Modern Approaches to Synthesis of Organic Materials: Green Chemistry, Recent Developments and Future Perspectives: *Review Article*

Krinal K Shrivastav[1*] ,Vishakha H Solanki [2] , Chirag G Makwana[1]

[1]. Department of Chemistry, Gokul Global University , Siddhpur, Dist. Patan,Gujarat ,India

[2].Department Of Chemistry, Hemchandracharya North Gujarat University, Patan -384265.Gujarat ,India

*Corresponding author: parmarkokila63@gmail.com

Abstract

In modern organic syntheses, a paradigm shift is taking place from the development of yield-oriented methodologies to process designs that, concurrently, consider resource efficiency, safety, energy consumption, waste avoidance and life cycle implications. The transition is driven by the conceptual principles of green chemistry and made possible by modern synthetic technologies including catalysis, organ catalysis, photo catalysis, electro synthesis, electro photocatalysis, biocatalysis, mechanochemistry, aqueous and micellar chemistry, deep eutectic solvents, microwave-assisted synthesis and continuous-flow processing. This study deals with current advances in sustainable organic syntheses. It reports advancements in the years 2024-2026. Emphasis is placed on solvent choice, catalytic efficiency, renewable feedstocks, one-pot and multicomponent reactions, energy-efficient activation, C–C and C-heteroatom bond formation, and emerging hybrid platforms based on light, electricity, enzymes, and heterogeneous catalysts. The study also covers quantitative green chemistry measures including atom economy, E-factor, process mass intensity, reaction mass efficiency, energy intensity, and life-cycle evaluation and stresses that a high chemical yield alone is not enough to prove sustainability. Recent breakthroughs point to the most promising future approach as not a single “green” technology but an integrated process design that considers reaction development, separation, solvent recovery, catalyst recycling, feedstock selection, and scale-up concurrently. Artificial intelligence, high-throughput experimentation, continuous manufacturing and data-driven life-cycle evaluation are anticipated to speed the development and implementation of safer and more resource-efficient synthetic pathways. Other problems to be addressed include scalability, catalyst durability, solvent recovery,

© The Author(s) 2026
P. Bagchi et al. (eds.), *Proceedings of the International Conference on Information Systems Design And Intelligent Applications (ICISDA 2026)*, Advances in Intelligent Systems Research 215,
https://doi.org/10.2991/978-94-6239-821-4_13

repeatability, standardization of sustainability criteria, and the compromise between laboratory performance and industrial practicality.

Keywords: green chemistry; sustainable organic synthesis; catalysis; photocatalysis; electrosynthesis; electrophotocatalysis; biocatalysis; mechanochemistry; green solvents; flow chemistry; multicomponent reactions; life-cycle assessment; artificial intelligence

1. Introduction

The basis for medicines, agrochemicals, polymers, dyes, electronic materials, perfumes and many innovative functional materials is organic production [1]. Conventional synthesis provides access to vast molecular diversity but many established routes are associated with excess reagents, volatile or hazardous solvents, protecting group operations, stoichiometric oxidants and reductants, energy intensive heating or cooling and repeated chromatographic purification [2]. The ensuing environmental impact is of particular importance at process scale, when solvent consumption and downstream separations might dominate the mass and energy footprint of a synthesis [3]. Recent critical reviews point out that sustainable synthesis must thus go beyond reaction yield, and must encompass waste control, cleaner solvents, choice of catalyst, origin of resources, isolation of the product and end-of-life concerns [4-5].

Green chemistry, codified in the twelve principles of Anastas and Warner, tries to avoid pollution at the molecular and process-design level rather than to remediate waste after it is created [6]. In current organic syntheses, these concepts are progressively being realized via catalytic vs stoichiometric transformations, enhanced atom economy, renewable feedstocks, solvent reduction, benign reaction media, energy efficient activation and real-time process control. A study by Springer Nature in 2025 showed that green chemistry has progressed from a collection of conceptual ideas to a multidisciplinary approach that combines synthesis, analytical chemistry, nanotechnology, industrial practice, and sustainable development [7-10].

The period 2024-2026 has been very fruitful. Reviews and perspectives have covered aqueous micellar chemistry, metal-free and bio-based methods, microwave-assisted synthesis, mechanochemistry, standard synthesis, electrophotocatalysis, deep eutectic solvents, multicomponent reactions, continuous flow chemistry, and AI-assisted route design [11-14]. The purpose of this study is to synthesize these achievements into a consistent scheme for contemporary synthesis of organic materials and to suggest research areas that are likely to impact sustainable chemical manufacture in the coming decade [15,16].

2. Green Chemistry as a Design Tool for Natural Synthesis

Green chemistry is best understood as a design technique rather than a list of ecologically desirable chemicals. The key concern is not whether an individual reagent or solvent is branded "green," but if the whole process decreases danger, resource consumption and waste while maintaining the function that is needed [17-19]. The most significant concepts for synthesis of organic compounds are avoidance of waste, atom economy, less hazardous synthesis, cleaner solvents and auxiliaries, energy efficiency, use of renewable feedstocks, catalysis, design for degradation and real-time analysis [20-23].

This design approach is crucial because apparent advantages at the response level might be nullified by downstream activities [24]. For instance, the use of water as solvent for an organic reaction does not inevitably lead to a sustainable method if substantial amounts of organic solvent are then needed for extraction and chromatography [25,26]. This challenge is explicitly addressed in recent work on aqueous micellar catalysis, where surfactant enabled nanoreactors are used to improve the organic-substrate compatibility with water and in certain circumstances to facilitate the separation [27].

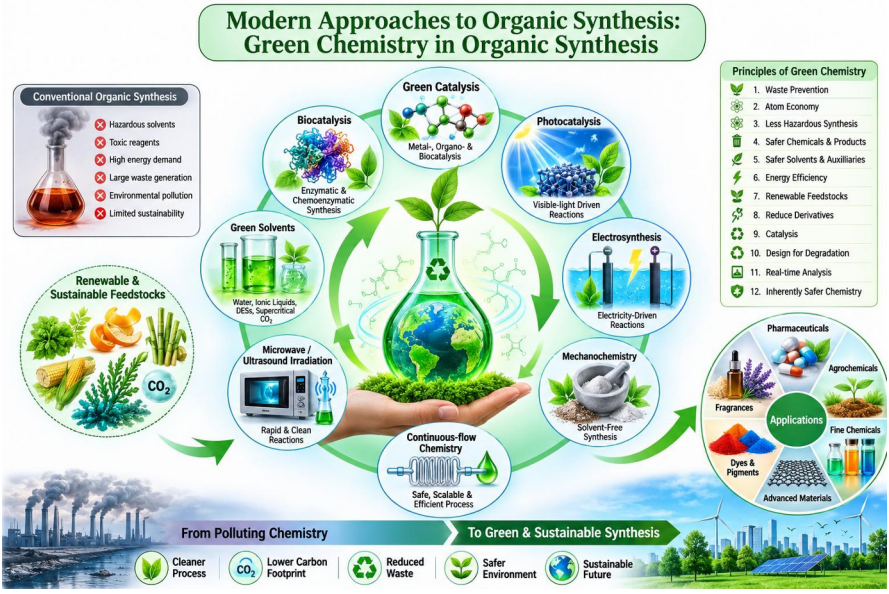


Figure 1. Current trends for green and sustainable organic syntheses.

Figure 1. Green and sustainable ways in synthesis using organic materials. The schematic depicts the transition from classical organic chemical synthesis to sustainability by applying

renewable feedstocks, green solvents, catalysis, photocatalysis, electrosynthesis, biocatalysis, mechanochemistry, microwave-assisted synthesis, continuous-flow chemistry and efficient reaction design [28].

2.1 Quantitative metrics of sustainable synthesis

A rigorous examination of synthetic methods should decouple chemical performance from environmental performance. Common measures include atom economy (AE), reaction mass efficiency (RME), E-factor, process mass intensity (PMI), solvent intensity, energy intensity, carbon footprint, and life-cycle assessment (LCA)[29,30]. Atom Economy is a measure of the theoretical integration of reactant atoms into the intended product and PMI is a measure of the total mass of materials utilized per mass of product. The E-factor is directly tied to the development of trash. These measurements might lead to varied ranks, hence numerous indications are better than a single score [31].

This is notably useful for industrial translation of PMI and solvent intensity, since isolation and purification are often the dominating factors in total material consumption. LCA takes this limit one step further by including raw material extraction, production, transportation, energy generation, process operation and disposal [32,33]. Thus a process that rates well on a laboratory green-chemistry metric might be poor at scale, if it relies on rare catalysts, hard-to-recycle solvents or energy-intensive equipment [34].

Table 1. Selected green chemistry metrics applicable to organic chemical synthesis

Metric	Meaning	Main limitation
Atom economy	Fraction of reactant atoms theoretically incorporated into product.	Does not include solvent, work-up or energy burden [35].
E-factor	Mass of waste generated per mass of product.	Definition of waste and process boundary can vary [36].
Process mass intensity	Total mass of inputs divided by mass of product.	Can be sensitive to reporting boundaries [37].
Reaction mass efficiency	Product mass relative to stoichiometric reactant mass.	Often excludes solvents and auxiliary operations [38].
Energy intensity	Energy required per amount of product.	Requires consistent process and energy boundaries [39].
Life-cycle assessment	Environmental impacts across the full value chain.	Data-intensive and dependent on assumptions [40].

3 Catalysis and Selective Bond Formation

Catalysis is still the most generally potent tool to reduce waste and improve selectivity. The field of modern catalysis has evolved from precious-metal cross-coupling to earth-abundant metals, organocatalysts, heterogeneous catalysts, single-atom catalysts, photocatalysts, electrocatalysts and enzyme-based systems. The biggest sustainability benefit is achieved when the catalytic turnover is high, the catalyst loading is low, the selectivity is high, and the catalyst is either recoverable or consists of plentiful, low-toxicity materials [41,42]. Recent systematic study suggests that heterogeneous catalysts and supported nanocatalysts can provide excellent activity and reusability, while biocatalysts frequently offer exceptional selectivity [43]. However, catalyst recovery should not be considered to be benign: nanoparticle preparation, support synthesis, metal procurement and even regeneration might bring hidden consequences. Therefore, the catalyst selection should evaluate combined activity, selectivity, longevity, critical-element dependency, toxicity, recovery and end-of-life treatment [44].

3.1 Transition Metal and Earth Abundant Catalysis

Transition-metal catalysis still cannot do without the production of C–C and C–heteroatom bonds. Suzuki, Heck, Negishi, Buchwald-Hartwig and similar coupling methods have revolutionized synthetic planning by diminishing the necessity of severe stoichiometric conversions. Current trends include reduced catalyst loading, simpler ligands, aqueous or bio-derived solvent systems, immobilized catalysts and substitution of rare metals by Fe, Co, Ni, Cu and Mn when possible [45,46]. Sustainable catalyst design involves the reduction of metal contamination in pharmaceutical products and the development of recovery systems that do not produce secondary waste.

Recent work on sustained C–C and C–heteroatom bond formation emphasizes the confluence of transition-metal catalysis with photocatalysis, organocatalysis and late-stage functionalization [47]. These techniques may reduce synthetic sequences and enhance molecular complexity per operation, yet wide substrate scope, repeatability, catalyst lifetime and scale-up are still critical issues.

3.2 Organocatalysis

Organocatalysis is the use of small organic molecules, such as amines, N-heterocyclic carbenes, phosphines, Brønsted acids, hydrogen-bond donors and amino-acid-derived catalysts, to promote transformations in the absence of metals. Its green potential relies on metal avoidance, ease of operation and compatibility with mild surroundings. Organocatalytic asymmetric reactions are of particular interest because good stereoselectivity may avoid the need for resolution or repeated purification. Challenges include particularly high catalyst loading for certain processes, catalyst recovery and environmental effect of catalyst manufacture itself [48-50].

4 Visible Light Photocatalysis for Organic Chemistry

Photocatalysis has emerged as a prominent platform for contemporary synthesis, since photons may induce single-electron and energy transfer processes that are difficult to perform thermally. Photocatalysis using visible light has enabled the formation of radicals under relatively moderate circumstances and has enlarged the scope of C–H functionalization, reductive coupling, oxidative coupling, cyclization, defluorination and late-stage functionalization. The green benefit is greatest when light is delivered effectively,

photocatalyst loading is modest and the process avoids harmful stoichiometric oxidants or reductants [51].

Key sustainability concerns remain. Photocatalytic processes may need dilute circumstances, specific LEDs, sacrificial reagents and photocatalysts using rare metals. Hence, the term "photocatalytic" should not be automatically linked with "green." In particular, current research is mostly devoted to organic photocatalysts, heterogeneous semiconductors, earth-abundant sensitizers, direct excitation, solar-light operation and flow photochemistry to maximize the usage of photons and scale-up [52].

5 Electrosynthesis and Electro-Photocatalysis

Electrosynthesis substitutes traditional stoichiometric redox reagents with electrons provided at an electrode. Electrochemical synthesis allows for tuning the applied voltage to access selected oxidation and reduction pathways while generating minimal reagent-derived waste. Recent studies have highlighted the advances in modern electro-organic production including electrode materials, electrolytes, reaction media, reactor design, micellar catalysis and scalability [53].

Electrophotocatalysis is a combination of photochemical stimulation and electrochemical control. This hybrid strategy may synthesize highly reactive open-shell intermediates under circumstances that are difficult to achieve by either method alone. In 2024 an article in Chemical Reviews classified electrophotocatalytic reactions into oxidative, reductive and redox neutral classes, and emphasized applications in C–H functionalization, reductive cross-coupling and olefin addition [54]. The approach has been more recently expanded to flow electrophotocatalysis and heterogeneous photoelectrochemical systems [55].

These approaches are especially interesting for future sustainable manufacturing, since power may be produced from renewable sources. But the sustainability is depending on the power mix, the lifespan of the electrodes, the recovery of the electrolyte, the reactor efficiency and the isolation of the product. Another substantial material cost might arise from the need of supporting electrolytes, spurring research toward electrolyte-free or mediator-minimized systems [56].

6 Biocatalysis and Photobiocatalysis

Biocatalysis delivers an excellent mix of selectivity and gentle working conditions. Enzymes catalyze oxidation, reduction, hydrolysis, acylation, amination and carbon-carbon bond

formation processes with strong chemo-, regio- and stereoselectivity. This may result in the minimization of protecting-group procedures and the elimination of metal-based catalysts. Enzyme engineering, immobilization, cofactor recycling, whole-cell catalysis and integration with non-biological catalytic modes have been the focus of recent effort [57].

An important trend that is developing is the combination of hydrolase biocatalysis with chemo-, electro- and photocatalysis. Such hybrid systems may use the selectivity of enzymes and the wide reactivity of synthetic catalysts in cascade reactions that would otherwise need numerous independent stages [58]. Photobiocatalysis also progressed fast, taking use of excited-state enzymes, external photocatalysts or hybrid enzyme-photocatalyst systems to achieve new-to-nature reactions [59].

The main issues are enzyme stability, substrate loading, cofactor cost, mass transfer, downstream isolation and process robustness. Immobilized enzymes and continuous-flow biocatalysis are attractive options, especially when the catalyst lifespan and recovery can be proved across numerous cycles [60].

7 Alternative reaction media and green solvent

Solvents often provide the biggest material contribution to an organic process. Thus, solvent selection is one of the most important considerations in green synthesis. Safer alternatives to very toxic conventional media may include water, ethanol, 2-methyltetrahydrofuran, ethyl acetate, ethanol/ethyl acetate combinations, propylene carbonate, dimethyl carbonate and certain bio-derived solvents. However, the solvent choice should be based on the whole process, including production, toxicity, flammability, recovery, purification and end of life [61].

7.1 Aqueous and micellar chemistry

Water is cheap and nonflammable and is accessible everyplace; yet, many organic substrates are poorly soluble in water. Surfactant-based micellar catalysis overcomes this barrier by offering nanoscopic hydrophobic environments in water. Recent work has showed that micellar systems may facilitate effective coupling and medicinal conversions and minimize the demand for traditional organic reaction solvents [62]. The final difficulty is to avoid merely shifting the solvent load on extraction and purification procedures.

7.2 Deep eutectic solvents

Deep eutectic solvents (DESs) are mixes of components that display a substantial melting-point depression, generally via hydrogen-bonding or Lewis/Brønsted acid–base interactions. They may be made from reasonably available components and can operate as both solvent and catalyst. A study in 2025 pointed out their tunability and promise in condensation, oxidation, esterification, carbon−carbon bond formation, multicomponent processes, biocatalysis and electrocatalysis [63]. Important constraints include high viscosity, water sensitivity, limited toxicological data for certain formulations, and problems with recycling and product separation.

Thus, DESs cannot be seen as intrinsically green but should be analyzed on a case-by-case basis. Report on the biodegradability and toxicity of each component, preparation energy, persistence, water demand and recovery approach.

8 Solvent-Free Synthesis and Mechanochemistry

Mechanochemistry is the application of mechanical energy, most often by grinding or ball milling, to drive reactions in the absence or with little bulk solvent. It may increase mass transfer, activate unreactive substances, lower reaction volumes and lead to transformations at relatively moderate temperatures. Recent studies highlight its suitability in one-pot multistep synthesis, heterocycle generation, functional-group interconversion and synthesis of active medicinal ingredients [64,65].

One-pot mechanochemical sequences are very desirable since they may avoid intermediary separation, solvent exchange and repetitive purification. In 2025, a study revealed an increased usage of successive one-pot mechanochemical techniques in multistep organic syntheses [66]. However, scale-up has to be considered carefully in terms of grinding energy, heat generated, equipment throughput, wear, mixing and repeatability. The environmental performance should be evaluated to improved solution operations, not inefficient legacy methods.

9 Microwave and Ultrasound Assisted Synthesis of Organic Materials

Microwave irradiation may speed up polar processes by fast volumetric heating, sometimes cutting reaction time and enhancing selectivity. Ultrasound may enhance mass transfer and cavitation-assisted activation. Recent studies on green synthesis have identified microwave-assisted, ultrasound-assisted and other enhanced approaches as viable solutions to reduce reaction time and energy consumption [67]. Their sustainability benefit relies on the efficiency of the equipment, and if the reduced response time translates into lower overall energy usage. Continuous microwave systems and flow reactors provide enhanced temperature control compared to traditional batch equipment for scale-up.

10 One-pot strategies and multi-component reactions

Multicomponent reactions (MCRs) synthesize complicated compounds from three or more building units in a one-pot procedure. The Biginelli, Ugi, Passerini, Mannich, Hantzsch, Petasis and Groebke–Blackburn–Bienaymé reactions are particularly significant to medical

and diversity-oriented synthesis. Their intrinsic step economy and convergency may decrease solvent consumption and purification needs [68].

Recent breakthroughs include the combination of MCRs with catalysts, water as reaction medium, solvent-free conditions, mechanochemistry, microwave activation and renewable resources. In a study in 2026, the possibility of green MCRs to include energy saving methods, renewable catalysts and cleaner solvents while minimizing waste and improving molecular complexity per operation is emphasized [69]. The fundamental difficulty is to ensure that the benefits are still applicable when the process boundary includes purification, solvent recovery and scaling up.

11 Process Intensification and Continuous Flow Chemistry

Continuous-flow chemistry offers fine control over residence duration, temperature, pressure, mixing, and photon or electrochemical exposure. The small reactor size lead to better heat and mass transmission and may make hazardous intermediates safer to work with. Flow systems are particularly useful for rapid exothermic reactions, photochemistry, electrochemistry, gas-liquid conversions and multistep telescoped sequences. Nature Reviews Methods 2025 The primers article discusses continuous flow as an increasingly relevant method for molecular synthesis both in academia and industry [70].

Flow chemistry also serves as a bridge between laboratory discoveries and production. Batch to batch variance may be reduced by inline monitoring and automatic optimization. However, the evaluation of process intensification should not be only based on throughput. Pumping energy, the manufacture of reactors, pressure drop, solvent recycling, downstream purification and equipment lifespan should all be included in sustainability assessments.

12 Renewable Feedstocks and Circular Organic Syntheses

The source of carbon atoms is becoming more and more discussed in sustainable organic production. Biomass-derived platform molecules, lignocellulosic components, waste lipids, carbohydrates, terpenes, glycerol and other renewable resources may lessen the dependency on fossil carbon when handled appropriately. The aim is not to replace molecules from petroleum with molecules from biomass but to invent efficient transformations that maintain the value of carbon and are less intense in processing [71].

Circular chemistry goes farther by recovering resources and turning waste streams into feedstocks. Biomass valorization may be a source of chemicals, solvents and catalytic

supports but its sustainability is a function of land usage, water consumption, collection logistics, pretreatment energy and competition with food systems . Therefore, renewable origin should be seen as one feature of sustainability and not as a general proxy for environmental supremacy [72].

13 Green Synthesis of C–C and C–Heteroatom Bonds

The production of C-C and C-N, C-O and C-S bonds lies at the heart of medicinal and materials chemistry. Conventional approaches may include the use of prefunctionalized, organometallic reagents or stoichiometric activators. Current strategies increasingly focus on direct C–H functionalization, reductive coupling, oxidative coupling, radical addition and late-stage diversification. These techniques may increase the step economy by circumventing prefunctionalization and minimizing the isolation of intermediates [73].

Photochemical, electrochemical and electrophotochemical C–N interaction has become a particularly active topic. These approaches allow the exploitation of radical and metal-free routes, as well as the fine-tuning of redox processes, as noted in a 2026 Nature Reviews Chemistry article [74]. Future development should concentrate on wide substrate tolerance, catalyst-free or catalyst-minimized versions, low energy activation and direct use of cheap feedstocks.

14 AI, Machine Learning and Digitalization for Green Synthesis of Organic Materials

Artificial intelligence and machine learning are becoming instruments for reaction prediction, catalyst selection, condition optimization, retrosynthesis and sustainability evaluation. The usefulness of their green-chemistry is because of the potential of lowering the number of trials necessary to discover efficient conditions and the incorporation of environmental goals directly into optimization [75].

The next generation of synthesis planning will probably include the simultaneous optimization of several objectives: yield, selectivity, cost, PMI, solvent hazard, catalyst criticality, energy consumption, and anticipated carbon footprint. Quality of experimental data and transparency of sustainability models will be needed for such systems. Hence, AI should be seen as a decision-support tool and not as a replacement for experimental validation or life-cycle analysis [76].

15 Applications in Pharmaceuticals, Fine Chemicals and Functional Materials

Pharmaceutical synthesis is a significant driver of green chemistry since medicinal chemistry generally involves the fast creation of structurally diverse compounds and manufacturing requires repeatable, scalable and impurity controlled procedures. Catalytic asymmetric synthesis, biocatalysis, aqueous micellar chemistry, flow processing, and telescoped sequences may all decrease the number of steps and the need for solvents. In fine chemicals, selective catalysis may increase the atom economy and minimize waste from protection-deprotection cycles. For functional materials, sustainable synthesis is increasingly related to the origin of monomer, solvent recovery, removal of catalyst and design of end of life [77].

The most convincing industrial examples mix response innovation with process change. Even a high yielding process may be ecologically bad if it needs a significant surplus of chemicals and a lot of chromatography. Conversely, a transformation that is catalytic, concentrated, solvent-efficient, telescoped and readily purified by crystallization or filtering may be advantageous even if it is moderate-yielding [78-82].

16 Challenges and Limitations

Scalability remains a major challenge for many advanced laboratory methods. A reaction that performs well on milligram scale may behave very differently at kilogram or tonne scale because heat transfer, light penetration, mixing, and mass transport become more difficult to control. Catalyst lifetime is equally important: high initial activity does not ensure long-term stability, and frequent replacement or complex recycling can undermine both environmental and economic benefits [83,84].

Solvent recovery must be evaluated across the entire process. Even a solvent considered safe during the reaction can generate substantial waste during extraction, purification, drying, or disposal. Likewise, some photocatalysts and transition-metal catalysts rely on scarce or critical raw materials, raising concerns about supply security, mining impacts, and cost volatility [85].

Energy use requires careful accounting. Short reaction times are not automatically energy-efficient if the process needs powerful lamps, continuous cooling, high-pressure equipment,

or energy-intensive separation steps. Comparisons are also complicated by inconsistent sustainability metrics: PMI, E-factor, and life-cycle assessment measure different boundaries and inputs, so results from separate studies may not be directly comparable [86,87].

Reproducibility presents another obstacle, especially for photochemical and mechanochemical processes. Small changes in reactor geometry, light source, milling conditions, temperature, or mixing can significantly affect yield and selectivity. For pharmaceutical and industrial adoption, processes must also meet strict regulatory requirements, including impurity control, validated analytical methods, reliable documentation, and robust supply chains [88].

Finally, economic trade-offs cannot be ignored. A technically greener route may still be impractical if catalysts are expensive, equipment investment is high, or product isolation requires difficult separations. Sustainable chemistry therefore needs to balance environmental gains with reliability, regulatory compliance, scale-up feasibility, and total manufacturing cost [89,90].

17 Future Perspectives

The future of green organic synthesizing will probably be one of integration rather than of replacement. Photochemistry may be combined with electrochemistry, enzymes with photocatalysts, mechanochemistry with microwave activation, and continuous-flow reactors can combine reaction, separation and inline analytics [91,92]. Such hybridization may facilitate transitions while mitigating particular shortcomings of each platform [93-95]. Another important area is “sustainability by design” where route selection starts with stated environmental aims. Instead of maximizing yield first and then assessing sustainability, chemists may establish acceptable solvent classes, maximum PMI, catalyst criticality limits, energy objectives and purification limitations before experimental work starts [96]. This is in line with recent appeals to include sustainability as a key factor in organic production and catalysis.

Digital chemistry will reinforce this foundation [97-99]. Automated flow platforms paired with high-throughput experimentation can quickly explore reaction space, machine learning can prioritize experiments, and multi-objective optimization can balance chemical and environmental performance. Ultimately good green chemistry should link molecular design, process design, manufacturing, supply-chain resilience and circularity [100].

18 Conclusions

Modern organic synthesizing is shifting toward a process-centered paradigm where efficiency, selectivity, safety and environmental performance are maximized simultaneously. Powerful instruments for this shift include recent advances in photocatalysis, electrosynthesis, electrophotocatalysis, biocatalysis, mechanochemistry, aqueous micellar chemistry, deep eutectic solvents, multicomponent processes, and continuous-flow synthesis. But there is no technology that is green in all situations. The sustainability relies on the catalyst origin and lifespan, solvent generation and recovery, energy supply, concentration, separation, waste treatment and scale.

Therefore, the most crucial future possibility is the integration of complementary technologies with quantitative sustainability evaluation. Green metrics, life-cycle analysis, automation and artificial intelligence may direct synthetic chemists toward chemically successful, resource-efficient and scalable methods. The integration of these ideas throughout the early stages of molecule and process design may make green chemistry a default approach rather than an alternative one for contemporary organic chemical synthesis.

References

1. Sharma S, Gallou F, Handa S. Towards a sustainable tomorrow: advancing green practices in organic chemistry. Green Chem. 2024;26:6289–6317. https://doi.org/10.1039/D4GC01826E.

2. Ali SK, Althikrallah HA, Alluhaibi MS, Hawsawi MB, Hakami O, Shariq M, Hassan DA, Hussain M. Electrochemical and photocatalytic synthesis of organic compounds utilizing a greener approach: a review. Mol Catal. 2024;559:114087. https://doi.org/10.1016/j.mcat.2024.114087.

3. Yenare PP, Patare RD, Sonawane BP, Sanap KK. Green chemistry innovation: a systematic review on sustainable catalysis and its strategic future directions. Catal Sci Technol. 2025;15:7295–7323. https://doi.org/10.1039/D5CY00559K.

4. Banerjee S, Periyasamy S, Muthukumaradoss KM, Deivasigamani P, Saravanan VV. Revolutionizing organic synthesis through green chemistry: metal-free, bio-based, and microwave-assisted methods. Front Chem. 2025;13:1656935. https://doi.org/10.3389/fchem.2025.1656935.

5. Anastas PT, Warner JC. Green Chemistry: Theory and Practice. Oxford University Press; 1998.

6. Kurul F, Doruk B, Topkaya SN. Principles of green chemistry: building a sustainable future. Discov Chem. 2025;2:68. https://doi.org/10.1007/s44371-025-00152-9.

7. Lamb MC, Steiniger KA, Trigoura LK, Wu J. Electrophotocatalysis for organic synthesis. Chem Rev. 2024;124:12264–12304. https://doi.org/10.1021/acs.chemrev.4c00464.

8. Raby-Buck SE, Devlin J, Gupta P, Battilocchio C, Baumann M, Polyzos A, Slater AG, Browne DL. Continuous flow chemistry for molecular synthesis. Nat Rev Methods Primers. 2025;5:44. https://doi.org/10.1038/s43586-025-00414-x.

9. Kaur P, Tyagi V. Hydrolase biocatalysis integrated with chemo-, electro-, and photocatalysis for sustainable organic synthesis. Org Biomol Chem. 2025. https://doi.org/10.1039/D5OB01698C.

10. Kqiku L, Paradisi F. Photobiocatalysis in 2024–2025: unlocking new-to-nature transformations via excited-state enzyme chemistry. Curr Opin Green Sustain Chem. 2026; article 101072. https://doi.org/10.1016/j.cogsc.2026.101072.

11. Arfelis S, Martín-Perales AI, Nguyen R. Linking mechanochemistry with the green chemistry principles: review article. Heliyon. 2024;10:e34655. https://doi.org/10.1016/j.heliyon.2024.e34655.

12. Biedermann N, Schnürch M. Advances in mechanochemical methods for one-pot multistep organic synthesis. Chemistry—A European Journal. 2025;31:e202500798. https://doi.org/10.1002/chem.202500798.

13. Xie G, Wright V, Lazarev A, Smejkal G, Gross V, Török B. Green synthesis of building blocks, drug candidates and fine chemicals by barochemistry: application of high pressure in organic synthesis. Green Chem. 2025;27:7096–7113. https://doi.org/10.1039/D5GC01075F.

14. Bisharat H, Javaid S, Ahmad Z. Recent advances in green catalytic multicomponent reactions for sustainable synthesis. ChemistrySelect. 2026;11:e06024. https://doi.org/10.1002/slct.202506024.

15. Ghosh A, Parida VK, Banerjee D. Challenges and opportunities on sustainable electrochemical transformations: application towards the synthesis of pharmaceuticals and precursors of drug-like molecules. Green Chem. 2024;26:5770–5789. https://doi.org/10.1039/D3GC04881K.

16. Gupta S, Manna S, Patel BK. Electro-organic synthesis at the crossroads of innovation and sustainability. Curr Opin Green Sustain Chem. 2026; article 101083. https://doi.org/10.1016/j.cogsc.2026.101083.

17. Xu XL. Electrocatalysis and photoelectrocatalysis: perspective from physicochemical mechanisms to applications. ACS Omega. 2026;11:47164–47202. https://doi.org/10.1021/acsomega.6c04248.

18. Wu H, Sui T, Chen F, et al. Heterogeneous mediator-free photoelectrochemical organic transformation. Green Chem. 2026;28:6608–6618. https://doi.org/10.1039/D6GC00076B.

19. Li B, Li N, Zhang H, et al. Photochemical, electrochemical and electrophotochemical C–N bond-forming cross-coupling reactions. Nat Rev Chem. 2026;10:332–349. https://doi.org/10.1038/s41570-026-00819-6.

20. Guzmán E. Catalysis with deep eutectic solvents: challenges and opportunities. ChemCatChem. 2025;17:e202500522. https://doi.org/10.1002/cctc.202500522.

21. Gaikwad AS. Green organic synthesis in drug discovery: emerging roles of artificial intelligence and quantum chemical approaches. Discov Chem. 2026;3:330. https://doi.org/10.1007/s44371-026-00784-5.

22. Handa S, Gallou F, Meier MAR, et al. Expectations for submissions on sustainable organic synthesis and sustainable catalysis relevant to organic synthesis for ACS Sustainable Chemistry & Engineering. ACS Sustain Chem Eng. 2025;13:12830–12834. https://doi.org/10.1021/acssuschemeng.5c07849.

23. Messire G, Caillet E, Berteina-Raboin S. Green catalysts and/or green solvents for sustainable multi-component reactions. Catalysts. 2024;14:593. https://doi.org/10.3390/catal14090593.

24. Venkatesh R, Chaudhary P. Green chemistry spotlight: metal-free organic transformations mediated by potassium persulfate. RSC Adv. 2025;15:43198–43237. https://doi.org/10.1039/D5RA06175J.

25. Deshmukh DS, Singh S, Badgujar KC, et al. Green innovations in C–H bond functionalisation: exploring homogeneous recyclable catalytic systems. Green Chem. 2024;26:3595–3626. https://doi.org/10.1039/D3GC05089K.

26. Afanasenko AM, Deak N, October J, Sole R, Barta K. 'Green' synthesis of amines from renewable resources? A detailed analysis of case studies using the CHEM21 green metrics toolkit. Green Chem. 2025;27:5947–5981. https://doi.org/10.1039/D5GC00924C.

27. Sheldon RA. The E factor: fifteen years on. Green Chem. 2007;9:1273–1283. https://doi.org/10.1039/B713736M.

28. Trost BM. The atom economy—a search for synthetic efficiency. Science. 1991;254:1471–1477. https://doi.org/10.1126/science.1962206.

29. Sheldon RA. Metrics of green chemistry and sustainability: past, present, and future. ACS Sustain Chem Eng. 2018;6:8132–8138.

30. Jiménez-González C, Curzons AD, Constable DJC, Cunningham VL. Cradle-to-gate life cycle assessment of pharmaceutical processes. Int J Life Cycle Assess. 2004;9:114–121.

31. Dunn PJ. The importance of green chemistry in process research and development. Chem Soc Rev. 2012;41:1452–1461. https://doi.org/10.1039/C1CS15117G.

32. Sheldon RA, Woodley JM. Role of biocatalysis in sustainable chemistry. Chem Rev. 2018;118:801–838. https://doi.org/10.1021/acs.chemrev.7b00203.

33. Anastas N, Eghbali N. Green chemistry: principles and case studies. Chem Soc Rev. 2010;39:301–312.

34. Poliakoff M, Licence P. Green chemistry: science and politics of change. Nature. 2007;450:810–812.

35. Horváth IT, Anastas PT. Innovations and green chemistry. Chem Rev. 2007;107:2169–2173.

36. Li CJ, Trost BM. Green chemistry for chemical synthesis. Proc Natl Acad Sci USA. 2008;105:13197–13202.

37. Clark JH, Tavener SJ. Alternative solvents: shades of green. Org Process Res Dev. 2007;11:149–155.

38. Capello C, Fischer U, Hungerbühler K. What is a green solvent? A comprehensive framework for the environmental assessment of solvents. Green Chem. 2007;9:927–934.

39. Prat D, Wells A, Hayler J, et al. CHEM21 selection guide of classical- and less classical-solvents. Green Chem. 2016;18:288–296.

40. Prat D, Hayler J, Wells A. A survey of solvent selection guides. Green Chem. 2014;16:4546–4551.

41. Henderson RK, Jiménez-González C, Constable DJC, et al. Expanding GSK's solvent selection guide—embedding sustainability into solvent selection starting at medicinal chemistry. Green Chem. 2011;13:854–862.

42. Byrne FP, Jin S, Paggiola G, et al. Tools and techniques for solvent selection: green solvent selection guides. Sustain Chem Process. 2016;4:7.

43. Cvjetko Bubalo M, Radošević K, Radojčić Redovniković I, Halambek J, Gaurina Srček V. Ionic liquids: beyond green solvents. Chem Biochem Eng Q. 2014;28:191–200.

44. Welton T. Room-temperature ionic liquids. Solvents for synthesis and catalysis. Chem Rev. 1999;99:2071–2084.

45. Plechkova NV, Seddon KR. Applications of ionic liquids in the chemical industry. Chem Soc Rev. 2008;37:123–150.

46. Abbott AP, Capper G, Davies DL, Rasheed RK, Tambyrajah V. Novel solvent properties of choline chloride/urea mixtures. Chem Commun. 2003:70–71.

47. Smith EL, Abbott AP, Ryder KS. Deep eutectic solvents (DESs) and their applications. Chem Rev. 2014;114:11060–11082.

48. Hansen BB, Spittle S, Chen B, et al. Deep eutectic solvents: a review of fundamentals and applications. Chem Rev. 2021;121:1232–1285.

49. Tang B, Row KH. Recent developments in deep eutectic solvents in green synthesis. Monatshefte Chem. 2013;144:1427–1454.

50. Hallett JP, Welton T. Room-temperature ionic liquids: solvents for synthesis and catalysis. 2. Chem Rev. 2011;111:3508–3576.

51. Sheldon RA. Green solvents for sustainable organic synthesis: state of the art. Green Chem. 2005;7:267–278.

52. Clark JH, Macquarrie DJ. Handbook of Green Chemistry and Technology. Blackwell Science; 2002.

53. Zangade SB, Patil NR. A review on microwave assisted organic reaction. Int J Pharm Sci Res. 2012;3:117–125.

54. Kappe CO. Controlled microwave heating in modern organic synthesis. Angew Chem Int Ed. 2004;43:6250–6284.

55. Kappe CO, Stadler A. Microwaves in Organic and Medicinal Chemistry. Wiley-VCH; 2005.

56. Loupy A, Petit A, Hamelin J, Texier-Boullet F, Jacquault P, Mathe D. New solvent-free organic synthesis using focused microwaves. Synthesis. 1998:1213–1234.

57. Mason TJ. Ultrasound in synthetic organic chemistry. Chem Soc Rev. 1997;26:443–451.

58. Cravotto G, Cintas P. Power ultrasound in organic synthesis: moving cavitational chemistry from academia to innovative and large-scale processing. Chem Soc Rev. 2006;35:180–196.

59. Cravotto G, Cintas P. The combined use of microwaves, ultrasound and high-speed stirring for chemical synthesis. Chem Soc Rev. 2007;36:1243–1250.

60. James SL, Adams CJ, Bolm C, et al. Mechanochemistry: opportunities for new and cleaner synthesis. Chem Soc Rev. 2012;41:413–447.

61. Do JL, Friščić T. Mechanochemistry: a force of synthesis. ACS Cent Sci. 2017;3:13–19.

62. Friščić T. Supramolecular concepts and new techniques in mechanochemistry: cocrystals, coordination polymers, organic reactions and metal-organic frameworks. Chem Soc Rev. 2012;41:593–601.

63. Rightmire NR, Hanusa TP. Mechanochemistry: solvent-free organic and organometallic reactions. Adv Synth Catal. 2016;358:1374–1382.

64. Howard JL, Cao Q, Browne DL. Mechanochemistry as an emerging tool for molecular synthesis. Chem Sci. 2018;9:3080–3094.

65. Ley SV, Baxendale IR, et al. The evolution of flow chemistry as a tool for sustainable synthesis. Chem Rev. 2015;115:1001–1102.

66. Wegner J, Ceylan S, Kirschning A. Ten key issues in modern flow chemistry. Chem Commun. 2011;47:4583–4592.

67. Plutschack MB, Pieber B, Gilmore K, Seeberger PH. The Hitchhiker's Guide to Flow Chemistry. Chem Rev. 2017;117:11796–11893.

68. Noël T, Hessel V. Photochemical reactions in continuous flow. ChemSusChem. 2013;6:155–165.

69. Harper KC, Dunn AL, Grynova G, et al. Photochemical reactions in flow: a practical guide. React Chem Eng. 2020;5:169–180.

70. Cambié D, Bottecchia C, Straathof NJW, Hessel V, Noël T. Applications of continuous-flow photochemistry in organic synthesis, material science, and water treatment. Chem Rev. 2016;116:10276–10341.

71. Yoshida JI. Basics of electrosynthesis. Top Curr Chem. 2017;375:79.

72. Möhle S, Zirbes M, Rodrigo E, Gieshoff T, Wiebe A, Waldvogel SR. Modern electrochemical aspects for the synthesis of value-added organic products. Angew Chem Int Ed. 2018;57:6018–6041.

73. Yan M, Kawamata Y, Baran PS. Synthetic organic electrochemical methods since 2000: on the verge of a renaissance. Chem Rev. 2017;117:13230–13319.

74. Wiebe A, Gieshoff T, Möhle S, Rodrigo E, Zirbes M, Waldvogel SR. Electrifying organic synthesis. Angew Chem Int Ed. 2018;57:5594–5619.

75. Röckl JL, Pollok D, Waldvogel SR. Electro-organic synthesis—a 21st century technique. Chem Rev. 2020;120:11810–11956.

76. Francke R, Little RD. Redox catalysis with electrochemistry: from molecules to materials. Chem Soc Rev. 2014;43:2492–2521.

77. Prier CK, Rankic DA, MacMillan DWC. Visible light photoredox catalysis with transition metal complexes: applications in organic synthesis. Chem Rev. 2013;113:5322–5363.

78. Romero NA, Nicewicz DA. Organic photoredox catalysis. Chem Rev. 2016;116:10075–10166.

79. Narayanam JMR, Stephenson CRJ. Visible light photoredox catalysis: applications in organic synthesis. Chem Soc Rev. 2011;40:102–113.

80. Schultz DM, Yoon TP. Solar synthesis: prospects in visible light photocatalysis. Science. 2014;343:1239176.

81. Nicewicz DA, MacMillan DWC. Merging photoredox catalysis with organocatalysis: the direct asymmetric alkylation of aldehydes. Science. 2008;322:77–80.

82. Stephenson CRJ, Yoon TP, MacMillan DWC, editors. Visible Light Photocatalysis in Organic Chemistry. Wiley-VCH; 2018.

83. Melchiorre P. Photochemical organocatalysis: an emerging synthetic strategy. Angew Chem Int Ed. 2009;48:6464–6466.

84. Narayanam JM, Tucker JW, Stephenson CRJ. Electron-transfer photoredox catalysis: development of a practical method for the reduction of aryl halides. J Am Chem Soc. 2009;131:8756–8757.

85. Romero NA, Margrey KA, Tay NE, Nicewicz DA. Site-selective N–H alkylation of primary sulfonamides using organic photoredox catalysis. Science. 2015;349:1326–1329.

86. MacMillan DWC. The advent and development of organocatalysis. Nature. 2008;455:304–308.

87. List B. Emil V. Markovnikov and the birth of organocatalysis. Angew Chem Int Ed. 2010;49:1730–1734.

88. Dalko PI, Moisan L. Enantioselective organocatalysis. Angew Chem Int Ed. 2001;40:3726–3748.

89. Berkessel A, Gröger H. Asymmetric Organocatalysis: From Biomimetic Concepts to Applications in Asymmetric Synthesis. Wiley-VCH; 2005.

90. Sheldon RA, Woodley JM. Role of biocatalysis in sustainable chemistry. Chem Rev. 2018;118:801–838.

91. Bornscheuer UT, Huisman GW, Kazlauskas RJ, Lutz S, Moore JC, Robins K. Engineering the third wave of biocatalysis. Nature. 2012;485:185–194.

92. Bornscheuer UT, Hauer B, Jaeger KE, Schwaneberg U. Directed evolution empowered redesign of natural enzymes for the sustainable production of chemicals. Angew Chem Int Ed. 2019;58:36–40.

93. Turner NJ, O'Reilly E. Biocatalytic retrosynthesis. Nat Chem Biol. 2013;9:285–288.

94. Bell EL, Finnigan W, France SP, et al. Biocatalysis. Nat Rev Methods Primers. 2021;1:46.

95. Sheldon RA, Brady D. Broadening the scope of biocatalysis in sustainable organic synthesis. Chem Commun. 2018;54:6088–6104.

96. Boström J, Brown DG, Young RJ, Keserü GM. Expanding the medicinal chemistry toolbox with high-throughput experimentation. Nat Rev Drug Discov. 2018;17:709–727.

97. Coley CW, Rogers L, Green WH, Jensen KF. Computer-assisted retrosynthesis based on molecular similarity. ACS Cent Sci. 2017;3:1237–1245.

98. Schwaller P, Petraglia R, Zepel T, et al. Molecular Transformer: a model for uncertainty-calibrated chemical reaction prediction. ACS Cent Sci. 2019;5:1572–1583.

99. Segler MHS, Preuss M, Waller MP. Planning chemical syntheses with deep neural networks and symbolic AI. Nature. 2018;555:604–610.

100. Schwaller P, Laino T, Gaudin T, Bolgar P, Hunter CA, Bekas C, Lee AA. Molecular Transformer: a model for uncertainty-calibrated chemical reaction prediction. ACS Cent Sci. 2019;5:1572–1583.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (http://creativecommons.org/licenses/by-nc/4.0/), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

