

Indexing and Abstracting in Following Database

Crossref



Published by
AkiNik Publications,
#169, C-11, Sector - 3, Rohini,
Delhi-110085, India
Toll Free (India): 18001234070



Attribution-NonCommercial-ShareAlike
4.0 International (CC BY-NC-SA 4.0)

Peer Reviewed & Refereed

Modern Trends in **CHEMICAL SCIENCES**

Chief Editor
Dr. Milan Hait

Co-editor
Dr. Gourisankar Roymahapatra
Dr. Utpal Jana

Volume - 7

AKINIK
PUBLICATIONS



AkiNik Publications

Printing Press License No.: F.1 (A-4) press 2016

Publication Certificate

Ref. No.: MTCS-07-0403

Date: 26-07-2025

To,
Dear Sable Yuvraj R

This certificate confirms that **Sable Yuvraj R** is the author of book chapter titled "**Eco-Friendly Synthetic Routes and Catalytic Systems**" of published book entitled "**Modern Trends in Chemical Sciences (Volume - 7)**" having ISBN **978-93-7150-848-3**.

Yours Sincerely,



Brij Mohan Gupta
Manager
AkiNik Publications

Modern Trends in CHEMICAL SCIENCES

Volume - 7

Chief Editor

Dr. Milan Hait

Associate Professor, Department of Chemistry, Dr. C.V. Raman University,
Kargi Road, Kota, Bilaspur, Chhattisgarh, India

Co-Editor

Dr. Gourisankar Roymahapatra

Associate Professor of Chemistry, Department of Applied Sciences, Haldia
Institute of Technology (Autonomous), ICARE Complex, Haldia, West
Bengal, India

Dr. Utpal Jana

Professor and HOD, Department of Pharmaceutics, Anand College of
Education, Kabilpur, Debra, Paschim Medinipur, West Bengal, India

AkiNik Publications®
New Delhi

Published By: AkiNik Publications

AkiNik Publications

169, C-11, Sector - 3,

Rohini, Delhi-110085, India

Toll Free (India) – 18001234070

Phone No.: 9711224068, 9911215212

Website: www.akinik.com

Email: akinikbooks@gmail.com

Chief Editor: Dr. Milan Hait

Co-Editor: Dr. Gourisankar Roymahapatra and Dr. Utpal Jana

The author/publisher has attempted to trace and acknowledge the materials reproduced in this publication and apologize if permission and acknowledgements to publish in this form have not been given. If any material has not been acknowledged please write and let us know so that we may rectify it.

The responsibility for facts stated, opinion expressed or conclusions reached and plagiarism, if any, in this book is entirely that of the author. So, the views and research findings provided in this publication are those of the author/s only. The Editor & Publishers are in no way responsible for its contents.

© AkiNik Publications™

Publication Year: 2025

Pages: 107

Paperback ISBN: 978-93-7150-848-3

E-Book ISBN: 978-93-7150-034-0

Book DOI: <https://doi.org/10.22271/ed.book.3356>

Price: ₹ 717/-

Registration Details

➤ Printing Press License No.: F.1 (A-4) press 2016

➤ Trade Mark Registered Under

- Class 16 (Regd. No.: 5070429)
- Class 35 (Regd. No.: 5070426)
- Class 41 (Regd. No.: 5070427)
- Class 42 (Regd. No.: 5070428)

Contents

Chapters	Page No.
1. Pharmaceutical Chemistry: Principles, Processes and Perspectives <i>(Monika Yadav, Pradeep Kumar and Raj Luxmi)</i>	01-13
2. Reaction Mechanisms: Unraveling Pathways in Organic Chemistry <i>(Monika Yadav, Aman Kumar and Pradeep Kumar)</i>	15-26
3. Spinel Phase Mixed-Metal Oxides: An Efficient Catalyst <i>(Umesh Sankpal)</i>	27-35
4. Eco-Friendly Synthetic Routes and Catalytic Systems <i>(Kamble Prashant D, Salunkhe Suraj S, Sable Yuvraj R and Patil Priyanka T)</i>	37-53
5. The Chemical Basis of Life <i>(Monika Yadav, Sweety and Raj Luxmi)</i>	55-67
6. Structure-Activity Relationship (SAR) and its Role in Drug Design <i>(Monika Yadav, Sweety and Raj Luxmi)</i>	69-84
7. Silica Nanoparticles in Medicine: A Comprehensive Review of their Diagnostic and Therapeutic Potential <i>(Ankita L. Chaudhary)</i>	85-106

Chapter - 4

Eco-Friendly Synthetic Routes and Catalytic Systems

Kamble Prashant D, Salunkhe Suraj S, Sable Yuvraj R and Patil Priyanka T

Abstract

The escalating environmental challenges and the urgent need for sustainable development have compelled the scientific community to re-evaluate traditional chemical synthesis pathways. Conventional methods often involve hazardous reagents, toxic solvents, and energy-intensive conditions, leading to significant ecological and health impacts. In response, the field of green chemistry has emerged as a transformative approach to designing safer, cleaner, and more efficient chemical processes. This chapter delves into eco-friendly synthetic routes and catalytic systems that adhere to the core principles of green chemistry. It emphasizes innovations aimed at minimizing waste, reducing energy consumption, and eliminating toxic by-products. Particular attention is given to the development and application of environmentally benign catalysts, including biocatalysts, organocatalysts, and heterogeneous systems, which enable selective transformations under mild conditions. Additionally, the use of alternative reaction media such as water, ionic liquids, and supercritical fluids is explored for their role in replacing conventional organic solvents. Energy-efficient methodologies such as microwave-assisted synthesis, mechanochemistry, and flow chemistry are also discussed for their potential to revolutionize chemical manufacturing. By integrating sustainable practices with cutting-edge research, this chapter offers insights into the future of eco-conscious chemical synthesis and underscores the importance of catalysis in achieving green, scalable, and economically viable solutions.

Keywords: Green chemistry, sustainable synthesis, eco-friendly catalysis, MCRs, Microwave-assisted synthesis, mechanochemistry, flow chemistry, biocatalysts

1. Introduction

The growing global concern over environmental degradation, resource depletion, and the impact of industrial pollution has led to an urgent call for

more sustainable and eco-conscious approaches across all scientific disciplines ^[1]. Within the field of chemistry, this has given rise to a transformative discipline known as green chemistry ^[2]. Recognized as a fundamental scientific approach, green chemistry emphasizes the design, development, and implementation of chemical products and processes that reduce or eliminate the generation of hazardous substances ^[3, 4]. Traditional chemical synthesis methods, although effective in terms of yield and selectivity, often rely on toxic reagents, volatile organic solvents, and energy-intensive procedures. These practices not only pose serious health risks to humans and the environment but also contribute to air and water pollution, greenhouse gas emissions, and the generation of chemical waste. Additionally, the reliance on non-renewable petroleum-based resources in conventional chemical manufacturing raises concerns about long-term sustainability and the ethical responsibility of modern science to future generations ^[5-7]. In contrast, green chemistry advocates a holistic, preventative approach rather than one that simply manages waste after it has been created. It encourages chemists to consider the environmental impact of their work at every stage of the chemical lifecycle from raw material selection to final product disposal. By prioritizing safety, efficiency, and environmental stewardship, green chemistry aims to develop processes that are both economically viable and ecologically sound. Central to this movement are the Twelve Principles of Green Chemistry, formulated by Paul Anastas and John Warner. These principles serve as a comprehensive guideline for researchers and industries alike. They emphasize concepts such as atom economy (maximizing the incorporation of all materials used in the process into the final product), the use of less hazardous chemical syntheses, designing safer chemicals, and the adoption of renewable feedstocks. Moreover, green chemistry promotes energy efficiency, real-time monitoring to prevent pollution, and the use of catalysts rather than stoichiometric reagents to minimize waste ^[8-11].

Innovative technologies have played a crucial role in advancing the goals of green chemistry. For instance, microwave-assisted and ultrasound-assisted reactions reduce reaction times and energy consumption significantly ^[12]. Similarly, the development of water-based and solvent-free reactions helps eliminate the environmental hazards posed by conventional organic solvents. Catalysis, particularly using biocatalysts, heterogeneous systems, and metal-free organocatalysts, offers high selectivity and reusability, making reactions cleaner and more sustainable ^[13-15]. Another important aspect is the shift toward using renewable feedstocks such as

plant-derived materials or waste biomass instead of finite petrochemical sources. This not only reduces dependence on fossil fuels but also promotes circular economy models in chemical production.

2. Alternative reaction media

Solvents play a crucial role in chemical reactions, often serving as the medium in which reactants interact, but they also represent one of the largest sources of waste in chemical manufacturing and laboratory practices ^[16-17]. Traditional organic solvents, such as benzene, chloroform, and dichloromethane, are often volatile, flammable, toxic, and environmentally persistent, posing significant risks to both human health and ecosystems ^[18-19]. As a result, the search for greener, safer alternatives has become a priority within the scope of sustainable chemistry. One of the most promising eco-friendly solvents is water ^[20]. Due to its natural abundance, low cost, non-toxicity, and biodegradability, water is considered an ideal green solvent, especially in aqueous-phase reactions and enzymatic processes ^[21]. Reactions in water can offer improved selectivity and reaction rates due to hydrophobic effects and hydrogen bonding ^[22]. Another class of alternative solvents gaining attention is ionic liquids salts that are liquid at or near room temperature. These solvents are non-volatile, thermally stable, and highly tunable, allowing chemists to modify their properties for specific applications ^[23]. Their ability to dissolve a wide range of compounds, including inorganic and organic substances, makes them particularly valuable in catalysis and separation processes. Additionally, supercritical fluids, especially supercritical carbon dioxide (scCO₂), have emerged as sustainable solvents for extraction, chromatography, and certain types of organic reactions. Supercritical CO₂ is non-toxic, recyclable, and can be easily removed from the reaction mixture by depressurization, leaving no solvent residue ^[24-26]. It offers unique properties, combining the diffusivity of gases with the solvating power of liquids, enabling efficient mass transfer and reaction kinetics. Together, these alternative solvents not only reduce environmental hazards but also enhance reaction efficiency and selectivity, aligning with the principles of green chemistry. The continued development and adoption of such solvent systems are essential for advancing sustainable practices in both academic research and industrial chemical synthesis.

3. Green catalytic systems

3.1 Biocatalysts (Enzymes) ^[27-31]

Biocatalysts, particularly enzymes, are natural catalysts that facilitate a wide range of chemical transformations under mild conditions. Their

operation at ambient temperatures and pressures makes them energy-efficient and environmentally benign. Enzymes exhibit remarkable chemo-, regio-, and enantioselectivity, which are crucial for the synthesis of complex organic molecules, especially in the pharmaceutical and fine chemical industries. They function in aqueous environments, which reduces the need for harmful organic solvents. Furthermore, enzymes are biodegradable and can be produced from renewable resources, adding to their sustainability. Advances in protein engineering and immobilization techniques have further expanded their utility, enhancing their stability, substrate range, and reusability.

3.2 Heterogeneous catalysts ^[32-34]

Heterogeneous catalysts exist in a different phase than the reactants, usually as solids in liquid or gas-phase reactions. Their key advantage lies in their ease of separation from the reaction mixture, which allows for catalyst recovery and reuse. This reduces both cost and waste generation. These catalysts are widely used in large-scale industrial processes such as hydrogenation, oxidation, and catalytic reforming. Their robustness, stability under harsh conditions, and adaptability to continuous flow systems make them ideal for sustainable chemical manufacturing. Moreover, supporting the active component on inert materials (e.g., alumina, silica) often enhances surface area and catalytic efficiency.

3.3 Organocatalysts ^[35-39]

Organocatalysts are small, metal-free organic molecules that can efficiently catalyze a variety of reactions. They offer significant environmental and safety advantages, as they eliminate the need for toxic or expensive transition metals. Organocatalysis has emerged as a powerful tool in asymmetric synthesis, providing high enantioselectivity critical for the production of chiral compounds in drug development. These catalysts often operate under solvent-free or aqueous conditions, aligning well with green chemistry principles. Additionally, organocatalysts are typically stable, easy to handle, and can be designed for a broad range of reactions including aldol, Mannich, and Michael additions.

3.4 Photocatalysis and Electrocatalysis ^[40-44]

Photocatalysis involves the use of light energy typically UV or visible light to activate a catalyst and drive chemical reactions. Common photocatalysts like titanium dioxide (TiO₂) absorb light to generate reactive electron-hole pairs that can participate in redox reactions. Photocatalysis is

particularly effective for environmental applications, including degradation of pollutants, water splitting for hydrogen production, and CO₂ reduction. Electrocatalysis, on the other hand, uses electrical energy to initiate or accelerate chemical reactions. It is fundamental to technologies such as water electrolysis (for hydrogen fuel generation), fuel cells, and electrochemical CO₂ conversion. Electrocatalytic systems often use renewable electricity sources, offering a clean and controllable route for sustainable chemical transformations. Both techniques support ambient condition reactions and minimize the need for harmful chemicals or extreme processing parameters, contributing significantly to green and sustainable chemistry initiatives.

4. Sustainable synthetic methodologies

4.1 Multicomponent Reactions (MCRs) ^[45-47]

Multicomponent reactions (MCRs) are powerful synthetic strategies in which three or more reactants combine in a single reaction vessel to form a product that incorporates substantial portions of each starting material. This one-pot methodology offers significant advantages in terms of atom economy, step-efficiency, and waste reduction. Unlike traditional stepwise synthesis, MCRs reduce the number of purification steps and eliminate the need for intermediate isolation, saving time, energy, and resources. These reactions are particularly valuable in the synthesis of complex organic molecules, pharmaceuticals, and natural product analogs. The simplicity of MCRs also lends itself to automation and high-throughput screening. Common examples include the Ugi and Biginelli reactions, which allow the rapid construction of diverse molecular scaffolds. MCRs exemplify the green chemistry principle of maximizing resource utilization while minimizing environmental impact. As a result, they have become an essential tool for sustainable and economically viable synthetic chemistry.

4.2 Microwave-assisted synthesis ^[48-50]

Microwave-assisted synthesis is an innovative approach that utilizes microwave irradiation to heat reaction mixtures, offering faster reaction rates and higher yields compared to conventional heating methods. This technique significantly reduces reaction time often from hours to minutes and lowers energy consumption, aligning well with the principles of green chemistry. The efficiency stems from the direct interaction of microwaves with polar molecules and solvents, which leads to rapid, uniform heating and improved control over reaction conditions. Additionally, microwave-assisted synthesis can enhance reaction selectivity and minimize the formation of by-products.

It is particularly useful in organic synthesis, pharmaceutical research, and material science, enabling the efficient formation of heterocycles, peptides, and nanoparticles. Reactions that once required refluxing for extended periods can now be completed in a fraction of the time. By improving both operational efficiency and sustainability, microwave-assisted synthesis is now widely adopted in both academic and industrial laboratories as a green synthetic tool.

4.3 Mechanochemistry ^[51-53]

Mechanochemistry involves performing chemical reactions through the application of mechanical force, typically using ball mills or grinders, rather than traditional solvents or heat. This solvent-free approach drastically reduces the environmental footprint of chemical processes by eliminating hazardous organic solvents and lowering energy inputs. The process relies on grinding solid reactants together to promote chemical transformations, often leading to products with high purity and excellent yields. Mechanochemical techniques are particularly advantageous for solid-state reactions, cocrystal formation, and the synthesis of coordination compounds and metal-organic frameworks (MOFs). Moreover, mechanochemistry can sometimes enable novel reactivity not accessible in solution-based chemistry. It supports green chemistry by enhancing safety, improving atom economy, and reducing waste. As mechanochemical protocols continue to evolve, they offer scalable and sustainable alternatives to classical synthesis, suitable for both small-scale research and industrial applications. Mechanochemistry is rapidly gaining recognition as a frontier in green and innovative chemical synthesis.

4.4 Flow chemistry ^[54-56]

Flow chemistry, or continuous flow synthesis, involves conducting chemical reactions in a continuously flowing stream rather than in traditional batch reactors. This method provides several advantages, including enhanced safety, improved scalability, and precise control over reaction parameters such as temperature, pressure, and mixing. In flow systems, reagents are pumped through microreactors or tubular setups, allowing for efficient heat transfer and minimized risk of hazardous conditions, especially when handling reactive intermediates or exothermic reactions. The compact design of flow reactors enables rapid optimization and integration with real-time monitoring tools. Additionally, the consistent and reproducible conditions in flow chemistry lead to higher product consistency and reduced waste. This

technique is ideal for pharmaceutical manufacturing, fine chemicals, and nanoparticle synthesis. As industries move toward greener production methods, flow chemistry stands out as a transformative technology, supporting continuous processing, automation, and the principles of green chemistry for cleaner, safer, and more sustainable chemical production.

5. Challenges and Future directions

Despite remarkable advancements in the development and application of green chemistry principles, several critical challenges continue to hinder the widespread adoption of eco-friendly synthetic methods across industrial and academic settings ^[57]. One of the primary concerns is the economic feasibility of green technologies ^[58]. Many sustainable processes, such as the use of biocatalysts or advanced catalytic systems, often require expensive raw materials, complex preparation techniques, or specialized equipment, making them less attractive to industries focused on cost-efficiency ^[59]. Moreover, the scalability of green methodologies remains a significant barrier. While many eco-friendly processes show excellent results at the laboratory scale, translating these methods to large-scale production often exposes limitations in terms of reaction efficiency, product yield, and operational stability ^[60]. For instance, biocatalysts that perform well under controlled lab conditions may lose activity or selectivity in industrial reactors due to fluctuations in temperature, pH, or pressure. Another pressing issue is the integration of green chemistry into existing industrial infrastructures, which are predominantly built around conventional petrochemical processes ^[61]. Retrofitting plants to accommodate new solvent systems, catalytic pathways or continuous flow technologies involves considerable investment, training, and regulatory adjustments.

Additionally, the lack of universal green catalysts those that are broadly applicable across different types of reactions, substrates, and conditions limits the versatility of sustainable chemistry ^[62]. Research efforts should be directed toward designing robust, reusable, and cost-effective catalysts that combine high activity with low environmental impact. There is also an urgent need to develop alternative solvent systems that can replace volatile organic compounds while maintaining reaction efficiency, product purity, and ease of separation. Water, ionic liquids, and supercritical fluids show promise but often come with challenges related to compatibility, cost, or environmental persistence. Equally important is the adoption of comprehensive lifecycle assessments (LCAs) for chemical processes. LCAs evaluate the total environmental impact of a chemical product or process

from raw material extraction through production, use, and disposal providing a holistic view that can guide more informed and sustainable decisions. Currently, LCAs are underutilized due to their complexity, data requirements, and the absence of standardized methodologies across sectors. To truly embed sustainability in chemical sciences, it is imperative that future research also emphasizes interdisciplinary collaboration among chemists, engineers, environmental scientists, and policymakers ^[63]. Educational reforms that integrate green chemistry concepts into curricula will play a crucial role in cultivating a new generation of scientists equipped with the skills and mindset necessary for sustainable innovation ^[64]. Regulatory frameworks and government incentives can further accelerate the transition by encouraging industries to adopt cleaner technologies and invest in green research and development. Ultimately, while the journey toward fully sustainable chemical synthesis is complex and multifaceted, ongoing scientific innovation, combined with policy support and public awareness, can pave the way for a cleaner, safer, and more responsible chemical industry.

6. Conclusion

Eco-friendly synthetic routes and catalytic systems represent a transformative approach in chemical science, offering innovative solutions that align with the goals of environmental sustainability. These green methodologies aim to reduce the reliance on toxic reagents, hazardous solvents, and energy-intensive processes by promoting safer, cleaner, and more efficient alternatives. Techniques such as multicomponent reactions, microwave-assisted synthesis, mechanochemistry, and flow chemistry have demonstrated the potential to enhance reaction efficiency while minimizing waste and resource consumption. Catalysts whether enzymatic, heterogeneous, organocatalytic, or based on photocatalysis and electrocatalysis play a pivotal role in achieving selectivity and reducing environmental impact by lowering activation energies and enabling reactions under milder conditions. By adhering to the twelve principles of green chemistry, eco-friendly synthesis fosters a shift toward sustainable industrial practices. This not only benefits the environment through reduced emissions and waste but also enhances economic feasibility by improving atom economy and process efficiency. Moreover, the integration of life cycle assessments ensures that environmental impact is evaluated holistically. As the global community seeks to address pressing issues like climate change and resource depletion, green synthetic and catalytic approaches offer a

scientifically sound and ethically responsible pathway forward. Their continued development and implementation are essential for a more sustainable and resilient future in chemical manufacturing.

References

1. Wang J, Azam W. Natural resource scarcity, fossil fuel energy consumption and total greenhouse gas emissions in top emitting countries. *Geoscience Frontiers*. 2023;15(2):101757. <https://doi.org/10.1016/j.gsf.2023.101757>
2. Anastas PT, Beach ES. Green chemistry: the emergence of a transformative framework. *Green Chemistry Letters and Reviews*. 2007;1(1):9-24. <https://doi.org/10.1080/17518250701882441>
3. United States Environmental Protection Agency. Basics of green chemistry. US EPA; 2025. Available from: <https://www.epa.gov/greenchemistry/basics-green-chemistry>
4. Amoneit M, Weckowska D, Spahr S, *et al*. Green chemistry and responsible research and innovation: moving beyond the 12 principles. *Journal of Cleaner Production*. 2024;144011. <https://doi.org/10.1016/j.jclepro.2024.144011>
5. Nyabadza A, McCarthy É, Makhesana M, *et al*. A review of physical, chemical and biological synthesis methods of bimetallic nanoparticles and applications in sensing, water treatment, biomedicine, catalysis and hydrogen storage. *Advances in Colloid and Interface Science*. 2023;321:103010. <https://doi.org/10.1016/j.cis.2023.103010>
6. Kharissova OV, Kharisov BI, González CMO, *et al*. Greener synthesis of chemical compounds and materials. *Royal Society Open Science*. 2019;6(11):191378. <https://doi.org/10.1098/rsos.191378>
7. Pena-Pereira F, Kloskowski A, Namieśnik J. Perspectives on the replacement of harmful organic solvents in analytical methodologies: a framework toward the implementation of a generation of eco-friendly alternatives. *Green Chemistry*. 2015;17(7):3687-3705. <https://doi.org/10.1039/c5gc00611b>
8. Fegade SL. Red chemistry: principles and applications. *Next Sustainability*. 2024;4:100048. <https://doi.org/10.1016/j.nxsust.2024.100048>

9. American Chemical Society. 12 principles of green chemistry. Available from: <https://www.acs.org/green-chemistry-sustainability/principles/12-principles-of-green-chemistry.html>
10. Sigma-Aldrich. Green chemistry principles. Available from: <https://www.sigmaaldrich.com/IN/en/technical-documents/technical-article/analytical-chemistry/green-chemistry-principles>
11. De Marco BA, Rechelo BS, Tótolí EG, *et al.* Evolution of green chemistry and its multidimensional impacts: a review. Saudi Pharmaceutical Journal. 2018;27(1):1-8. <https://doi.org/10.1016/j.jsps.2018.07.011>
12. Majhi S, Manickam S, Cravotto G. Ultrasound-assisted green synthesis of functionalised xanthene derivatives: advancing sustainable sonochemical strategies. Ultrasonics Sonochemistry; 2025. p. 107367. <https://doi.org/10.1016/j.ultsonch.2025.107367>
13. Osman AI, Ayati A, Krivoshapkin P, *et al.* Coordination-driven innovations in low-energy catalytic processes: advancing sustainability in chemical production. Coordination Chemistry Reviews. 2024;514:215900. <https://doi.org/10.1016/j.ccr.2024.215900>
14. Meher AK, Zarouri A. Green analytical chemistry-recent innovations. Analytica. 2025;6(1):10. <https://doi.org/10.3390/analytica6010010>
15. Gawande MB, Shelke SN, Zboril R, Varma RS. Microwave-assisted chemistry: synthetic applications for rapid assembly of nanomaterials and organics; 2014.
16. Welton T. Solvents and sustainable chemistry. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences. 2015;471(2183):20150502. <https://doi.org/10.1098/rspa.2015.0502>
17. Taylor CJ, Pomberger A, Felton K, Grainger D, Barecka M, Chamberlain TW, *et al.* A brief introduction to chemical reaction optimization. Chemical Reviews. 2023. <https://pubs.acs.org/doi/10.1021/acs.chemrev.2c00798>
18. Kumar A, Devi D, Jothirmae J, Jyothi V, Kumar N, Venkatesh M. A review on green chemistry: a sustainable approach to chemical innovation. 2025.
19. Welton T. Solvents and sustainable chemistry. Proceedings of the Royal Society A. 2015;471:20150502. <https://doi.org/10.1098/rspa.2015.0502>

20. Zhou F, Hearne Z, Li C. Water-the greenest solvent overall. *Current Opinion in Green and Sustainable Chemistry*. 2019;18:118-123. <https://doi.org/10.1016/j.cogsc.2019.05.004>
21. Lajoie L, Fabiano-Tixier AS, Chemat F. Water as green solvent: methods of solubilisation and extraction of natural products-past, present and future solutions. *Pharmaceuticals (Basel)*. 2022;15(12):1507. <https://doi.org/10.3390/ph15121507>. PMID: 36558959; PMCID: PMC9788067
22. Yang B, Ren P, Xing L, Wang S, Sun C. Roles of hydrogen bonding interactions and hydrophobic effects on enhanced water structure in aqueous solutions of amphiphilic organic molecules. *Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy*. 2023;296:122605. <https://doi.org/10.1016/j.saa.2023.122605>
23. Sowbhagyam NDDV. Ionic liquids as green solvents: a comprehensive review. *Deleted Journal*. 2024;2(2):220-224. <https://doi.org/10.47392/irjaeh.2024.0035>
24. Wu T, Han B. Supercritical carbon dioxide (CO₂) as green solvent. In: *Green Chemistry and Chemical Engineering*. Springer; 2019. p. 173-197. https://doi.org/10.1007/978-1-4939-9060-3_391
25. Khaw K, Parat M, Shaw PN, Falconer JR. Supercritical fluid technologies to extract bioactive compounds from natural sources: a review. *Molecules*. 2017;22(7):1186. <https://doi.org/10.3390/molecules22071186>
26. Oakes RS, Clifford AA, Rayner CM. The use of supercritical fluids in synthetic organic chemistry. *Journal of the Chemical Society, Perkin Transactions 1*. 2001;(9):917-941. <https://doi.org/10.1039/b101219n>
27. Kuo C, Huang C, Shieh C, Dong C. Enzymes and biocatalysis. *Catalysts*. 2022;12(9):993. <https://doi.org/10.3390/catal12090993>
28. Cooper GM. The central role of enzymes as biological catalysts. In: *The Cell: A Molecular Approach*. NCBI Bookshelf; 2000. Available from: <https://www.ncbi.nlm.nih.gov/books/NBK9921/>
29. Reisenbauer JC, Sicinski KM, Arnold FH. Catalyzing the future: recent advances in chemical synthesis using enzymes. *Current Opinion in Chemical Biology*. 2024;83:102536. <https://doi.org/10.1016/j.cbpa.2024.102536>

30. Martin A, Solanki I, Haarr MB, O'Reilly E. Enzyme-triggered reactions for the synthesis of organic molecules. *European Journal of Organic Chemistry*, 2023, 2023(47). <https://doi.org/10.1002/ejoc.202300858>
31. Wu S, Snajdrova R, Moore JC, *et al.* Biocatalysis: enzymatic synthesis for industrial applications. *Angewandte Chemie International Edition*. 2020;60(1):88-119. <https://doi.org/10.1002/anie.202006648>
32. Libre Texts. 14.4: Heterogeneous catalysts. *Chemistry Libre Texts*; 2024 Jan. Available from: [https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Inorganic_Chemistry_\(LibreTexts\)/14%3A_Organometallic_Reactions_and_Catalysis/14.04%3A_Heterogeneous_Catalysts](https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Inorganic_Chemistry_(LibreTexts)/14%3A_Organometallic_Reactions_and_Catalysis/14.04%3A_Heterogeneous_Catalysts)
33. Klaewkla R, Arend M, Wasserscheid F. A review of mass transfer controlling the reaction rate in heterogeneous catalytic systems. In *Tech eBooks*; 2011. <https://doi.org/10.5772/22962>
34. Haufe LA, Timoshev V, Seifert M, Busse O, Weigand JJ. Crucial role of silica-alumina binder mixtures for hydrocarbon cracking with ZSM-5 additives. *ACS Omega*. 2022;7(49):44892-44902. <https://doi.org/10.1021/acsomega.2c05003>
35. Oliveira V, Cardoso M, Forezi L. Organocatalysis: a brief overview on its evolution and applications. *Catalysts*. 2018;8(12):605. <https://doi.org/10.3390/catal8120605>
36. Van Der Helm MP, Klemm B, Eelkema R. Organocatalysis in aqueous media. *Nature Reviews Chemistry*. 2019;3(8):491-508. <https://doi.org/10.1038/s41570-019-0116-0>
37. Yang F, Huang T, Lin Y, Gong L. Advancements in organocatalysis for radical-mediated asymmetric synthesis: a recent perspective. *Chem Catalysis*. 2023;4(4):100812. <https://doi.org/10.1016/j.checat.2023.100812>
38. Heravi MM, Asadi S. Recent applications of organocatalysts in asymmetric aldol reactions. *Tetrahedron: Asymmetry*. 2012;23(20-21):1431-1465. <https://doi.org/10.1016/j.tetasy.2012.10.002>
39. Viji M, Lanka S, Sim J, Jung C, *et al.* Regiodivergent organocatalytic reactions. *Catalysts*. 2021;11(8):1013. <https://doi.org/10.3390/catal11081013>

40. Mohamadpour F, Amani AM. Photocatalytic systems: reactions, mechanism, and applications. *RSC Advances*. 2024;14(29):20609-20645. <https://doi.org/10.1039/d4ra03259d>
41. Molinari R, Lavorato C, Argurio P. Visible-light photocatalysts and their perspectives for building photocatalytic membrane reactors for various liquid phase chemical conversions. *Catalysts*. 2020;10(11):1334. <https://doi.org/10.3390/catal10111334>
42. Pitre SP, Yoon TP, Scaiano JC. Titanium dioxide visible light photocatalysis: surface association enables photocatalysis with visible light irradiation. *Chemical Communications*. 2017;53(31):4335-4338. <https://doi.org/10.1039/c7cc01952a>
43. El-Shafie M. Hydrogen production by water electrolysis technologies: a review. *Results in Engineering*. 2023;20:101426. <https://doi.org/10.1016/j.rineng.2023.101426>
44. Kumar SS, Lim H. An overview of water electrolysis technologies for green hydrogen production. *Energy Reports*. 2022;8:13793-13813. <https://doi.org/10.1016/j.egy.2022.10.127>
45. Ganem B. Strategies for innovation in multicomponent reaction design. *Accounts of Chemical Research*. 2009;42(3):463-472. <https://doi.org/10.1021/ar800214s>
46. Ugi I. Recent progress in the chemistry of multicomponent reactions. *Pure and Applied Chemistry*. 2001;73(1):187-191. <https://doi.org/10.1351/pac200173010187>
47. Tokyo Chemical Industry Co., Ltd. Multicomponent reaction (MCR). Available from: <https://www.tcichemicals.com/OP/en/product/pick/multicomponent-reaction>
48. Li S, Ma H, Ouyang P, Li Y, Duan Y, *et al.* Advanced microwave synthesis strategies for innovative photocatalyst design. *Green Energy & Environment*; 2024. <https://doi.org/10.1016/j.gee.2024.11.005>
49. Gabano E, Ravera M. Microwave-assisted synthesis: can transition metal complexes take advantage of this “green” method? *Molecules*. 2022;27(13):4249. <https://doi.org/10.3390/molecules27134249>
50. Tiwari G, Khanna A, Mishra VK, Sagar R. Recent developments on microwave-assisted organic synthesis of nitrogen-and oxygen-

- containing preferred heterocyclic scaffolds. *RSC Advances*. 2023;13(47):32858-32892. <https://doi.org/10.1039/d3ra05986c>
51. Pagola S. Outstanding advantages, current drawbacks, and significant recent developments in mechanochemistry: a perspective view. *Crystals*. 2023;13(1):124. <https://doi.org/10.3390/cryst13010124>
52. Li S, Liu J, Wang ZL, Wei D. Mechano-driven chemical reactions. *Green Energy & Environment*; 2024. <https://doi.org/10.1016/j.gee.2024.08.001>
53. Harris KDM. How grinding evolves. *Nature Chemistry*. 2012;5(1):12-14. <https://doi.org/10.1038/nchem.1539>
54. De Souza JM, Galaverna R, De Souza AA, *et al.* Impact of continuous flow chemistry in the synthesis of natural products and active pharmaceutical ingredients. *Anais da Academia Brasileira de Ciências*. 2018;90(1(2)):1131-1174. <https://doi.org/10.1590/0001-3765201820170778>
55. Porta R, Benaglia M, Puglisi A. Flow chemistry: recent developments in the synthesis of pharmaceutical products. *Organic Process Research & Development*. 2015;20(1):2-25. <https://doi.org/10.1021/acs.oprd.5b00325>
56. Capaldo L, Wen Z, Noël T. A field guide to flow chemistry for synthetic organic chemists. *Chemical Science*. 2023;14(16):4230-4247. <https://doi.org/10.1039/d3sc00992k>
57. Kurul F, Doruk B, Topkaya SN. Principles of green chemistry: building a sustainable future. *Discover Chemistry*, 2025, 2(1). <https://doi.org/10.1007/s44371-025-00152-9>
58. Söderholm P. The green economy transition: the challenges of technological change for sustainability. *Sustainable Earth Reviews*, 2020, 3(1). <https://doi.org/10.1186/s42055-020-00029-y>
59. Sheldon RA, Woodley JM. Role of biocatalysis in sustainable chemistry. *Chemical Reviews*. 2017;118(2):801-838. <https://doi.org/10.1021/acs.chemrev.7b00203>
60. Abdullah A, Saraswat S, Talib F. Barriers and strategies for sustainable manufacturing implementation in SMEs: a hybrid fuzzy AHP-TOPSIS framework. *Sustainable Manufacturing and Service Economics*. 2023;2:100012. <https://doi.org/10.1016/j.smse.2023.100012>

61. Santi M, Sancineto L, Nascimento V, Azeredo JB, *et al.* Flow biocatalysis: a challenging alternative for the synthesis of APIs and natural compounds. *International Journal of Molecular Sciences*. 2021;22(3):990. <https://doi.org/10.3390/ijms22030990>
62. Rissman J, Bataille C, Masanet E, *et al.* Technologies and policies to decarbonize global industry: review and assessment of mitigation drivers through 2070. *Applied Energy*. 2020;266:114848. <https://doi.org/10.1016/j.apenergy.2020.114848>
63. Burgess A, Brennan D. Application of life cycle assessment to chemical processes. *Chemical Engineering Science*. 2001;56(8):2589-2604. [https://doi.org/10.1016/s0009-2509\(00\)00511-x](https://doi.org/10.1016/s0009-2509(00)00511-x)
64. Idul JJA, Jaculbe QMI, Lucine NS, *et al.* Green modules: integrating green and sustainable chemistry principles to secondary chemistry modules through process-oriented guided inquiry learning. *Journal of Chemical Education*; 2025. <https://doi.org/10.1021/acs.jchemed.4c01360>