



GREEN PHARMACY: ECO-FRIENDLY APPROACHES IN PHARMACEUTICAL MANUFACTURING – A REVIEW

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ABSTRACT

Green pharmacy is an emerging approach that integrates the principles of environmental sustainability into pharmaceutical research, manufacturing, distribution, use, and disposal of medicines. The pharmaceutical industry contributes significantly to environmental pollution through the generation of hazardous waste, solvent emissions, wastewater, and high energy consumption. Green pharmacy aims to minimize these environmental impacts by applying green chemistry principles, eco-friendly manufacturing technologies, waste minimization strategies, and sustainable resource management. This review discusses the concept and objectives of green pharmacy, principles of green chemistry, environmental issues associated with pharmaceutical manufacturing, eco-friendly manufacturing approaches, benefits, challenges, and future perspectives. The adoption of green pharmacy practices not only protects the environment but also improves manufacturing efficiency, regulatory compliance, and public health. Therefore, green pharmacy plays a vital role in achieving sustainable pharmaceutical development and ensuring environmental protection for future generations.^[1-8]

KEYWORDS: Green Pharmacy, Green Chemistry, Pharmaceutical Manufacturing, Environmental Sustainability, Waste Management, Eco-Friendly Technology.

INTRODUCTION

The pharmaceutical industry plays a significant role in improving human health but also contributes to environmental pollution through chemical waste, solvent emissions, wastewater, and excessive energy consumption. Increasing environmental concerns and stringent regulations have encouraged industries to adopt sustainable manufacturing practices. Green pharmacy applies the principles of green chemistry and environmental science throughout the lifecycle of medicines to reduce pollution and improve sustainability.^[1-4] The pharmaceutical industry is among the most rapidly expanding sectors globally and plays a pivotal role in enhancing public health by developing, producing, and supplying therapeutic medicines. Despite its significant contributions to healthcare, pharmaceutical manufacturing is associated with considerable

environmental challenges due to the extensive use of hazardous chemicals, organic solvents, large volumes of water, and substantial energy consumption. These manufacturing activities generate chemical waste, greenhouse gas emissions, and wastewater containing active pharmaceutical ingredients (APIs), all of which contribute to environmental pollution. The presence of pharmaceutical contaminants in surface water, groundwater, soil, and even drinking water has become a growing concern because of their potential ecological toxicity and their role in promoting antimicrobial resistance.

In response to these environmental concerns, the concept of green pharmacy has gained increasing attention as a sustainable framework that incorporates the principles of green chemistry, environmental protection, and

sustainable engineering throughout the entire life cycle of pharmaceutical products. This approach encompasses drug discovery, manufacturing, distribution, utilization, and disposal, with the objective of minimizing environmental impacts while maintaining the quality, safety, and therapeutic effectiveness of medicines. Green pharmacy promotes resource-efficient manufacturing processes, pollution prevention, waste reduction, and the adoption of environmentally benign technologies. Furthermore, major regulatory authorities and international organizations, including the World Health Organization (WHO), International Council for Harmonisation (ICH), U.S. Food and Drug Administration (FDA), European Medicines Agency (EMA), and International Pharmaceutical Federation (FIP), increasingly advocate sustainable manufacturing practices and environmental stewardship within the pharmaceutical sector. Consequently, green pharmacy has emerged as a fundamental strategy for advancing sustainable pharmaceutical development while safeguarding both environmental integrity and public health.

Objectives of Green Pharmacy

The primary objectives of green pharmacy are to:

- Minimize the production of hazardous chemicals and reduce the generation of pharmaceutical waste during manufacturing processes.
 - Prevent or significantly reduce environmental pollution associated with pharmaceutical production and disposal.
 - Encourage the implementation of green chemistry principles in the design and synthesis of pharmaceutical compounds.
 - Enhance energy efficiency in manufacturing operations while lowering greenhouse gas emissions.
 - Promote sustainable water management practices, including water conservation, treatment, and recycling.
 - Increase the utilization of renewable resources and environmentally biodegradable materials in pharmaceutical production.
 - Improve workplace health and safety by limiting occupational exposure to hazardous and toxic substances.
 - Ensure compliance with environmental regulations and sustainability standards established by national and international regulatory authorities.
 - Encourage the safe collection, handling, and environmentally sound disposal of unused and expired pharmaceutical products.
 - Support the transition toward sustainable healthcare systems by integrating circular economy principles into pharmaceutical manufacturing and supply chains.
- Reduce environmental pollution.^[1]
 - Minimize hazardous waste generation.^[2]
 - Promote eco-friendly manufacturing.^[3]

- Improve energy and water efficiency.^[4]
- Encourage proper disposal of pharmaceutical waste.^[5]
- Support sustainable healthcare.^[3]

Principles of Green Pharmacy

The principles include prevention of waste, safer chemical synthesis, use of renewable raw materials, energy-efficient manufacturing, environmentally friendly solvents, reduction of toxic by-products, and the design of biodegradable pharmaceutical products.^[1,2,6]

The concept of green pharmacy is based on the **Twelve Principles of Green Chemistry**, developed by **Paul T. Anastas and John C. Warner**, which serve as a foundation for designing environmentally sustainable pharmaceutical processes. These principles encourage the prevention of waste at its source rather than relying on waste treatment after production. They emphasize maximizing atom economy so that the majority of raw materials are incorporated into the final product while reducing the formation of unwanted by-products. Green chemistry also advocates the development of synthetic pathways that employ less hazardous substances, ensuring safer chemical processes and minimizing risks to human health and the environment.^[1]

Furthermore, these principles promote the design of pharmaceutical compounds with lower toxicity, the replacement of hazardous solvents with environmentally friendly alternatives, and the implementation of energy-efficient manufacturing methods. They encourage the utilization of renewable feed stocks instead of finite fossil-based resources, reduction of unnecessary derivatization steps, and the preference for catalytic reactions over stoichiometric reagents to improve reaction efficiency. Additional recommendations include designing biodegradable pharmaceutical products that decompose into harmless substances after use, applying real-time analytical monitoring to prevent pollution, and adopting inherently safer chemical processes to minimize the possibility of industrial accidents. Collectively, these principles provide a comprehensive framework for achieving cleaner production, enhanced process efficiency, and sustainable pharmaceutical manufacturing.^[1,2]

Environmental Challenges in Pharmaceutical Manufacturing

Pharmaceutical production is recognized as a significant contributor to environmental pollution because of its dependence on large quantities of chemicals, solvents, water, and energy. During manufacturing, emissions of volatile organic compounds (VOCs) can deteriorate air quality, while inadequately treated wastewater containing active pharmaceutical ingredients (APIs), antibiotics, hormones, and organic solvents can contaminate rivers, lakes, and groundwater. Improper disposal of pharmaceutical residues further contributes to soil pollution and poses risks to terrestrial ecosystems.^[7,9]

In addition to chemical contamination, pharmaceutical manufacturing is associated with considerable greenhouse gas emissions resulting from energy-intensive production processes and the continued use of fossil fuels. Large-scale consumption of water and electricity places additional stress on natural resources, whereas hazardous solid wastes generated during manufacturing require specialized disposal methods. The extensive use of plastic packaging also contributes to persistent environmental pollution. Moreover, the discharge of antibiotic residues into the environment promotes the emergence of antimicrobial-resistant microorganisms, while pharmaceutical contaminants may adversely affect aquatic organisms by disrupting their growth, reproduction, and overall ecosystem health.^[6,9]

Sustainable Approaches to Pharmaceutical Manufacturing

The pharmaceutical industry is increasingly adopting environmentally sustainable manufacturing strategies to reduce ecological impacts while maintaining product quality and regulatory compliance. Green chemistry-based synthesis represents one of the most effective approaches by reducing the use of hazardous chemicals, minimizing waste generation, and improving reaction efficiency. Likewise, continuous manufacturing has emerged as an advanced production technique that enhances process control, shortens manufacturing time, lowers energy consumption, and decreases production costs compared with conventional batch manufacturing.^[12,13]

The recovery and reuse of organic solvents are widely practiced to reduce hazardous waste and conserve valuable resources. Incorporating renewable energy sources, such as solar and wind power, into pharmaceutical manufacturing facilities further decreases greenhouse gas emissions and dependence on fossil fuels. Innovative technologies including microwave-assisted synthesis and continuous flow chemistry improve reaction rates, enhance product yields, and reduce solvent and energy requirements.^[12,14]

Biocatalysis, which utilizes enzymes or microorganisms as catalysts, provides an environmentally friendly alternative to conventional chemical synthesis because reactions occur under milder conditions and generate fewer toxic by-products. Process Analytical Technology (PAT) enables continuous monitoring and control of manufacturing operations, allowing manufacturers to detect process variations in real time and reduce material losses. Similarly, the application of Quality by Design (QbD) principles facilitates systematic process optimization and consistent product quality.^[15,16]

Recent advances in artificial intelligence (AI) have further strengthened sustainable pharmaceutical manufacturing by optimizing process parameters, predicting equipment failures, improving resource

utilization, and minimizing production inefficiencies. Other important green manufacturing initiatives include the implementation of environmentally friendly analytical techniques, zero-liquid-discharge wastewater management systems, membrane-based water purification technologies, carbon emission reduction programs, and the use of biodegradable or recyclable packaging materials.^[17,19]

Green Analytical Chemistry

Green analytical chemistry aims to reduce the environmental impact associated with pharmaceutical analysis while maintaining high analytical accuracy and reliability. This objective is achieved by minimizing solvent consumption, adopting miniaturized analytical procedures, and replacing hazardous chemicals with safer and more sustainable alternatives. Modern analytical techniques, including high-performance liquid chromatography (HPLC) utilizing environmentally friendly solvents and supercritical fluid chromatography (SFC), significantly decrease solvent waste and improve laboratory sustainability.^[20,21]

The increasing use of portable analytical instruments also reduces laboratory infrastructure requirements and energy consumption. Simplified sample preparation methods decrease reagent usage and shorten analytical procedures, thereby reducing waste generation. In addition, recycling and proper management of laboratory waste contribute to environmentally responsible analytical practices and support the broader objectives of sustainable pharmaceutical development.^[22,23]

Waste Management in Green Pharmacy

Waste management is an essential element of green pharmacy and focuses on minimizing environmental impacts throughout pharmaceutical production. The most effective strategy is waste prevention through source reduction, where manufacturing processes are optimized to generate minimal waste. Proper segregation of hazardous and non-hazardous waste streams facilitates recycling, treatment, and safe disposal while reducing environmental contamination.^[24]

Recovery and recycling of organic solvents decrease both manufacturing costs and hazardous waste production. Biological wastewater treatment technologies are increasingly employed to remove pharmaceutical contaminants before wastewater is discharged into the environment. Pharmaceutical wastes that cannot be recycled are safely destroyed through high-temperature incineration under carefully controlled conditions to prevent the release of toxic substances.^[26]

Additional sustainable waste management practices include medicine take-back and reverse distribution programs for expired pharmaceuticals, environmentally sound disposal methods for unused medicines, implementation of circular economy strategies that recover valuable materials from waste streams, and

extended producer responsibility programs that encourage pharmaceutical companies to manage environmental impacts throughout the product life cycle.^[25]

Regulatory Support for Green Pharmacy

The successful implementation of green pharmacy relies on the guidance provided by various national and international regulatory organizations. The **World Health Organization (WHO)** promotes environmentally sustainable healthcare systems and responsible pharmaceutical management.^[27] The **International Council for Harmonisation (ICH)** supports sustainable pharmaceutical development through guidelines such as **ICH Q8 (Pharmaceutical Development)**, **ICH Q9 (Quality Risk Management)**, and **ICH Q10 (Pharmaceutical Quality System)**, which encourage scientifically sound manufacturing practices and continuous quality improvement.^[28,29,30]

The **United States Environmental Protection Agency (US EPA)** actively promotes green chemistry initiatives aimed at pollution prevention and sustainable chemical design.^[31] The **U.S. Food and Drug Administration (FDA)** encourages the adoption of continuous manufacturing technologies to improve efficiency and product quality.^[32] Likewise, the **European Medicines Agency (EMA)** requires environmental risk assessments for medicinal products to evaluate their potential effects on ecosystems before market approval.^[33] International standards such as **ISO 14001 Environmental Management Systems**, **Good Manufacturing Practices (GMP)**, and the **United Nations Sustainable Development Goals (SDGs)** further encourage pharmaceutical manufacturers to integrate environmental sustainability into their production systems and corporate policies.

Advantages of Green Pharmacy

The implementation of green pharmacy principles provides significant environmental, economic, and social benefits. Sustainable manufacturing practices reduce pollution by lowering emissions, minimizing hazardous waste generation, and preventing contamination of natural resources.^[1,12,34] Improved process efficiency enables manufacturers to decrease production costs through reduced consumption of raw materials, energy, and water while increasing overall productivity.^[34,35]

Green pharmacy also enhances occupational health and safety by reducing worker exposure to hazardous chemicals and improving workplace conditions.^[36] Compliance with environmental regulations becomes more effective, helping pharmaceutical companies meet increasingly stringent sustainability requirements.^[37,38] Additional benefits include a lower carbon footprint, enhanced product quality, conservation of valuable natural resources, improved corporate reputation and public confidence, and long-term sustainability of both

the pharmaceutical industry and global healthcare systems.^[12,26,36]

Environmental Issues in Pharmaceutical Manufacturing

Pharmaceutical manufacturing can lead to air pollution, water contamination, hazardous waste generation, greenhouse gas emissions, and excessive consumption of energy and water.^[2,4,7]

Eco-Friendly Manufacturing Approaches

Green manufacturing involves green chemistry, solvent recovery, continuous manufacturing, process optimization, renewable energy utilization, wastewater treatment, and green analytical techniques.^[1,3,6,8]

Benefits of Green Pharmacy

Green pharmacy reduces environmental impact, improves worker safety, lowers manufacturing costs, enhances regulatory compliance, conserves natural resources, and supports sustainable development.^[2,3,8]

Challenges

Major challenges include high implementation costs, limited availability of green technologies, lack of awareness, technical limitations, and regulatory barriers.^[2,8]

Despite its numerous environmental and economic advantages, the widespread adoption of green pharmacy faces several technical, financial, and regulatory challenges that can limit its implementation across the pharmaceutical industry.

High Initial Investment

The transition from conventional manufacturing processes to green pharmaceutical technologies requires substantial capital investment. Pharmaceutical companies often need to purchase advanced equipment, upgrade existing manufacturing facilities, and install environmentally friendly technologies for waste treatment, solvent recovery, and energy-efficient production.^[1,12,34,35,36] These high upfront costs can be a significant barrier, particularly for small and medium-sized pharmaceutical enterprises.^[30,36]

Limited Availability of Green Technologies

Although considerable progress has been made in sustainable pharmaceutical manufacturing, many green technologies are still in the developmental or early commercialization stages.^[12,36] Advanced technologies such as continuous manufacturing, biocatalysis, membrane-based purification systems, and zero-liquid-discharge processes are not yet widely available or economically feasible for all manufacturers.^[39,40,41,42] This limited accessibility slows the global adoption of environmentally sustainable production methods.^[12,36,40]

Resistance to Technological Change

Many pharmaceutical manufacturers continue to rely on conventional manufacturing processes because they are well-established, validated, and familiar to industry professionals. The transition to greener alternatives often requires significant modifications to production systems, employee training, and operational procedures. Concerns regarding production interruptions, regulatory approvals, and financial risks may result in resistance to adopting new technologies.

Shortage of Skilled Professionals

Successful implementation of green pharmacy requires multidisciplinary expertise in green chemistry, environmental engineering, sustainable process design, analytical sciences, and regulatory compliance. However, there is a shortage of adequately trained professionals with specialized knowledge in these fields. Limited educational programs and insufficient industry training opportunities further contribute to the skills gap, particularly in developing countries.

Complex Regulatory Requirements

Pharmaceutical manufacturing is governed by stringent national and international regulatory standards to ensure product quality, safety, and efficacy. Introducing new green manufacturing processes often requires extensive regulatory review, documentation, and approval before implementation. Differences in regulatory frameworks among countries can further complicate the adoption of sustainable technologies on a global scale.

Validation of Green Manufacturing Processes

Every modification made to pharmaceutical manufacturing processes must undergo comprehensive validation to demonstrate that product quality, safety, efficacy, and consistency remain unaffected. Validation studies require considerable time, technical expertise, and financial resources, making the implementation of environmentally friendly technologies both challenging and resource-intensive.

Limited Awareness and Infrastructure in Developing Countries

In many low- and middle-income countries, awareness of green pharmacy concepts remains relatively low among manufacturers, healthcare professionals, policymakers, and consumers. Inadequate infrastructure, limited financial resources, insufficient government incentives, and lack of access to advanced technologies hinder the widespread adoption of sustainable pharmaceutical manufacturing practices.

Supply Chain and Raw Material Challenges

Green pharmaceutical manufacturing depends heavily on the availability of renewable raw materials, environmentally friendly solvents, sustainable packaging materials, and reliable suppliers. However, sourcing these materials consistently can be difficult due to limited production capacity, fluctuating availability,

higher procurement costs, and disruptions in global supply chains. These challenges may affect manufacturing efficiency and increase operational expenses.

High Research and Development Costs

The development of environmentally sustainable pharmaceutical products and manufacturing processes requires extensive research and innovation. Significant investments are needed for laboratory research, process optimization, pilot-scale studies, environmental risk assessments, and clinical evaluations. Additionally, the discovery of greener synthetic pathways, biodegradable drug formulations, and safer alternative materials demands long-term financial commitment and multidisciplinary collaboration, making research and development one of the most resource-intensive aspects of green pharmacy.

Overall, addressing these challenges will require collaborative efforts among pharmaceutical industries, academic institutions, regulatory authorities, and governments. Increased investment in research, technological innovation, workforce training, supportive regulatory policies, and financial incentives will play a crucial role in accelerating the global adoption of green pharmacy practices.

Future Perspectives of Green Pharmacy

Future developments include artificial intelligence-assisted green manufacturing, process analytical technology (PAT), biodegradable drug delivery systems, renewable energy integration, and circular economy practices.^[3,8]

The future of green pharmacy is closely linked to advances in digital technologies, sustainable manufacturing practices, and innovative pharmaceutical research. Continuous technological developments are expected to transform pharmaceutical manufacturing into a more environmentally responsible, resource-efficient, and economically sustainable industry. The integration of advanced engineering solutions with green chemistry principles will play a vital role in minimizing the environmental footprint of pharmaceutical production while maintaining high standards of product quality, safety, and regulatory compliance.

Artificial Intelligence-Driven Pharmaceutical Manufacturing

Artificial intelligence (AI) is expected to revolutionize pharmaceutical manufacturing by enabling intelligent process control, predictive maintenance, and automated decision-making. AI-based systems can continuously monitor manufacturing operations, identify process deviations in real time, and recommend corrective actions to improve efficiency. These technologies will help reduce energy consumption, minimize material waste, optimize production schedules, and enhance

product quality, thereby contributing significantly to sustainable pharmaceutical manufacturing.

Machine Learning for Process Optimization

Machine learning (ML), a branch of artificial intelligence, has enormous potential to optimize pharmaceutical production processes through data-driven analysis. ML algorithms can evaluate large datasets generated during manufacturing to predict process performance, improve reaction conditions, optimize formulation development, and identify quality risks before they occur. The use of machine learning is expected to reduce manufacturing costs, shorten product development timelines, improve resource utilization, and support environmentally sustainable production practices.

Digital Twin Technology

Digital twin technology involves the creation of a virtual replica of a pharmaceutical manufacturing process, equipment, or facility. This digital model allows manufacturers to simulate production conditions, evaluate process modifications, and predict system performance without interrupting actual manufacturing operations. By enabling real-time monitoring and virtual testing, digital twins can improve operational efficiency, reduce waste generation, minimize equipment downtime, and support continuous process improvement while lowering environmental impacts.

Industry 4.0 and Smart Manufacturing

The adoption of Industry 4.0 technologies is expected to accelerate the transition toward sustainable pharmaceutical manufacturing. Smart factories equipped with interconnected sensors, the Internet of Things (IoT), cloud computing, robotics, and advanced automation systems can continuously monitor production parameters and optimize resource utilization. These technologies facilitate real-time quality control, predictive maintenance, improved supply chain management, and enhanced manufacturing flexibility while reducing energy consumption, raw material losses, and greenhouse gas emissions.

Development of Sustainable Active Pharmaceutical Ingredients (APIs)

Future pharmaceutical research is likely to focus on designing active pharmaceutical ingredients that are both therapeutically effective and environmentally sustainable. The development of biodegradable APIs with lower environmental persistence will help reduce pharmaceutical contamination of water bodies and soil after patient use. Additionally, greener synthetic pathways that require fewer hazardous chemicals and generate minimal waste will contribute to safer and more sustainable pharmaceutical production.

Biodegradable Drug Delivery Systems

The development of biodegradable and environmentally friendly drug delivery systems represents another

promising direction in green pharmacy. Researchers are increasingly exploring the use of natural polymers, biodegradable biomaterials, and renewable resources to replace conventional non-degradable materials used in pharmaceutical formulations. These innovative delivery systems are expected to reduce pharmaceutical waste, minimize environmental pollution, and improve patient safety while maintaining therapeutic effectiveness.

Green Nanotechnology

Nanotechnology offers significant opportunities for improving the sustainability of pharmaceutical manufacturing and drug delivery. Green nanotechnology focuses on synthesizing nanoparticles using environmentally benign solvents, renewable biological materials, and energy-efficient processes. Such approaches reduce the use of toxic chemicals and lower environmental risks associated with nanoparticle production. In addition, nanotechnology can improve drug targeting, increase therapeutic efficacy, reduce dosage requirements, and minimize adverse effects, thereby contributing to more sustainable healthcare practices.

Carbon-Neutral Pharmaceutical Manufacturing Facilities

Achieving carbon neutrality has become an important long-term objective for the pharmaceutical industry. Future pharmaceutical manufacturing plants are expected to incorporate renewable energy sources such as solar, wind, and biomass energy, together with energy-efficient production technologies and carbon capture strategies. The implementation of sustainable building designs, low-carbon transportation systems, and optimized manufacturing processes will significantly reduce greenhouse gas emissions and support global climate change mitigation efforts.

Intelligent Waste Management Systems

Future pharmaceutical industries are likely to adopt advanced waste management systems that utilize artificial intelligence, automation, and real-time monitoring technologies to improve waste segregation, recycling, and disposal. Smart waste management systems can identify different waste streams, optimize recycling processes, monitor hazardous waste generation, and ensure compliance with environmental regulations. These technologies will improve resource recovery while reducing environmental contamination and operational costs.

Circular Economy in the Pharmaceutical Sector

The concept of a circular pharmaceutical economy is expected to become a cornerstone of sustainable pharmaceutical development. Unlike the traditional linear production model based on "take, make, and dispose," a circular economy emphasizes reducing resource consumption, extending product life cycles, recovering valuable materials, and recycling manufacturing waste. Future pharmaceutical companies

are likely to integrate solvent recovery, water reuse, sustainable packaging, medicine take-back programs, and resource-efficient manufacturing into their operations. These practices will conserve natural resources, reduce waste generation, lower production costs, and promote long-term environmental sustainability.

Overall, the future of green pharmacy will depend on multidisciplinary collaboration among pharmaceutical industries, academic institutions, regulatory agencies, healthcare organizations, and policymakers. Continued investment in innovative technologies, sustainable research, workforce development, and environmentally responsible policies will accelerate the transition toward a greener pharmaceutical industry that protects both human health and the environment while supporting the global goals of sustainable development.

CONCLUSION

Green pharmacy is an effective strategy for reducing the environmental impact of pharmaceutical manufacturing while maintaining product quality and patient safety. The implementation of green chemistry, sustainable manufacturing technologies, efficient waste management, and environmentally responsible practices will contribute to cleaner pharmaceutical production and support sustainable healthcare.^[1-8]

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