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Mechanistic Insights into Organic Reactions: Fundamental Principles and Practical Applications

Shohel Rana [1]*

[1]Student, Department of Chemistry, Government Azizul Haque College, Bogra, Bangladesh.

A B S T R A C T :

Organic chemistry is a vital branch of chemistry that focuses on the study of carbon-based compounds and their transformations. Central to this field is understanding reaction mechanisms, which describe the step-by-step processes that occur during chemical reactions, including the formation and transformation of intermediates. This knowledge is essential for predicting reaction outcomes, designing new synthetic pathways, and optimizing existing processes. Mechanistic studies have evolved significantly, with advancements in experimental techniques like spectroscopy, kinetics, and isotope labelling, as well as computational methods such as density functional theory (DFT). These tools have enabled researchers to investigate reaction pathways with greater precision and efficiency. A deep understanding of reaction mechanisms is not only important for academic research but also for practical applications in various industries, including pharmaceuticals, materials science, and environmental chemistry. In pharmaceuticals, for instance, mechanistic insights are crucial for developing efficient synthetic routes for drug molecules and improving their efficacy. Additionally, in industrial chemistry, mechanistic knowledge aids in the development of sustainable, efficient, and selective processes. This review highlights the fundamental principles of organic reaction mechanisms, experimental and computational approaches used to study them, and their practical applications in different fields of chemical research and industry.

Keywords: Organic Chemistry, Reaction Mechanisms, Chemical Reactions, Intermediates, Spectroscopy, Pharmaceuticals, Green Chemistry.

1. Introduction

Organic chemistry is a central discipline in the field of chemistry, focusing on the study of carbon-based compounds [1]. A fundamental aspect of organic chemistry is understanding the mechanisms through which chemical reactions occur [2]. Reaction mechanisms describe the step-by-step sequence of events, including the formation and transformation of intermediates, that lead to the formation of products. The study of reaction mechanisms is crucial for gaining insight into the reactivity, selectivity, and efficiency of organic reactions. By deciphering these mechanisms, chemists can predict the outcomes of reactions, design new synthetic routes, and optimize existing processes, all of which are essential in fields such as pharmaceuticals, materials science, and environmental chemistry [3]. Over the years, mechanistic studies have evolved significantly, driven by advances in experimental techniques and computational methods [4]. Early mechanistic investigations relied primarily on empirical observations, but as the field progressed, scientists developed sophisticated tools such as spectroscopy, kinetics, and isotope labeling to investigate reaction pathways in greater detail [5]. In the modern era, computational chemistry has played an increasingly pivotal role in mechanistic studies, allowing researchers to predict reaction mechanisms with a high degree of accuracy and efficiency [6]. These developments have not only expanded our understanding of fundamental principles in organic chemistry but have also opened the door to the design of novel reactions and the discovery of new reagents and catalysts [7].

The importance of understanding reaction mechanisms extends beyond academic curiosity. In synthetic organic chemistry, where the goal is to develop efficient and selective reactions for the preparation of complex molecules, mechanistic knowledge is key to achieving optimal yields and minimizing side reactions [8]. In pharmaceutical research, mechanistic insights are essential for designing efficient synthetic pathways for drug molecules [9]. Furthermore, in industrial chemistry, where scalability and sustainability are paramount, the mechanistic understanding of reactions guides the development of greener, more sustainable processes [10]. This review aims to explore the fundamental principles of organic reaction mechanisms, examine key experimental and computational techniques used to elucidate these mechanisms, and highlight their practical applications in various fields of chemical research and industry.

2. Fundamental Principles of Organic Reactions

Chemical bonds are broken and formed during organic reactions, transforming organic compounds [11]. A thorough understanding of organic reactions requires an examination of a number of underlying concepts. These ideas aid in the explanation of how and why reactions take place, forecast their results, and provide guidance on how to regulate and enhance reactions for particular uses. We will look at the main ideas in this part, such as the many kinds of reactions, the function of reaction intermediates, energy profiles, and the different elements that affect reactivity.

2.1 Types of Organic Reactions

- **Substitution Reactions:** An atom or group of atoms in a molecule gets swapped out for another atom or group in a substitution process [12]. Alkanes and halogenated compounds are examples of saturated organic molecules that often undergo substitution reactions. A leaving group (electron-poor species) is swapped out for a nucleophile (electron-rich species). Depending on the substrate type and reaction circumstances, this reaction may proceed via an SN1 or SN2 mechanism [13].
- **Addition Reactions**: In an addition reaction, no atoms are lost when two reactants join to generate a single product. When the π-bond in the double or triple bond is broken, additional atoms or groups may bind to the carbon atoms in addition reactions, which are frequent in alkenes and alkynes [14]. Among them are hydration, halogenation, and hydrogenation.
- **Elimination Reactions:** Two atoms or groups are taken out of a molecule in an elimination process, which often results in the creation of a double bond [15]. The reverse of an addition reaction is this. Dehydrohalogenation of alkyl halides and dehydration of alcohols to generate alkenes are frequent examples.
- **Rearrangement Reactions:** In these reactions, atoms or groups inside a molecule are rearranged without any new atoms being added or removed [16]. A distinct structural isomer is produced by rearranging the molecule's functional groups or carbon backbone. The Wagner–Meerwein rearrangement in carbocation chemistry serves as one example.

2.2 Reaction Intermediates

Reaction intermediates are transient species that form during the course of a chemical reaction but are not present in the final products [18]. Understanding intermediates is crucial for understanding the mechanism of a reaction, as they play key roles in determining the reaction pathway. The common types of reaction intermediates include:

- **Carbocations**: The carbon atom in these species bears the positive charge, making them positively charged. Usually created during electrophilic substitution or elimination events, carbocations are very reactive [18]. One important element influencing the pace and result of reactions is the stability of carbocations. For instance, the inductive and hyperconjugative actions of alkyl groups make tertiary carbocations more persistent than primary ones.
- **Carbanions**: A carbon atom bears the negative charge in carbanion species, which are negatively charged [19]. When it comes to nucleophilic substitution and addition processes, these intermediates are crucial. Resonance stabilization and the presence of electron-withdrawing groups are two examples of the variables that affect carbanions' stability.
- **Radicals**: An unpaired electron makes a radical a neutral species. These very reactive intermediates play a role in polymerization, radical substitution, and certain kinds of addition processes [20]. Because of their great reactivity, radicals usually need certain circumstances to develop and react, such light or the presence of a radical initiator.
- **Carbenes**: The divalent carbon atom in these neutral species possesses two non-bonding electrons [21]. Carbenes engage in a range of processes, such as insertion and rearrangement reactions, and may function as both electrophiles and nucleophiles.
- **Transition States:** These high-energy configurations are found at the reaction pathway's apex [22]. Transition states are essential for figuring out the reaction rate and mechanism, despite not being separate species. They stand for the location of maximal potential energy, where bonds are created and partly destroyed.

2.3 Energy Profiles and Transition States

The idea of energy profiles is essential to comprehending the process of the reaction. A reaction's energy profile illustrates how the system's energy shifts when reactants give way to products [23]. The activation energy (Ea), sometimes referred to as the energy barrier, is the energy needed to get from the reactants to the transition state. The reaction will occur more slowly if the activation energy is higher.

- **Exothermic and Endothermic Reactions:** Energy may be released (exothermic) or absorbed (endothermic) via reactions. Products in endothermic processes have a greater energy than those in exothermic reactions, which have a lower energy than the reactants. The ΔH (enthalpy change) is the energy difference between reactants and products.
- **Reaction Coordinate Diagrams:** The potential energy of the reaction system is plotted against the reaction's progress in these graphs. The activation energy is indicated by the height of the energy barrier, and the diagram usually displays reactants, intermediates, transition states, and products.
- **Catalysts**: Substances known as catalysts increase a reaction's pace by lowering its activation energy. By offering a different reaction route with a lower activation energy, catalysts accomplish this. They may be used again and are not consumed in the reaction. In many organic reactions, including industrial chemical processes and biological reactions mediated by enzymes, catalysis is essential.

2.4 Factors Influencing Reactivity

Several factors influence the rate and outcome of organic reactions. These include:

- **Substrate Effects**: The structure and electronic properties of the substrate significantly impact the reaction. For instance, the nature of the carbon–leaving group bond determines the ease of bond cleavage, while electron-withdrawing or electron-donating groups can affect the reactivity of a substrate by stabilizing or destabilizing intermediates.

- **Solvent Effects**: Solvents can affect the rate of a reaction by stabilizing or destabilizing certain intermediates. Polar solvents tend to stabilize charged species, such as carbocations and carbanions, and can thus influence reaction mechanisms. Aprotic solvents, for instance, may favor nucleophilic substitution (SN2), while protic solvents might promote SN1 reactions.
- **Temperature and Pressure**: Increasing the temperature typically increases the rate of a reaction, as it provides more kinetic energy to the reacting molecules. Similarly, pressure can affect reactions involving gases, especially when dealing with addition or elimination reactions involving gaseous species.
- **Concentration**: The concentration of reactants can influence the rate of reaction. In many reactions, the rate is directly proportional to the concentration of one or more reactants (first-order reactions), while in others, it may depend on the concentration of intermediates or catalysts.

3. Elucidating Mechanisms: Experimental and Computational Approaches

Understanding the mechanism of a reaction is a fundamental step in organic chemistry, as it provides insights into how reactants are converted into products, what intermediates are formed, and what factors influence the rate and pathway of the reaction [24]. To elucidate these mechanisms, chemists rely on a variety of experimental and computational techniques [25]. These approaches allow for the identification of intermediates, the determination of reaction pathways, and the prediction of reaction outcomes [26]. In this section, we will explore the key experimental methods used to study organic reaction mechanisms, as well as the powerful role that computational chemistry plays in this process.

3.1 Experimental Approaches

Since experimental methods provide direct proof of intermediates and reaction routes, they are essential for researching organic reaction processes. Spectroscopy methods like NMR, IR, MS, and UV-Vis make it possible to see how structures change when reactions occur [27]. IR finds changes in functional groups, but NMR is better at following chemical intermediates [28]. MS assists in determining the molecular weight and structure of intermediates, whereas UV-Vis tracks conjugated system processes [29]. In order to get insight into the rate-determining step and overall process, kinetic studies assess reaction rates under various situations. Isotope labeling helps identify intermediates by substituting isotopes for reactant atoms to track atom mobility during the process. Reaction pathway trapping allows the study of highly reactive intermediates, such as radicals or carbocations, by introducing chemicals to stabilize them. A thorough comprehension of response dynamics and processes is provided by these integrated approaches.

3.2 Computational Approaches

By modeling molecular behavior at the atomic level, computational chemistry is essential to understanding organic reaction processes. Methods like ab initio computations and Density Functional Theory (DFT) are often used to estimate activation energies, forecast transition states, and model reaction pathways [29]. With the use of these techniques, chemists may produce energy profiles that highlight important intermediates and transition states as well as the most advantageous chemical paths. Insights into the stability and reactivity of different species may be gained by simulating the electronic structure of reactants, intermediates, and products using quantum mechanical simulations. Molecular dynamics (MD) simulations are a useful tool for understanding reaction kinetics, solvent interactions, and the impact of temperature on reaction pathways [30]. They do this by simulating the movement of atoms over time. Combined, computational methods provide a thorough and accurate knowledge of reaction processes, directing reaction design and experimental research.

3.4 Synergy Between Experimental and Computational Approaches

A potent and complementary method for clarifying organic reaction processes is the combination of computational and experimental methods. Computational chemistry provides predicted insights into the molecular-level specifics of the reaction process, while experimental approaches give direct, empirical data on reaction intermediates, product generation, and reaction rates [31]. The identification of chemical intermediates and the validation of suggested processes are aided by experimental methods including spectroscopy, kinetics, and isotope labeling. Nevertheless, the system's intricacy or the stability of the intermediates may sometimes place restrictions on these approaches. On the other hand, computational methods enable the investigation of reaction pathways that could be challenging to investigate via experimentation, including the modeling of reaction dynamics across time or the characterisation of transition states.

Researchers may clarify reaction processes, confirm computational predictions with experimental data, and find novel insights that would not be possible with either technique alone by integrating the two methodologies. This collaboration facilitates the design of more effective reactions, speeds up the identification of new reaction routes, and deepens our knowledge of reaction dynamics. In the end, the integration of computational and experimental methods improves the capacity to forecast, optimize, and regulate organic processes, resulting in advancements in materials science, synthetic chemistry, and catalysis.

4. Practical Applications of Organic Reaction Mechanisms

In addition to being essential for basic chemical research, an understanding of organic reaction processes has significant real-world implications in a variety of sectors. In order to improve the sustainability, efficiency, and selectivity of chemical processes, mechanistic insights are essential [32]. In industries including industrial chemistry, materials science, and pharmaceuticals, scientists and engineers may create more sustainable processes, improve current ones, and design novel reactions by using their understanding of mechanistics. This section will examine a number of important real-world uses for organic reaction processes.

4.1 Pharmaceutical Synthes

One of the main industries that uses organic reaction mechanisms is the pharmaceutical sector. The design and synthesis of complex compounds, which often include many stages and reaction pathways, are crucial to the drug development process [33]. Chemists may find effective synthetic pathways, reduce byproducts, and increase yields with the aid of a thorough grasp of reaction processes. For instance, selective reactions guided by mechanistic research are often used to provide the exact control over stereochemistry needed for the production of chiral medicinal compounds. Chemistry professionals may develop more effective synthetic routes for the production of active pharmaceutical ingredients (APIs) by comprehending the specifics of processes like electrophilic addition, nucleophilic substitution, and catalytic cycles [33].

4.2 Materials Science and Polymer Chemistry

In materials research, where it facilitates the creation of novel materials with particular characteristics, mechanistic comprehension is also essential. Polymers, adhesives, coatings, and other materials with a variety of uses in the electronics, automotive, aerospace, and medical sectors are often produced by organic processes [34]. Classic examples of polymerization processes where mechanistic understanding are crucial for regulating molecular weight, polymer architecture, and material qualities include addition polymerization and ring-opening polymerization.

4.3 Green Chemistry and Sustainable Practices

The discipline of green chemistry, which aims to create chemical processes that are more sustainable, energy-efficient, and ecologically benign, has seen one of the most significant uses of organic reaction mechanisms in recent years. Chemists may create novel reactions that limit the energy needed for chemical operations, lower the amount of hazardous waste produced, and utilize fewer toxic solvents by comprehending reaction mechanics [35]. For example, the creation of more effective catalytic cycles as a result of mechanistic research has decreased waste generation and the need for stoichiometric reagents. One such field where mechanistic insight has produced more environmentally friendly substitutes for conventional metal-catalyzed processes is organocatalysis, which uses tiny organic molecules to catalyze reactions.

4.4 Industrial Chemical Synthesis

A mechanistic knowledge of organic processes is also beneficial for the industrial manufacture of chemicals, including petrochemicals, polymers, fertilizers, and specialty compounds. Large-scale commercial synthesis requires the capacity to optimize reactions in terms of yield, selectivity, and scalability [36]. Development of more effective, economical, and ecologically friendly processes is made possible by mechanistic studies, which provide light on reaction conditions, the function of catalysts, and the impact of impurities or byproducts on the reaction. For example, mechanistic insights enable the selective synthesis of desired products over undesirable side reactions in the manufacturing of fine compounds (used in flavors, perfumes, and additives).

5. Challenges And Future Works

Despite a number of obstacles, the science of organic reaction mechanisms has a bright future. Significant progress will be fueled by the integration of AI, developments in sustainable chemistry, novel catalytic systems, and real-time monitoring technologies. Organic chemistry will continue to address global issues, such as healthcare innovation and environmental sustainability, via multidisciplinary cooperation and enhanced computational and experimental techniques.

- The study of organic reaction mechanisms is challenging due to the complexity of reactions, involving multiple intermediates, competing pathways, and intricate electronic effects.
- Many organic reactions involve highly reactive intermediates like carbocations, radicals, carbanions, and carbenes, which are hard to isolate and observe, complicating the determination of reaction pathways.
- Computational chemistry is crucial for understanding reaction mechanisms, but methods like DFT and ab initio calculations have limitations in modeling complex reactions.
- AI and ML are set to transform the study of organic reaction mechanisms by processing large data sets to predict outcomes, identify new pathways, and optimize reaction conditions.
- The demand for sustainable chemical processes is driving green chemistry research, with mechanistic studies focusing on reactions that minimize waste, reduce energy use, and utilize renewable feedstocks.
- The development of new catalysts remains a significant area of focus. Mechanistic studies will help improve the efficiency and selectivity of both homogeneous and heterogeneous catalysts.

6. Conclusion

An important component of organic chemistry is the study of organic reaction processes, which provide deep understanding of how molecules change and interact. Chemists may create more effective, selective, and sustainable reactions by comprehending reaction pathways, intermediates, and transition states. This is essential for a variety of applications in industrial chemistry, materials science, medicines, and catalysis. The invention of novel synthetic pathways, process improvement, and creative solutions to modern problems like healthcare and environmental sustainability are all fueled by this knowledge. Even with great advancements, there are still difficulties in completely understanding reaction processes, especially in the areas of complicated reaction modeling, transient intermediate characterization, and reaction scaling up for commercial use. The development of experimental and computational methods, including time-resolved spectroscopy, isotope labeling, and quantum mechanical simulations, is necessary to overcome these challenges. Furthermore, researchers will be able to more effectively design new reactions, optimize conditions, and predict reaction outcomes by combining mechanistic studies with contemporary tools like artificial intelligence and machine learning.

Future directions for organic reaction mechanisms include developing catalytic processes, investigating mechanisms in intricate contexts such as biological systems, and enhancing sustainability via green chemistry. We will keep pushing the limits of our knowledge and use of response mechanisms via improved computer models, multidisciplinary research, and real-time monitoring. In the end, these developments will allow chemists to create novel approaches to global issues in health, energy, and the environment, guaranteeing that organic chemistry stays at the forefront of scientific research and technological development.

REFERENCES

1. Jorner, K., Tomberg, A., Bauer, C., Sköld, C., & Norrby, P. O. (2021). Organic reactivity from mechanism to machine learning. Nature Reviews Chemistry, 5(4), 240-255.
2. Ji, C., Xu, M., Yu, H., Lv, L., & Zhang, W. (2022). Mechanistic insight into selective adsorption and easy regeneration of carboxyl-functionalized MOFs towards heavy metals. Journal of Hazardous Materials, 424, 127684.
3. Smith, M. B. (2020). March's advanced organic chemistry: reactions, mechanisms, and structure. John Wiley & Sons.
4. Chen, B. W., Xu, L., & Mavrikakis, M. (2020). Computational methods in heterogeneous catalysis. Chemical Reviews, 121(2), 1007-1048.
5. Yan, X., Huang, J., Guo, L., Liu, C., Dong, S., & Peng, Z. (2021). Interrogating lithium–oxygen battery reactions and chemistry with isotope-labeling techniques: A mini review. Energy & Fuels, 35(6), 4743-4750.
6. Lang, Y., Li, C. J., & Zeng, H. (2021). Photo-induced transition-metal and external photosensitizer-free organic reactions. Organic Chemistry Frontiers, 8(13), 3594-3613.
7. Burrows, A., Holman, J., Lancaster, S., Overton, T., Parsons, A., Pilling, G., & Price, G. (2021). Chemistry3: Introducing inorganic, organic and physical chemistry. Oxford university press.
8. Kwon, K., Simons, R. T., Nandakumar, M., & Roizen, J. L. (2021). Strategies to generate nitrogen-centered radicals that may rely on photoredox catalysis: development in reaction methodology and applications in organic synthesis. Chemical reviews, 122(2), 2353-2428.
9. John, S. E., Gulati, S., & Shankaraiah, N. (2021). Recent advances in multi-component reactions and their mechanistic insights: a triennium review. Organic Chemistry Frontiers, 8(15), 4237-4287.
10. Baumann, M., Moody, T. S., Smyth, M., & Wharry, S. (2020). A perspective on continuous flow chemistry in the pharmaceutical industry. Organic Process Research & Development, 24(10), 1802-1813.
11. Hone, C. A., & Kappe, C. O. (2021). Towards the standardization of flow chemistry protocols for organic reactions. Chemistry‐Methods, 1(11), 454-467.
12. An, X. D., & Xiao, J. (2020). Fluorinated alcohols: magic reaction medium and promoters for organic synthesis. The Chemical Record, 20(2), 142-161.
13. Westaway, K. C. (2020). Nucleophilic aliphatic substitution. Organic Reaction Mechanisms· 2016: An annual survey covering the literature dated January to December 2016, 369-421.
14. Zhou, W., Xu, Z., & Zhao, J. (2023). A Novel Lewis Structure and Its Utilization in the Examination of Mechanisms of Organic Chemical Reactions. Journal of Chemical Education, 100(9), 3694-3702.
15. BABAAMER, Z. (2021). Organic chemistry–Courses and corrected exercises.
16. Jana, S., Guo, Y., & Koenigs, R. M. (2021). Recent perspectives on rearrangement reactions of ylides via carbene transfer reactions. Chemistry–A European Journal, 27(4), 1270-1281.
17. Ma, J., Miao, T. J., & Tang, J. (2022). Charge carrier dynamics and reaction intermediates in heterogeneous photocatalysis by time-resolved spectroscopies. Chemical Society Reviews, 51(14), 5777-5794.
18. Roytman, V. A., & Singleton, D. A. (2020). Solvation dynamics and the nature of reaction barriers and ion-pair intermediates in carbocation reactions. Journal of the American Chemical Society, 142(29), 12865-12877.
19. Donabauer, K., & König, B. (2020). Strategies for the Photocatalytic Generation of Carbanion Equivalents for Reductant-Free C–C Bond Formations. Accounts of chemical research, 54(1), 242-252.
20. Gong, X., Caglayan, M., Ye, Y., Liu, K., Gascon, J., & Dutta Chowdhury, A. (2022). First-generation organic reaction intermediates in zeolite chemistry and catalysis. Chemical Reviews, 122(18), 14275-14345.
21. Chen, X., Wang, H., Jin, Z., & Chi, Y. R. (2020). N‐heterocyclic carbene organocatalysis: activation modes and typical reactive intermediates. Chinese Journal of Chemistry, 38(10), 1167-1202.
22. Tantillo, D. J. (2021). Beyond transition state theory—Non-statistical dynamic effects for organic reactions. In Advances in Physical Organic Chemistry (Vol. 55, pp. 1-16). Academic Press.
23. Young, T. A., Silcock, J. J., Sterling, A. J., & Duarte, F. (2021). autodE: automated calculation of reaction energy profiles—application to organic and organometallic reactions. Angewandte Chemie, 133(8), 4312-4320.

24. Dood, A. J., & Watts, F. M. (2022). Students' strategies, struggles, and successes with mechanism problem solving in organic chemistry: a scoping review of the research literature. Journal of Chemical Education, 100(1), 53-68.

25. Crawford, J. M., Kingston, C., Toste, F. D., & Sigman, M. S. (2021). Data science meets physical organic chemistry. Accounts of chemical research, 54(16), 3136-3148.

26. Chauhan, D. S., Verma, C., & Quraishi, M. A. (2021). Molecular structural aspects of organic corrosion inhibitors: Experimental and computational insights. Journal of Molecular Structure, 1227, 129374.

27. Džodić, J., Milenković, D., Marković, M., Marković, Z., & Dimić, D. (2023). Application of quantum–chemical methods in the forensic prediction of psychedelic drugs' spectra (IR, NMR, UV–VIS, and MS): a case study of LSD and its analogs. Applied Sciences, 13(5), 2984.

28. Pesek, M., Juvan, A., Jakoš, J., Košmrlj, J., Marolt, M., & Gazvoda, M. (2020). Database independent automated structure elucidation of organic molecules based on IR, 1H NMR, 13C NMR, and MS data. Journal of chemical information and modeling, 61(2), 756-763.

29. Morgante, P., & Peverati, R. (2020). The devil in the details: A tutorial review on some undervalued aspects of density functional theory calculations. International Journal of Quantum Chemistry, 120(18), e26332.

30. Devarajan, D., Liang, L., Gu, B., Brooks, S. C., Parks, J. M., & Smith, J. C. (2020). Molecular dynamics simulation of the structures, dynamics, and aggregation of dissolved organic matter. Environmental Science & Technology, 54(21), 13527-13537.

31. Grygorenko, O. O., Volochnyuk, D. M., Ryabukhin, S. V., & Judd, D. B. (2020). The symbiotic relationship between drug discovery and organic chemistry. Chemistry–A European Journal, 26(6), 1196-1237.

32. Yang, Z., Stivanin, M. L., Jurberg, I. D., & Koenigs, R. M. (2020). Visible light-promoted reactions with diazo compounds: a mild and practical strategy towards free carbene intermediates. Chemical Society Reviews, 49(19), 6833-6847.

33. Kumar, V., Bansal, V., Madhavan, A., Kumar, M., Sindhu, R., Awasthi, M. K., ... & Saran, S. (2022). Active pharmaceutical ingredient (API) chemicals: a critical review of current biotechnological approaches. Bioengineered, 13(2), 4309-4327.

34. Romio, M., Trachsel, L., Morgese, G., Ramakrishna, S. N., Spencer, N. D., & Benetti, E. M. (2020). Topological polymer chemistry enters materials science: expanding the applicability of cyclic polymers. ACS Macro Letters, 9(7), 1024-1033.

35. Zuin, V. G., Eilks, I., Elschami, M., & Kümmerer, K. (2021). Education in green chemistry and in sustainable chemistry: perspectives towards sustainability. Green Chemistry, 23(4), 1594-1608.

36. Leech, M. C., Garcia, A. D., Petti, A., Dobbs, A. P., & Lam, K. (2020). Organic electrosynthesis: from academia to industry. Reaction chemistry & engineering, 5(6), 977-990.