' long-term retention of learned material (Akhtar et al., 2024; Morgan et al., 2000), which demonstrated that group learning enhances students' long-term retention of learnt material. Furthermore, research has demonstrated that group learning fosters the development of advanced skills to a greater extent than a conventional lecture-based learning setting (Sloffer et al., 1999). Through small groups, students maintain learning goals by helping each other in social settings (Pateşan et al., 2016). Group learning supports intellectual exploration and consensus-building through social interaction (Adu-Gyamfi & Asaki, 2022; Hanson, 2017; Sibomana et al., 2020). Students are not only preparing for examinations but also constructing a learning environment conducive to comprehensive academic development (Karacop, 2016; Tran, 2014; Yash & Singh, 2011). Group-based learning is based on the theory of learning that relates to the social arrangement of constructivism. Constructivism posits that the process of learning will primarily engage students by enhancing their capacity to conceptualise the knowledge being learned (Yassin et al., 2018). Effective learning is enhanced when students actively engage in social interactions. By utilising learning methods that encourage students to conceptualise their subjects and interact with both their peers and teachers, academic achievement can be improved. This is because students have the opportunity to learn from each other's unique perspectives and concepts, which may not be directly taught by educators.

However, two studies focus on Process-Oriented Guided Inquiry Learning (POGIL) and Peer-Led Team Learning (PLTL) did not report significant improvement in student learning outcomes. While both are rooted in social constructivist theory (Eberlein et al., 2008), the study by Wilson & Varma-Nelson (2019) found that students participating in PLTL often relied on memorizing reaction tables rather than conceptual understanding. The authors suggest that students' limited practice with drawing mechanisms such as electron-pushing formalism contributed to this outcome. This phenomenon aligns with Vygotsky's notion of verbalism, where learners mimic terminology without internalizing conceptual meaning (Vygotsky, 1986).

In the case of POGIL, the lack of improvement may be due to student unfamiliarity with the method. As Shadiev et al. (2023) suggest, cognitive processing is enhanced in familiar learning environments, whereas unfamiliar instructional designs may create additional cognitive burden. Familiarity reduces the cognitive resources needed for situational adjustment, allowing students to focus more effectively on content.

What Are the Technologies Used to Improve Cognitive Achievement of Students on the Topics of Organic Chemistry Learning?

E-learning is the predominant form of educational technology today (Elaine Allen et al., 2008; Kigozi Kahiigi et al., 2008; Lau et al., 2014; Kavitha & Lohani, 2019). This result is supported by Kavitha & Lohani (2019), who state that e-learning has provided benefits that vary in purpose and features that are generally suitable for people with any learning style. E-learning also offers many benefits, such as flexibility, accessibility and diversity (Barrot et al., 2021; Jantrasee, 2022). E-learning allows educators and teaching instructors to graphically present course content in a digital learning environment, enabling students to engage in an online setting (Chikileva et al., 2023). E-learning facilitates self-directed learning for students, allowing them to study at their own convenience and location. It also enables teaching activities to be conducted without the need for actual classrooms (Zedan, 2021;Masalimova et al., 2022).

Multimedia and models become the second choice of researchers to enhance student achievement in organic chemistry learning. Multimedia in the form of video is a good choice to enhance student achievement in organic chemistry learning. By utilizing features such as pausing, speeding up, slowing down, and replaying specific sections of the video, students have the capacity to learn at their own pace and can revisit the content as needed (Dangelo, 2014; Kraft et al., 2012; Richards-Babb et al., 2014). Models widely recognized that the study of conventions and the utilization of visual-spatial representations, such as different forms of molecular diagrams, are crucial for effective communication (Gilbert, 2008; Gilbert & Treagust, 2009). Teachers frequently promote the utilization of models as a means for students to enhance their learning (Stieff, 2011). The ability of students to perform actual actions rather than imagined ones when manipulating molecular models can help explain this finding (Maglio, 1994). These findings can be explained using cognitive load theory (Sweller, 2020). According to Sweller, the capacity of working memory is restricted, which means that only a few cognitive operations can be managed simultaneously.

What Are the Appropriate Types of Instructional Approaches and Technology Used for Formal and Laboratory Classes?

Based on the data analysis, it is seen that in the classroom, group-based learning and models become instructional approaches and technology that are mostly used to improve student achievement. These finding can be explained by constructivism theory and cognitive load theory. The process of building knowledge occurs in students themselves through social interaction with friends in the group (Vygotsky, 1986). Furthermore, models can help students to perform actual actions rather than imagined ones when manipulating molecular models (Maglio, 1994). Consequently, this decreases the requirement for working memory and minimizes the cognitive load on children (Chandler & Sweller, 1991). Reducing cognitive load allows students to allocate more cognitive effort towards understanding mapping conventions and translating diverse representations, leading to improved learning outcomes (H.-K. Wu & Shah, 2004).

Meanwhile, the data showed that the lab only applied technology as an alternative strategy for improving student cognitive achievement. Cognitive load theory explain that in intricate settings like organic chemistry lab courses, students mostly concentrate on practical inquiries pertaining to investigations (Agustian & Seery, 2017; Johnstone et al., 1994). This cognitive limitation reduces students' ability to reflect on theoretical and conceptual aspects of laboratory experiments. Therefore, improving the quality of learning in laboratory-based courses requires careful preparatory support. One effective strategy is the integration of pre-laboratory instructional materials, such as guided tutorials, simulation exercises, or digital modules, which help students develop familiarity with experimental procedures before entering the lab(Agustian & Seery, 2017; Rollnick et al., 2001). Such preparation enhances conceptual readiness and reduces the cognitive load during hands-on activities.

Additionally, the use of technology as a pre-class support tool can reduce the reliance on working memory and help alleviate students' cognitive burden (Chandler & Sweller, 1991). Digital materials provided in advance allow students to rehearse procedures and concepts, making them feel more confident and better prepared (Chaytor et al., 2017; D'Ambruoso et al., 2018) . This sense of preparedness also contributes to more positive attitudes toward laboratory work (Supasorn et al., 2008).

What Are the Types of Instructional Approaches and Technology Suitable for Different Levels of Education?

Based on the analysis of the available data, group-based learning appears to be the most commonly implemented instructional approach across various educational levels, particularly in high school and higher education. Although the number of reviewed studies is limited, this trend suggests that collaborative learning strategies are consistently used to support student achievement in organic chemistry education. Instructional activities such as small-group discussions, cooperative problem solving, and hands-on practical tasks have been identified as effective in promoting meaningful learning outcomes (Omwirhiren et al., 2016; Çimer, 2007). These approaches facilitate social interaction, which is a key factor in the construction of knowledge. When students engage actively with peers and instructors, they are more likely to develop a deeper understanding of subject matter through the exchange of perspectives (Sibomana et al., 2021). An effective chemistry teaching approach involves not only the delivery of content, but also the encouragement of conceptual application across different learning contexts. Teachers play a central role in promoting student engagement and helping learners to connect abstract concepts with real-world applications (Adu-Gyamfi & Asaki, 2023).

On the other hand, e-learning mostly used in high school and multimedia in higher education. Technology helps the learning process of teaching by improving its quality and value (Schindler et al., 2017). Technology can be used in a variety of ways that help teachers and students study their respective subjects in high school students. Students engage in technology-based courses that involve real activities, which aim to enhance their comprehension of the subject matter (Ghavifekr & Rosdy, 2015; Jantrasee, 2022). Besides, students in schools and colleges have high expectations of ICT integration in the classroom, as a new generation has been born and grown up with technology and can be defined as a native digital phenomenon (Chien et al., 2014).

Conclusion and Implications

Based on the findings of this review, group-based learning approaches such as cooperative learning, flipped classrooms, peer-led team learning, collaborative learning, and problem-based instruction are frequently implemented to support academic performance and student retention in organic chemistry. Although these methods are not new, the present synthesis provides updated insights into their application across different learning environments and educational levels.

With regard to technological interventions, e-learning tools including digital modules, self-directed e-books, web-based platforms, and educational games are commonly applied in classroom instruction. Multimedia resources, such as instructional videos and simulations, appear more frequently in laboratory-based learning. However, no reviewed study specifically reported the use of instructional approaches in laboratory settings, suggesting an area that requires further investigation.

At both high school and higher education levels, group-based learning remains a widely reported instructional strategy. E-learning is more often applied in high school settings, while multimedia tools are more commonly used in higher education contexts. These findings indicate that group-based learning and technology-enhanced instruction contribute positively to student learning outcomes in organic chemistry.

The findings suggest that instructional strategies and technology integration should be aligned with educational level, topic complexity, and cognitive demands to optimize learning outcomes in organic chemistry. These insights can guide educators, curriculum designers, and policymakers in selecting evidence-based interventions tailored to specific contexts and learners.

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