Open Access Review Article

ISSN: 2349-9818
November - December 2025, Vol. 12 (6), 01-09

Tropical Journal of Pharmaceutical and Life Sciences
(An International Peer Reviewed Journal)
Journal homepage: http://informativejournals.com/journal/index.php/tjpls

Intervention of Green Chemistry in the Development of Pharmaceutical Research

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ARTICLE INFO:

Received: 06th Dec. 2025; **Received** in revised form: 22nd Dec. 2025; **Accepted:** 25th Dec. 2025; **Available online:** 27th Dec. 2025.

Abstract

Green chemistry has become a revolutionary concept in contemporary chemical operations, radically changing the way chemical products and processes are developed, produced, and used in various industries. The field has a strong emphasis on reducing environmental impact through the use of renewable resources, energy efficiency, and waste reduction. Industrial chemical processes have been transformed by recent developments in biomimicry, catalysis, and sustainable synthesis techniques. Significant advancements in polymer manufacture, nanomaterial synthesis, and pharmaceutical manufacturing have resulted from the use of green chemistry principles. Green sustainable synthesis promotes safer and more effective techniques that are in line with ecological principles while minimizing waste, energy use, and hazardous ingredients. In addition to improving human and animal health, the use of drugs in medical and veterinary care has increased food production and economic wellbeing. In order to improve drug research and discovery, medicinal chemistry has developed to fully integrate advances in computer modelling, artificial intelligence (AI), and molecular biology. Green sustainable synthesis promotes safer and more effective techniques that are in line with ecological principles while minimizing waste, energy use, and hazardous ingredients. The current analysis focuses on the techniques that medicinal chemists can employ in their day-to-day work to protect the environment and human health by reducing and preventing pollution in addition to increasing yields. Green chemistry has several applications in drug development, from environmentally compliant large-scale pharmaceutical manufacture to safer laboratory procedures. By reducing waste and resource utilization, it improves worker safety, decreases production costs, and helps reduce harmful emissions. Due to their common objective of sustainable development, many of these forms of green chemistry are used in tandem. To improve reaction conditions, flow chemistry, for example, may use green solvents and biocatalysis.

Keywords: Green chemistry, Chronological development, Current scenario, Future development.

Introduction

Green chemistry is a sustainable approach to drug development that focuses on creating safer, more effective chemical processes and products that use fewer hazardous substances and have less of an impact on the environment. By encouraging environmentally friendly techniques throughout the drug lifetime, it plays a

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DOI: https://doi.org/10.61280/tjpls.v12i6.228

crucial part in contemporary pharmaceutical development. Drug discovery makes use of a number of important forms of green chemistry, such as flow chemistry, atom-economical reactions, microwave and ultrasound-assisted synthesis, biocatalysis, and the use of green solvents like ethanol or water. These methods increase product yield and reaction efficiency while lowering waste and energy usage.

Merck's creation of sitagliptin, which greatly reduced waste and increased efficiency by using an enzyme-based approach rather than metal catalysts, is an example of green chemistry in action. Another is Pfizer's redesign of the sertraline (Zoloft) synthesis pathway, which reduced the environmental impact of the process by using greener solvents and catalysts. These illustrations show how green chemistry improves drug development efficiency and creativity while simultaneously helping the environment.

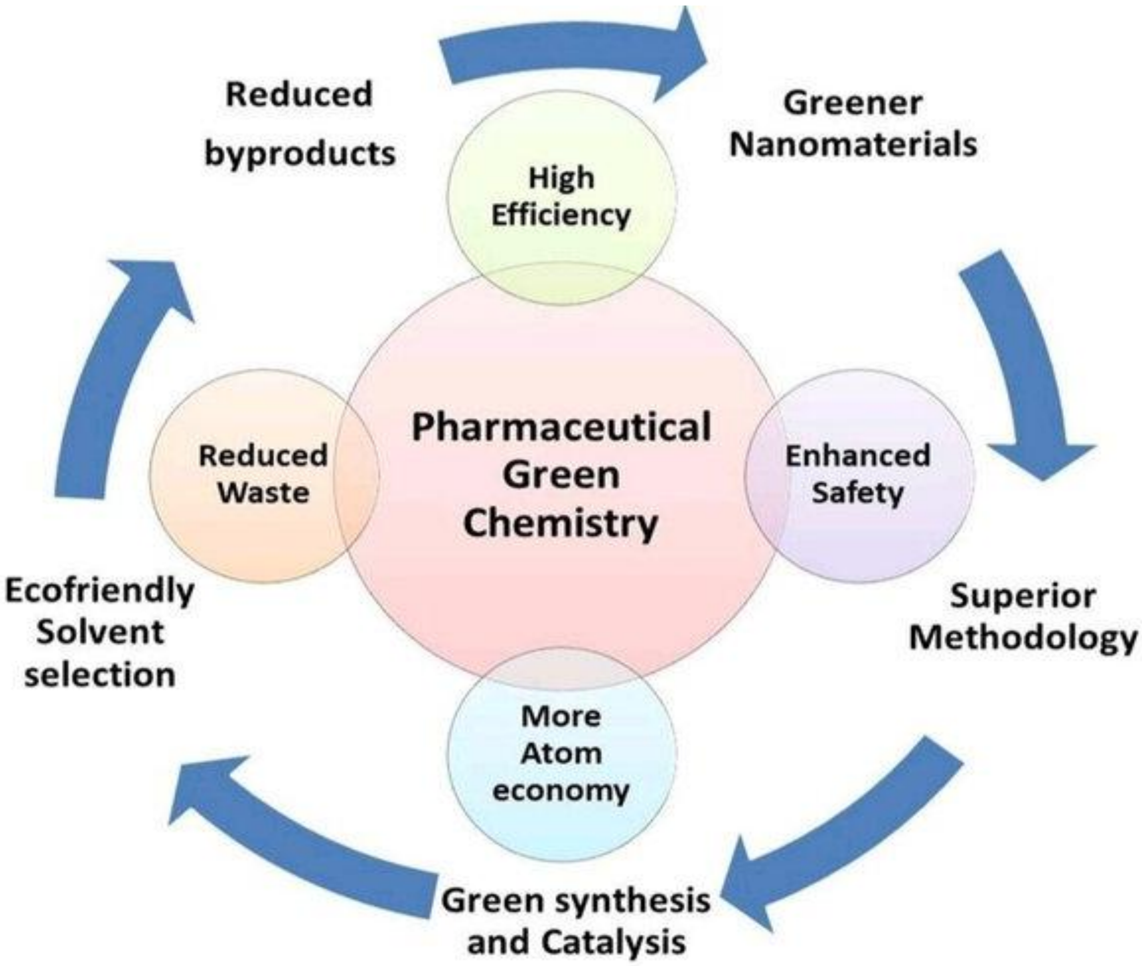


Figure 1: Representation of the procedures of pharmaceutical industries towards green chemistry principles

History

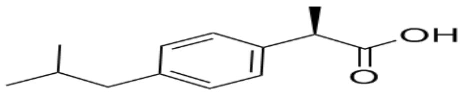
Green chemistry first appeared in the history of drug discovery thanks to developments like solvent-free reactions, enzymatic catalysis, and aqueous-phase synthesis. Merck's sitagliptin synthesis and Pfizer's sertraline procedure are two examples of eco-friendly pharmaceutical development techniques that minimize waste, dangerous chemicals, and energy use.

Table 1: Application of Green Chemistry in Drug Discovery

Green Chemistry Technique	Description	Historical Milestone	Impact on Drug Discovery
Biocatalysis	Use of enzymes or microorganisms to catalyze reactions	1990s: Widely adopted for chiral synthesis in pharma	Improved selectivity, reduced need for metal catalysts or harsh reagents
Green Solvents	Use of environmentally benign solvents (e.g., water, ethanol, supercritical CO_2)	2000s: Shift from toxic solvents like dichloromethane	Reduced toxicity, safer working conditions, better waste management
Microwave-Assisted Synthesis	Rapid heating of reactions using microwaves to speed up reactions	Early 2000s: Adopted for medicinal chemistry	Shortened reaction times, increased yield, reduced energy use
Continuous Flow Chemistry	Conducting reactions in continuously flowing systems rather than batch setups	2010s: Industrial adoption for process intensification	Enhanced safety, easier scale-up, better reaction control
Atom Economy & Catalysis	Designing reactions to maximize incorporation of all materials into the product	1998: Principle 2 of Green Chemistry (Anastas & Warner)	Reduced waste, fewer by-products, improved synthetic efficiency
Renewable Feedstocks	Use of raw materials derived from renewable sources (e.g., plant-based sugars)	2010s: Increased focus on bio-based precursors	Lower environmental footprint, reduced reliance on petrochemicals

Table 2: Chronological Development of Green Chemistry with Medicinal Chemistry

Period	Key Events	Green Chemistry Influence In Medicinal Chemistry
Pre - 1990	Traditional drug synthesis with little focus on environment impact-high use of toxic solvents and reagents.	Minimal awareness of green principles wasteful and hazardous processes accepted as standard.
1990 - 1998	EPA Launches green chemistry program [1991]-12 principles of green chemistry formulated [1998]	Initial awareness in pharmaceutical industry-early discussions on cleaner synthesis and solvent reduction
1998- 2010	Adoption of green chemistry in pharma R and D – Pfizer, GSK, Merck begin green initiatives green chemistry awards [by ACS, EPA]	Use of safer solvents [e.g., water, ethanol]-catalysis and atom economy principle applied in synthesis- early biocatalysis and enzymatic processes.

2010 - 2020	Continuous flow chemistry gains popularity - increased emphasis on lifecycle analysis of drugs	Waste minimization and energy efficiency priotized- use of renewable feedstocks greener drugs like ibuprofen. 
2020	Nitration of Al and green chemistry for drug design emphasis on sustainable pharmaceutical manufacturing regulatory encouragement for green.	MRNA drugs with cleaner production lines- development of degradable and environmentally benign of pharmaceeuticals.

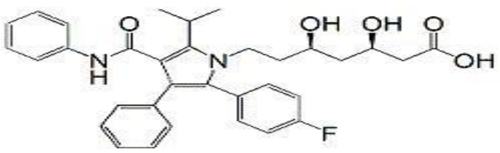
Currently, green chemistry in drug discovery emphasizes eco-friendly solvents, catalytic efficiency, and process intensification. Pharmaceutical companies adopt greener synthesis routes, like flow chemistry and bio transformations, to reduce environmental impact, improve safety, and meet regulatory and sustainability goals.

Table 3: Examples of Green Chemistry in Drug Discovery in Current Scenario

Green Chemistry Practice	Current View/Use in Drug Discovery	Benefits	Challenges
Biocatalysis	Widely used for asymmetric synthesis and complex molecule construction	High selectivity, mild conditions, less waste	Limited enzyme availability, stability issues
Green Solvents (e.g., water, EtOH, Me-THF)	Actively replacing toxic solvents like DMF, DCM	Lower toxicity, improved biodegradability	Solubility and reaction compatibility
Microwave-Assisted Synthesis	Used in medicinal chemistry labs for fast screening and optimization	Shorter reaction times, energy efficiency	Not easily scalable to industrial production
Continuous Flow Chemistry	Increasing use in both discovery and development phases	Better control, safer scale-up, integrated purification	High setup cost, technical expertise required
Photoredox Catalysis	Emerging for C–H activation and complex transformations under mild conditions	Enables novel transformations, uses light as energy source	Requires specialized equipment and expertise
Use of Renewable Feedstocks	Growing interest in using bio-based reagents and solvents	Reduces fossil fuel dependency, supports circular economy	Supply chain variability, cost
In Silico Tools for Green Design	Computational tools used to predict greener synthetic routes early in R&D	Avoids wasteful routes, enhances sustainability planning	Requires integration into standard drug design pipelines

Green chemistry, also known as sustainable chemistry, aims to prevent and eradicate pollution production at its source by developing safe synthetic methodologies for the preparation of molecules. It has become a significant goal for the pharmaceutical industry to comply with its principles throughout the discovered life cycle or else utilize safer and greener alternatives.

Table 4: Representing the Current Research of Green Chemistry and Medicinal Chemistry

Aspect	Medicinal chemistry today	Green chemistry integration
Drug Design	Targeted therapies, Al-assisted design, precision medicine. **Example:** The development Of inhibitor for the TBK1/ IKK kinase, used to treat Inter-feronopathies.	Use of computational tools to reduce experimental waste and energy consumption. **Example:** Using biocatalysis Minimizing waste, and Employing solvent.
Synthesis methods	Complex, multi-step syntheses of small molecules and biologics.	Catalysis [enzymatic and metal-based], solvent free reaction flow chemistry
Solvents and reagents	Traditionally organic solvents [e.g., DCM, THF] **Example:** Waste, ethanol, Methanol and acetone.	Replacement with greener alternatives**.** **Example:** Waste, ethanol, and ethyl acetate.
Raw materials	Petroleum based and synthetic Feedstocks.	Shift towards renewable feedstcks and biobased raw materials
Manufacturing	Batch production of APIs and biologic. **Example:** The development Of statin medications, like Atorvastatin. 	Continuous flow manufacturing , reduced emissions, solvent recovery system.
Waste management	High E factor [waste to product ratio] I pharma. **Example:** minimizing and Sately disposing of Pharmaceutical waste.	E- Factor reduction strategies, lifecycle analayis **Example:** Replacing Hazardous sorbents with Non-hazardous alternatives And using renewable.

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Future Development Related To Green Energy

Future trends in green chemistry for pharmaceuticals emphasize sustainable synthesis methods, including greener biocatalysts, innovative synthetic routes, and advanced computational tools to minimize environmental impact.

Table 5: Representing the future studies of Medicinal chemistry and Green chemistry

Focus area	Future outlook	Green chemistry role	Expected impact
Drug discovery	AI/ML- enhanced, bio based leads.	Eco-friendly compound libraries, in silico screening.	Faster, cleaner and more targeted drug discovery.
Synthesis strategies	Custom, on-demand synthesis	Catalysis, biocatalysis, flow chemistry, solvent free methods.	Reduction in waste, time and cost
Education and collaboration	Interdisciplinary R&D culture	Training in green chemistry and sustainable pharma.	Skilled workforce ready for eco-innovation
Policy and regulation	Global harmonization of green pharma standards.	Incentives for green innovation, stricter waste laws.	Safer industry practices worldwide

Conclusion

Green chemistry has emerged as a crucial pillar in the development of drug discovery, encouraging safer, more effective, and sustainable methods across the pharmaceutical sector. These methods, which range from biocatalysis and green solvents to cutting-edge technologies like continuous flow chemistry and AI-driven route design, are transforming the pharmaceutical industry and guaranteeing that environmental impact is kept to a minimum while enhancing the effectiveness and safety of pharmaceutical operations. With developments like solar-powered reactions, waste-free synthesis, and the incorporation of carbon capture technologies giving the promise to make drug research even more sustainable, the future of green chemistry in drug discovery appears bright. There are still issues, though, such as the scalability of some techniques and the requirement for additional funding for research and infrastructure. Notwithstanding these obstacles, incorporating green chemistry concepts into medication development remains an essential step in improving human health and building a more sustainable, healthy world.

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How to cite this article: Prof. (Dr.) Niraj Gupta. "Intervention of Green Chemistry in the Development of Pharmaceutical Research". *Tropical Journal of Pharmaceutical and Life Sciences*, vol. 12, no. 6, Dec. 2025, pp. 1-11, doi:10.61280/tjpls.v12i6.228.

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