e - ISSN – 2393-9672

European Journal of Environmental Ecology

Journal homepage: www.mcmed.us/journal/ejee

GREEN CHEMISTRY APPROACHES IN PHARMACEUTICAL MANUFACTURING: ENVIRONMENTAL PERSPECTIVES

Meena D

Assistant Professor, Seven Hills College of Pharmacy, Tirupati, Andhra Pradesh 517561, India

Corresponding Author
Meena D

Email: - meenakabi@yahoo.co.in

Article Info

Received 24/01/2026; Revised 25/02/2026
Accepted 21/03/2026

ABSTRACT

The pharmaceutical industry plays a vital role in healthcare advancement but is also associated with significant environmental challenges due to the use of hazardous chemicals, high energy consumption, and generation of large volumes of waste. Green chemistry has emerged as a sustainable framework aimed at minimizing the environmental impact of chemical processes by promoting safer, more efficient, and eco-friendly alternatives. In pharmaceutical manufacturing, the application of green chemistry principles focuses on reducing toxic solvent usage, improving atom economy, enhancing energy efficiency, and minimizing waste generation throughout the drug development lifecycle. Techniques such as biocatalysis, continuous flow chemistry, solvent-free synthesis, and the use of renewable feedstocks have demonstrated considerable potential in improving process sustainability. Additionally, the integration of green analytical methods and lifecycle assessment tools enables better evaluation and optimization of environmental performance. Regulatory agencies and industry stakeholders are increasingly adopting green chemistry practices to meet environmental standards and corporate sustainability goals. Despite these advancements, challenges such as cost, scalability, and technological limitations continue to hinder widespread implementation. This review provides a comprehensive overview of green chemistry approaches in pharmaceutical manufacturing, highlighting recent innovations, industrial applications, and environmental benefits. It also discusses current challenges and future directions for achieving sustainable and environmentally responsible pharmaceutical production.

Keywords: Green chemistry; Pharmaceutical manufacturing; Sustainable processes; Bio catalysis.

INTRODUCTION

The pharmaceutical industry is a cornerstone of modern healthcare, responsible for the development and production of life-saving drugs and therapeutic agents; however, it is also recognized as one of the most resource-intensive and environmentally impactful sectors within the chemical industry. Conventional pharmaceutical manufacturing processes often involve the extensive use of hazardous solvents, toxic reagents, and energy-intensive reactions, resulting in significant waste generation and environmental pollution. The concept of green chemistry, introduced to promote sustainable chemical practices, provides a strategic framework for redesigning pharmaceutical processes to reduce environmental impact while maintaining efficiency and product quality[1]. Based on principles such as waste prevention, atom economy, safer solvent use, energy efficiency, and the use of renewable feedstock's, green chemistry aims to minimize the ecological footprint of chemical manufacturing. In the context of pharmaceuticals, these principles are increasingly being integrated into drug synthesis, formulation, and analytical processes. Advances in technologies such as biocatalysts, which utilizes enzymes for selective and mild chemical transformations, and continuous flow chemistry, which enhances reaction efficiency and scalability, have significantly contributed to the adoption of greener manufacturing practices. The use of alternative solvents, including water, ionic liquids, and supercritical fluids, has further reduced reliance on hazardous organic solvents[2]. Additionally, process intensification techniques, such as microwave-assisted synthesis and ultrasound technologies, have improved reaction rates and reduced energy consumption. Lifecycle assessment approaches are also being employed to evaluate the environmental impact of pharmaceutical products from raw material sourcing to disposal. Regulatory bodies and industry leaders are increasingly recognizing the importance of sustainability, leading to the incorporation of green chemistry principles into guidelines and best practices. Despite these advancements, challenges such as high implementation costs, regulatory constraints, and the need for technological innovation remain barriers to widespread adoption. As global demand for pharmaceuticals continues to rise, there is an urgent need to transition toward environmentally sustainable manufacturing practices. This review aims to explore the application of green chemistry approaches in pharmaceutical manufacturing, emphasizing their environmental benefits, technological advancements, and future potential in achieving sustainable development goals.

Concept of Green Chemistry in Pharmaceuticals

Green chemistry in pharmaceuticals refers to the application of environmentally benign principles and practices in the design, synthesis, and production of drug substances and formulations to minimize hazardous substances and reduce environmental impact. Rooted in the 12 principles of green chemistry, this concept emphasizes waste prevention, atom economy, safer solvents, energy efficiency, and the use of renewable feedstock's. In pharmaceutical contexts, it seeks to redesign traditional synthetic routes that often involve multiple steps, toxic reagents, and large solvent volumes, thereby reducing environmental burden and improving process efficiency. The concept extends beyond chemical synthesis to include formulation, packaging, and lifecycle considerations, promoting a holistic approach to sustainability[3]. By prioritizing non-toxic reagents, biodegradable intermediates, and efficient catalytic processes, green chemistry aims to enhance safety for both human health and the environment. Techniques such as biocatalysts, solvent-free reactions, and continuous flow processes have gained prominence due to their ability to improve selectivity, reduce waste, and lower energy consumption. Additionally, green analytical chemistry plays a role in minimizing solvent usage and hazardous waste during quality control processes. The integration of computational tools and predictive modeling further supports the identification of sustainable pathways during early drug development stages. Green chemistry also aligns with regulatory expectations and corporate sustainability goals, encouraging pharmaceutical companies to adopt environmentally responsible practices. Despite its advantages, challenges such as cost, scalability, and resistance to change in established processes can hinder widespread implementation[4]. However, growing environmental awareness and stricter regulations are driving the transition toward greener practices. Overall, the concept of green chemistry in pharmaceuticals represents a paradigm shift toward sustainable innovation, balancing therapeutic efficacy with environmental stewardship.

Figure 1: Concept of Green Chemistry in Pharmaceuticals

Importance of Sustainable Manufacturing

Sustainable manufacturing in the pharmaceutical industry is essential for reducing environmental impact while maintaining economic viability and ensuring the availability of high-quality medicines. Traditional pharmaceutical processes are often resource-intensive, involving large quantities of raw materials, solvents, and energy, leading to significant waste generation and emissions. Sustainable manufacturing aims to optimize resource utilization, minimize waste, and reduce environmental pollution through the adoption of efficient and eco-friendly practices. This approach not only addresses environmental concerns but also enhances operational efficiency and cost-effectiveness.[5] By implementing green chemistry principles, pharmaceutical manufacturers can reduce the use of hazardous substances, improve reaction efficiency, and lower energy consumption. Sustainable practices such as recycling and reuse of solvents, waste valorization, and process optimization contribute to reducing the overall environmental footprint. Additionally, the integration of renewable energy sources and advanced technologies, such as continuous manufacturing and automation, further enhances sustainability. Sustainable manufacturing also plays a crucial role in regulatory compliance, as environmental regulations become increasingly stringent worldwide. Companies adopting sustainable practices can gain a competitive advantage by meeting regulatory requirements and improving their corporate image. Furthermore, sustainable manufacturing supports global efforts to achieve environmental and public health goals, including the reduction of greenhouse gas emissions and conservation of natural resources[6,7]. Despite its benefits, challenges such as high initial investment costs, technological limitations, and the need for skilled personnel can impede implementation. However, long-term benefits, including cost savings, improved efficiency, and reduced environmental impact, outweigh these challenges. The transition toward sustainable manufacturing is not only a necessity but also an opportunity for innovation and growth in the pharmaceutical industry, ensuring a balance between economic development and environmental protection[8].

Relevance to Pharmaceutical Industry

Green chemistry and sustainable practices are highly relevant to the pharmaceutical industry due to its significant environmental footprint and the increasing demand for environmentally responsible manufacturing processes. The industry is characterized by complex synthetic pathways, high solvent usage, and substantial waste generation, making it a prime candidate for the adoption of green chemistry principles. Implementing these principles can lead to improved process efficiency, reduced environmental impact, and enhanced product quality. The relevance of green chemistry is further underscored by regulatory pressures and the need to comply with environmental standards set by agencies worldwide. Pharmaceutical companies are increasingly incorporating sustainability into their business strategies, recognizing its importance for long-term success and social responsibility[1,7]. Green chemistry also supports innovation by encouraging the development of new synthetic methods, alternative solvents, and efficient catalytic systems. These advancements can lead to cost savings, improved scalability, and reduced time-to-market for new drugs. Additionally, sustainable practices contribute to risk reduction by minimizing the use of hazardous chemicals and improving workplace safety. The adoption of green chemistry is also driven by consumer awareness and demand for environmentally friendly products. Companies that prioritize sustainability can enhance their reputation and gain a competitive advantage in the global market. Collaboration between academia, industry, and regulatory bodies is essential for advancing green chemistry initiatives and overcoming challenges related to implementation. Overall, the relevance of green chemistry to the pharmaceutical industry lies in its ability to drive innovation, improve efficiency, and reduce environmental impact, making it a key component of sustainable development in healthcare.[9]

Figure:2 Relevance to Pharmaceutical Industry

Environmental Impact of Conventional Pharmaceutical Manufacturing

Conventional pharmaceutical manufacturing processes are associated with significant environmental impacts due to the extensive use of hazardous chemicals, large volumes of solvents, and energy-intensive operations. These processes often generate substantial amounts of waste, including toxic byproducts and emissions that can contaminate air, water, and soil. The use of organic solvents, which are often volatile and flammable, contributes to air pollution and poses risks to human health and the environment. Additionally, inefficient reaction pathways with low atom economy result in the generation of large quantities of waste relative to the desired product[10]. Wastewater generated during manufacturing may contain active pharmaceutical ingredients, intermediates, and residual solvents, which can enter natural water bodies if not adequately treated. This contamination can affect aquatic ecosystems and contribute to the development of antimicrobial resistance. Energy consumption in pharmaceutical manufacturing is another major concern, as many processes require high temperatures and pressures, leading to increased greenhouse gas emissions. The environmental impact is further exacerbated by the use of non-renewable raw materials and the generation of hazardous waste that requires specialized disposal methods. Regulatory requirements for waste management and environmental protection are becoming increasingly stringent, necessitating the adoption of cleaner and more efficient processes. Addressing the environmental impact of conventional manufacturing is essential for achieving sustainability and protecting ecosystem health[11,12].

Supercritical Fluids in Drug Synthesis

Supercritical fluids, particularly supercritical carbon dioxide ($scCO_2$), have gained significant attention as environmentally friendly alternatives to conventional organic solvents in pharmaceutical synthesis. A supercritical fluid is a substance that exhibits properties of both liquids and gases when subjected to conditions above its critical temperature and pressure, allowing it to dissolve compounds like a liquid while maintaining gas-like diffusivity. Supercritical CO_2 is especially attractive due to its non-toxic, non-flammable, and readily available nature, as well as its low environmental impact. In drug synthesis and formulation, $scCO_2$ is used for processes such as extraction, particle formation, and purification[13,14]. Its tunable solvent properties, achieved by adjusting temperature and pressure, enable selective solubilization of compounds, improving reaction efficiency and product purity. Additionally, $scCO_2$ can be easily removed from the final product by depressurization, eliminating the need for solvent recovery and reducing waste generation. This technology is particularly useful for producing nanoparticles and improving drug solubility and bioavailability. Despite its advantages, challenges such as high equipment costs and the need for specialized infrastructure can limit its widespread adoption. However, ongoing research and technological advancements are expected to overcome these barriers, making supercritical fluids a key component of green pharmaceutical manufacturing[15].

Catalysis in Green Pharmaceutical Synthesis

Catalysis plays a central role in green pharmaceutical synthesis by enhancing reaction efficiency, selectivity, and sustainability. Catalysts enable chemical reactions to proceed under milder conditions, reducing energy consumption and minimizing the formation of unwanted byproducts. In pharmaceutical manufacturing, catalytic processes are widely used to improve atom economy and reduce waste generation. Bio catalysis, which involves the use of enzymes as catalysts, has gained prominence due to its high specificity and ability to operate under mild conditions. Enzymatic reactions often eliminate the need for hazardous reagents and solvents, making them environmentally friendly.[16] Additionally, catalytic processes can be integrated into continuous flow systems, further improving efficiency and scalability. The development of novel catalysts and catalytic systems continues to drive innovation in green chemistry, enabling the synthesis of complex pharmaceutical compounds in a more sustainable manner. Catalysis also contributes to cost reduction by increasing reaction yields and reducing the need for purification steps. Overall, catalytic approaches are essential for achieving sustainable pharmaceutical manufacturing and minimizing environmental impact.[17]

Heterogeneous and Homogeneous Catalysis

Heterogeneous and homogeneous catalysis are two fundamental approaches in green pharmaceutical synthesis, each offering distinct advantages and applications. Homogeneous catalysts are present in the same phase as the reactants, typically in solution, and provide high activity and selectivity due to their uniform distribution. These catalysts are widely used in pharmaceutical synthesis for complex reactions requiring precise control. However, their separation from reaction mixtures can be challenging, leading to additional purification steps and potential waste generation. In contrast, heterogeneous catalysts exist in a different phase, usually as solids in contact with liquid or gaseous reactants[18]. They offer advantages such as ease of separation, reusability, and stability, making them suitable for large-scale industrial applications. Heterogeneous catalysts are often used in processes such as hydrogenation and oxidation, where they can be easily recovered and reused, reducing waste and cost. Advances in catalyst design, including the development of Nano catalysts and supported catalysts, have improved the performance and applicability of both types. The choice between homogeneous and heterogeneous catalysis depends on factors such as reaction type, desired selectivity, and scalability. Integrating these catalytic approaches into pharmaceutical manufacturing processes can significantly enhance sustainability and efficiency.[19]

Energy Efficiency in Pharmaceutical Manufacturing

Energy efficiency is a critical aspect of sustainable pharmaceutical manufacturing, as traditional processes often involve high energy consumption due to heating, cooling, and pressure requirements. Reducing energy usage not only lowers operational costs but also minimizes greenhouse gas emissions and environmental impact. Green chemistry approaches aim to improve energy efficiency by optimizing reaction conditions, reducing process steps, and adopting alternative technologies. Techniques such as microwave-assisted synthesis and ultrasound-assisted reactions enable faster reaction rates and lower energy consumption compared to conventional methods.[20] Continuous flow processing further enhances energy efficiency by maintaining optimal reaction conditions and reducing energy losses. The use of renewable energy sources, such as solar and wind power, is also being explored to reduce the carbon footprint of pharmaceutical manufacturing. Energy-efficient equipment and process integration strategies contribute to improved overall efficiency. Despite the initial investment required for implementing energy-efficient technologies, the long-term benefits in terms of cost savings and environmental sustainability are significant. Enhancing energy efficiency is essential for achieving sustainable manufacturing and meeting global environmental goals[12,21].

Green Drug Design and Lifecycle Assessment

Green drug design and lifecycle assessment are essential components of sustainable pharmaceutical development, focusing on minimizing environmental impact throughout the entire lifecycle of a drug, from design and production to use and disposal. Green drug design involves the development of pharmaceutical compounds that are effective, safe, and environmentally benign, with an emphasis on biodegradability and reduced toxicity. By considering environmental factors during the early stages of drug development, it is possible to design compounds that degrade more readily after use, reducing their persistence in the environment. Lifecycle assessment (LCA) is a systematic approach used to evaluate the environmental impact of a product at each stage of its lifecycle, including raw material extraction, manufacturing, distribution, use, and disposal [22]. LCA provides valuable insights into resource consumption, emissions, and waste generation, enabling the identification of areas for improvement. Integrating green design principles with lifecycle assessment helps optimize pharmaceutical processes and reduce environmental burden. This approach also supports regulatory compliance and corporate sustainability goals. Advances in computational modeling and predictive tools are enhancing the ability to design environmentally friendly drugs. Overall, green drug design and lifecycle assessment are critical for achieving sustainable pharmaceutical development.

Table 1: Principles of Green Chemistry in Pharmaceutical Manufacturing

Principle	Description
Waste Prevention	Design chemical processes to minimize waste generation.
Atom Economy	Maximize the incorporation of all materials into the final product.
Safer Solvents	Use less hazardous solvents or avoid them altogether.
Energy Efficiency	Minimize energy consumption during chemical reactions.
Renewable Feedstocks	Use renewable materials as raw materials in chemical processes.

Case Studies in Green Pharmaceutical Manufacturing

Several case studies demonstrate the successful implementation of green chemistry principles in pharmaceutical manufacturing, highlighting the potential for reducing environmental impact while maintaining efficiency and profitability. One notable example is the use of biocatalysis in the synthesis of chiral intermediates, which has significantly reduced the need for hazardous reagents and improved reaction selectivity. Continuous flow chemistry has been adopted in the production of active pharmaceutical ingredients, enabling better control over reaction conditions, reduced waste, and enhanced scalability. The replacement of traditional organic solvents with greener alternatives, such as water and supercritical fluids, has also been successfully implemented in various processes. In addition, process intensification techniques have led to shorter reaction times and lower energy consumption. These case studies illustrate the benefits of integrating green chemistry into pharmaceutical manufacturing, including cost savings, improved efficiency, and reduced environmental impact. Collaboration between industry and academia has played a key role in developing and implementing these innovations. Despite challenges such as initial investment and technological adaptation, the success of these case studies demonstrates the feasibility and advantages of green manufacturing practices.

CONCLUSION

Green chemistry approaches in pharmaceutical manufacturing represent a transformative pathway toward achieving environmental sustainability while maintaining the efficiency and quality of drug production. The traditional pharmaceutical industry, characterized by high resource consumption, extensive solvent usage, and significant waste generation, has long contributed to environmental degradation and ecological imbalance. In contrast, the integration of green chemistry principles—such as waste prevention, atom economy, safer solvent use, energy efficiency, and the adoption of renewable resources—offers a systematic and scientifically grounded strategy to minimize these impacts. Advances in catalytic technologies, including biocatalysis and heterogeneous catalysis, have enabled more selective and efficient reactions under mild conditions, thereby reducing energy requirements and hazardous byproducts. Similarly, the use of alternative reaction media such as supercritical fluids, water, and ionic liquids has significantly reduced dependence on toxic organic solvents. Process intensification techniques, including continuous flow chemistry and microwave-assisted synthesis, have further enhanced operational efficiency and scalability, contributing to reduced environmental footprints. Energy efficiency measures and the integration of renewable energy sources have also played a crucial role in lowering greenhouse gas emissions associated with pharmaceutical production. Moreover, green drug design and lifecycle assessment approaches ensure that environmental considerations are incorporated from the early stages of drug development through to disposal, promoting a holistic perspective on sustainability. Despite these advancements, challenges such as high initial investment costs, technological limitations, regulatory complexities, and the need for skilled expertise continue to hinder widespread adoption. However, the long-term benefits, including cost savings, improved process efficiency, enhanced regulatory compliance, and reduced environmental impact, strongly justify the transition toward greener practices. The success of various industrial case studies demonstrates the feasibility and effectiveness of implementing green chemistry in real-world pharmaceutical manufacturing. Moving forward, interdisciplinary collaboration among scientists, engineers, policymakers, and industry stakeholders will be essential to drive innovation and facilitate the large-scale adoption of sustainable technologies. Additionally, increased regulatory support, public awareness, and investment in research and development will accelerate the integration of green chemistry principles across the pharmaceutical sector. In conclusion, green chemistry is not merely an optional strategy but a critical necessity for the future of pharmaceutical manufacturing, ensuring that the industry continues to meet global healthcare demands while preserving environmental integrity and supporting sustainable development goals.

REFERENCES

1. Dey, V. D., Verma, V. S. V., Pandey, A. P., Gupta, N., Chandrakar, J. C., & Yadav, P. K. Y. (2025). Green pharmaceutical manufacturing: A focus on sustainable approaches to drug formulation development, production & case studies. *Indian J Pharm Chem Anal Tech*, 1–20.
2. Onagun, Q., & Gbenga, A. (2024). Green chemistry in medicinal chemistry: A review on sustainable approaches to the synthesis of biologically active compounds. *World J Adv Res Rev*, 24, 1371–1382.
3. Ran, J. (2024). The application and prospect of green chemistry in the pharmaceutical field. *TNS*, 58, 55–59.
4. Beaver, M. G., Caille, S., Içten, E., Michalak, S. E., St-Pierre, G., & Thiel, O. R. (2021). Green chemistry as a driver for innovation in the pharmaceutical industry. *Israel Journal of Chemistry*, 61, 369–379.
5. Raval, D. (2020). Green chemistry approaches in pharmaceutical manufacturing. *Zykra*.
6. Idoko, F., Ezeamii, G., & Ojochogwu, O. (2024). Green chemistry in manufacturing: Innovations in reducing environmental impact. *World J Adv Res Rev*, 23, 2826–2841.
7. Kumar, A., Verma, M., Kumar, R., & Ahmed, S. (2025). Sustainable pharmaceuticals. In *Iterative International Publishers Selfypage Developers Pvt Ltd* (pp. 107–119).
8. McElhone, D., & Cassey, B. (2024). Why greener pharmaceutical manufacturing is vital for the industry and our health. *Open Access Government*, 42, 54–55.
9. Grover, T., Chauhan, R., Gajjar, A., Dhameliya, T., & Vaja, M. (2023). Impact of green approaches in pharmaceutical industries. 65–90.
10. Colberg, J., Tucker, J. L., Martínez, I., Bailey, J. D., Briddell, C., Koenig, S. G., et al. (2025). Environmental sustainability strategy of active pharmaceutical ingredient manufacturing: A perspective from the American Chemical Society Green Chemistry Institute Pharmaceutical Roundtable. *ACS Sustainable Chem Eng*, 13, 10268–10284.
11. Wani, S. P., Kulkarni, S. Y., Pingale, P. L., & Amrutkar, S. V. (2025). Sustainable wastewater management in the pharmaceutical industry. In *IGI Global* (pp. 367–398).
12. Muthoni, L. K. (2025). Sustainable practices in pharmaceutical manufacturing. *NIJPP*, 6, 42–49.
13. Razzak, F. S. A. (2021). Review on green solvent supercritical carbon dioxide and its chemical reactions. *JSR*, 65, 17–22.
14. Aionicesei, E., Škerget, M., & Knez, Ž. (2021). Supercritical CO2, a clean alternative to traditional methods of processing polymeric biomaterials. *AMB*, 2, 19–24.
15. Sodeifian, G., & Usefi, M. M. B. (2022). Solubility, extraction, and nanoparticles production in supercritical carbon dioxide: A mini-review. *ChemBioEng Reviews*, 10, 133–166.
16. Masci, D., & Castagnolo, D. (2021). Biocatalysis, an introduction. Exploiting enzymes as green catalysts in the synthesis of chemicals and drugs. In *Royal Society Of Chemistry* (pp. 68–118).
17. Patel, P., Patel, P., & Mulla, T. (2025). Green chemistry approaches in pharmaceutical synthesis. *Asian Journal of Research in Chemistry*, 6, 401.
18. Sachdeva, G., Vaya, D., Rawat, V., & Rawat, P. (2022). Solid-supported catalyst in heterogeneous catalysis. In *CRC* (pp. 105–125).
19. Wang, H., & Yu, J. (2024). Future factory: A case study on energy and carbon reduction in a bio-pharmaceutical plant. *JREAS*, 9, 685–689.
20. Achieng, M. N. (2025). Green chemistry in pharmaceuticals: Reducing environmental impact. *NIJPP*, 6, 36–41.
21. (18193101) S., (22500889) M., (3346718) G., (1512790) J., & (1330920) E. (2025). Integrated life cycle assessment guides sustainability in synthesis: Antiviral letermovir as a case study. *Figshare*.
22. Bisaria, D. (2025). Green chemistry and its prospects in present era. *IJARSCT*, 559.