Green Pharmacy Approaches to Reduce Carbon Footprint in Healthcare: Sustainable Strategies for Pharmaceutical Manufacturing

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Abstract:

Climate change and environmental contamination are growing worldwide issues, and the healthcare and pharmaceutical industries play a substantial role through their carbon emissions, waste production, and intensive use of resources. Drug manufacturing involves high energy consumption, solvent-based chemical synthesis, significant packaging waste, and multifaceted distribution systems, all of which heighten the environmental impact of healthcare delivery. As a result, green pharmacy has gained attention as a sustainable concept designed to reduce ecological damage while maintaining therapeutic performance.

The review focuses on how green chemistry, eco-friendly drug development, and sustainable production technologies can help reduce the pharmaceutical sector's carbon emissions. Approaches including additive manufacturing, microfluidics, mechanochemistry, spray congealing, and continuous processing help reduce solvent consumption, energy demand, and waste generation. Circular pharmaceutical economy practices, such as recycling programs, medication take-back initiatives, and eco-friendly packaging, further enhance environmental responsibility. Support from regulatory policies and international sustainability frameworks promotes wider implementation of green practices in healthcare. Case studies, including sustainable ibuprofen synthesis and enzyme-based drug production, highlight real-world applications.

Collectively, embedding green pharmacy approaches within drug development, manufacturing processes, and healthcare delivery is key to lowering environmental burden and advancing sustainable healthcare. Ongoing advancements in green technologies, regulatory support, and multidisciplinary collaboration are expected to further enhance environmentally conscious pharmaceutical innovation.

Keywords: Green pharmacy, sustainable pharmaceuticals, carbon footprint, green chemistry, eco-friendly drug manufacturing.

Introduction:

Climate change is widely recognized as a critical global concern, and the healthcare sector has a considerable impact through its contribution to greenhouse gas emissions and environmental deterioration. Healthcare operations generate significant waste streams, including single-use plastics, hazardous components, and biodegradable materials, many of which are disposed of via incineration or landfill. Such disposal approaches lead to greenhouse gas emissions and increase the environmental impact of healthcare provision [1].

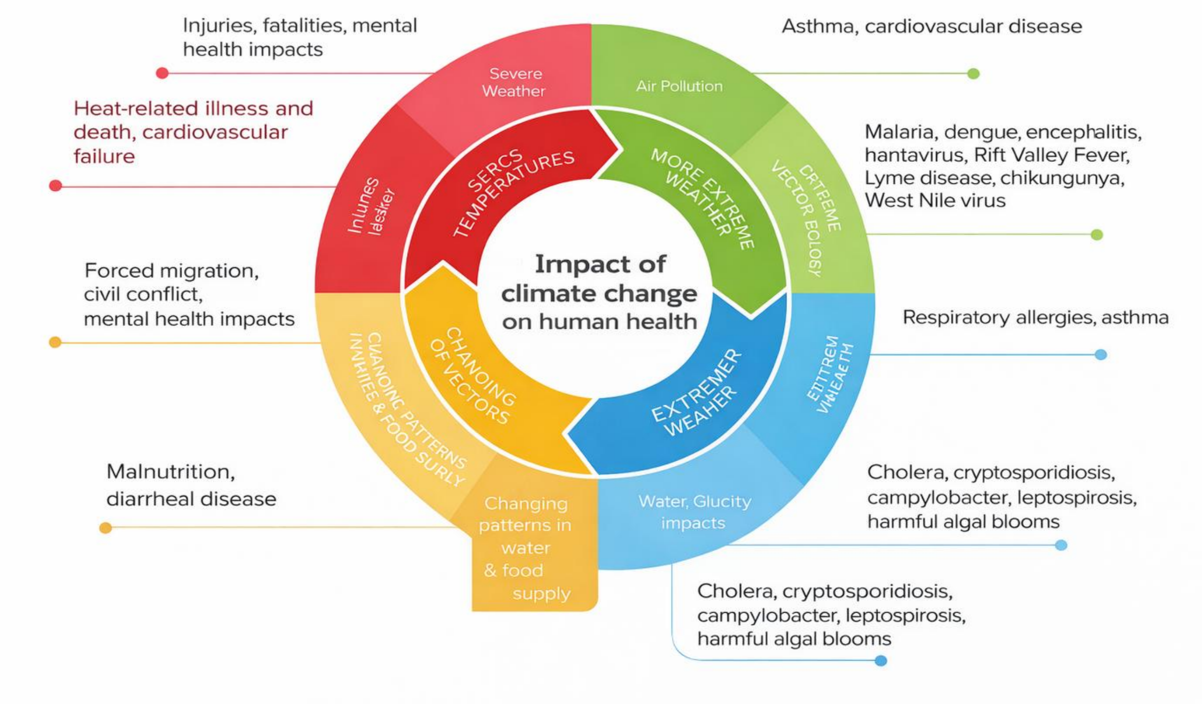

Figure 1: Impact of climate change on human health.

These concerns highlight the need for sustainable pharmaceutical advancements designed to minimize environmental harm without compromising treatment effectiveness. Such sustainable measures prioritize reduced energy demand, minimized waste output, adoption of renewable inputs, and optimization of manufacturing efficiency. Incorporating sustainability into pharmaceutical development not only helps lower carbon emissions but also improves operational efficiency and supports environmentally responsible healthcare systems. Such approaches support worldwide efforts to limit climate change impacts and ensure the continued availability of essential medications [1].

This article explores contemporary developments in green pharmacy strategies intended to lessen the environmental footprint of pharmaceutical manufacturing and healthcare systems. Through collaboration with other healthcare professionals, pharmacists play a pivotal role in promoting eco-pharmacy stewardship, identifying environmentally sustainable therapeutic alternatives, and lowering emissions linked to medication use [2].

Green Pharmacy: Environmental Impact and Green Chemistry Solutions:

Although the pharmaceutical industry is crucial to healthcare, it significantly adds to global carbon emissions. High-energy manufacturing, chemical consumption, packaging waste, and worldwide supply chains increase the environmental impact of drug production and healthcare services. Despite this impact, inadequate monitoring and limited accountability for pharmaceutical emissions have slowed recognition of the issue. Consequently, reducing the carbon footprint associated with drug manufacturing and supply chains has become increasingly important, emphasizing the need for sustainable pharmaceutical practices and green pharmacy approaches [3].

Green pharmacy emphasizes lowering the environmental footprint of medicines through sustainable design, production, distribution, and disposal methods. Environmental pollution is substantially influenced by the healthcare and pharmaceutical sectors due to their energy demands, chemical waste production, packaging usage, and emissions. These factors elevate the carbon footprint, contaminate aquatic systems, and disturb ecosystems, ultimately posing risks to human health [4].

Traces of active pharmaceutical ingredients have been found in surface water, groundwater, and drinking water, potentially affecting aquatic organisms and encouraging antimicrobial resistance. Environmental impacts are observed throughout the medicine life cycle, from manufacturing and consumption to inappropriate disposal. The burden is amplified during production due to widespread solvent use, high energy requirements, and generation of chemical by-products. Manufacturing emissions may include volatile organic compounds, unreacted reagents, and hazardous intermediates, contributing to atmospheric pollution and ecosystem disruption. These challenges highlight the necessity of implementing sustainable strategies to lessen environmental impacts throughout pharmaceutical processes[5].

Table 1: Comparison of Traditional and Green Pharmaceutical Manufacturing

Parameter	Traditional Manufacturing	Green Manufacturing
Solvents	Toxic organic solvents	Water / ethanol
Energy Use	High temperature	Mild conditions
Waste	High	Minimal
Raw materials	Petroleum based	Renewable
Environmental impact	High	Low

Green chemistry focuses on reducing environmental harm through the development of safer and sustainable pharmaceutical processes. These approaches include the use of safer solvents and reagents, waste reduction, energy-efficient processes, renewable raw materials, biodegradable drug design, environmentally friendly packaging, and proper medication disposal programs. Integrating green pharmacy practices is vital for advancing sustainable healthcare systems and ensuring the protection of human health and the environment [4].

Sustainable Drug Manufacturing Technologies

Sustainable drug manufacturing technologies are designed to lessen environmental impact, reduce waste generation, and enhance efficiency in pharmaceutical production. These methods align with green chemistry principles by limiting solvent use, decreasing energy requirements, and streamlining manufacturing steps. In addition, environmentally friendly technologies can improve scalability and increase the bioavailability of poorly soluble drugs [6].

Additive manufacturing (3D printing) allows the layer-by-layer fabrication of pharmaceutical products, which reduces material waste and facilitates the development of personalized medicine. **Microfluidic systems** utilize very small quantities of reagents, thereby reducing solvent consumption and enhancing manufacturing efficiency. Continuous manufacturing, in contrast to batch processing, lowers energy use, shortens production time, and improves product quality. **Electrospinning technology** generates nanofibers for drug delivery while using minimal materials, and solvent use can be avoided when melt electrospinning is employed [7].

Spray congealing is a solvent-free process in which a molten mixture of drug and excipients is atomized and rapidly cooled to produce solid microparticles. This technique minimizes the use of hazardous solvents, generates little waste, and yields ready-to-use powders with enhanced dissolution and stability. It is commonly applied for improving bioavailability, developing controlled-release formulations, and preparing solid dispersions [6]. **Green solvent** processing enhances sustainability by substituting toxic solvents with environmentally friendly alternatives, such as water-based or recyclable systems. **Process Analytical Technology (PAT)** improves sustainability through real-time monitoring, fewer batch failures, reduced waste, and better manufacturing efficiency [7].

Another sustainable strategy is **mechanochemical activation,** which utilizes mechanical energy, including milling, to modify drug solid-state properties. This technique enables particle size reduction, amorphization, and improved solubility and dissolution without relying on solvents. Furthermore, mechanochemistry allows solid-state salt formation and cocrystal generation, providing a greener alternative to conventional manufacturing methods. Overall, sustainable drug manufacturing technologies help lower solvent consumption, reduce energy requirements, minimize waste production, and enhance product quality. These green approaches promote environmentally responsible pharmaceutical production while improving drug performance and scalability [6].

Waste Management & Circular Pharmaceutical Economy

Pharmaceutical waste recycling focuses on the segregation, reuse, and material recovery from healthcare and pharmaceutical processes. Effective separation at the source facilitates efficient recovery of recyclable materials, including plastics, glass, and packaging components. Reusing sterilizable medical devices and implementing recycling programs can substantially decrease waste generation and environmental pollution. Recycling strategies also involve transforming non-hazardous waste into reusable materials and reducing reliance on single-use products [1].

Drug take-back programs enable consumers to return unused or expired medications to designated collection sites, including pharmacies, hospitals, and government facilities. These programs discourage unsafe disposal methods, such as flushing medicines into sinks or disposing of them with household waste, both of which can lead to groundwater contamination and adverse effects on wildlife. However, participation in these programs often remains low because of limited awareness and insufficient access to collection points, emphasizing the need for improved education and infrastructure [8].

Regulatory & Global Initiatives

Global initiatives and regulatory organizations are increasingly acknowledging the importance of reducing carbon emissions in healthcare and pharmaceutical research. International initiatives, such as United Nations climate commitments, stress the importance of reducing greenhouse gas emissions across all sectors, including healthcare and clinical research. Despite growing concerns, regulatory approval processes rarely incorporate carbon footprint assessments, and Institutional Review Boards (IRBs) or Ethics Committees usually do not examine the environmental implications of clinical trials [9].

The European Union's Green Deal and Zero Pollution Action Plan highlight the importance of lowering emissions, encouraging green chemistry, and strengthening environmental risk assessment for pharmaceuticals. Regulatory approaches such as environmental risk assessment, reverse logistics, and drug take-back initiatives further promote a circular pharmaceutical economy and responsible medicine use. However, inconsistent implementation and the absence of global standards remain significant challenges. Therefore, stronger regulations and enhanced international collaboration are required to achieve sustainable pharmaceutical practices [10].

Several gaps within the regulations of the Central Drugs Standard Control Organization affect effective drug quality monitoring. Fragmentation between central and state authorities results in inconsistent licensing, limited coordination, and uneven enforcement. In addition, shortages of drug inspectors and constrained laboratory capacity reduce routine inspections and delay the identification of substandard medicines. Additionally, ineffective recall systems, limited pharmacovigilance activities, and insufficient digital traceability restrict timely regulatory intervention. These shortcomings emphasize the need for stronger oversight, improved infrastructure, and enhanced enforcement to ensure drug safety [11].

Several initiatives have been implemented to enhance sustainability, including the promotion of teleconferencing, reduction of travel, adoption of renewable energy sources, and improved healthcare waste management. Numerous countries have committed to creating low-carbon and carbon-neutral healthcare systems, with research institutions encouraged to incorporate emission reduction measures during study design and implementation. Guidance documents, including carbon reduction frameworks for health research, further facilitate sustainable practices. Regulatory authorities are expected to assume a stronger role by incorporating carbon footprint assessments into approval processes, encouraging decentralized trials, minimizing unnecessary travel, and promoting digital monitoring. Strengthening global collaboration, adopting environmental risk assessment, and implementing sustainability guidelines can further reduce emissions and support environmentally responsible pharmaceutical and healthcare systems [9].

Case Studies in Green Pharmacy

1. Green Synthesis of Ibuprofen (BHC Process)

The Boots–Hoechst Celanese (BHC) process for ibuprofen synthesis represents a notable example of green chemistry in pharmaceutical manufacturing. Compared with the conventional six-step synthesis, the BHC approach condenses the process into three catalytic steps, thereby reducing waste generation and enhancing overall efficiency. The process utilizes highly selective catalytic reactions, which enhance atom economy and decrease the formation of by-products. This green synthesis also limits the use of stoichiometric reagents and reduces solvent consumption, thereby lowering environmental impact and operational costs. The BHC ibuprofen synthesis is considered a pioneering industrial application of green chemistry and has been honored with numerous awards for its environmentally sustainable design [12].

2. Enzyme-Based Drug Synthesis

Enzyme-based drug synthesis employs biocatalysts such as lipases, oxidoreductases, and proteases to perform selective chemical reactions under mild conditions. These reactions typically occur at ambient temperature and pressure, thereby reducing energy requirements and eliminating the need for harsh chemical reagents. Biocatalysis enhances reaction selectivity, thereby minimizing by-product formation and reducing the need for extensive purification steps. Consequently, enzyme-mediated synthesis promotes greener pharmaceutical manufacturing with lower waste generation and improved sustainability [13].

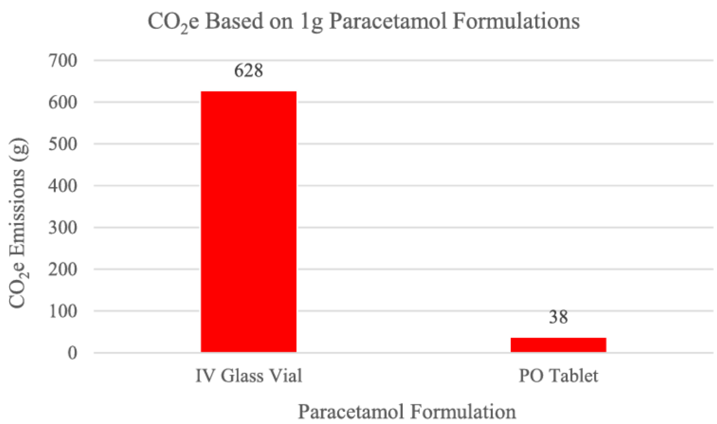

Figure 2: CO2e emissions from 1 g paracetamol based on a life cycle assessment by Davies et al. (2024).

According to life-cycle assessment data, intravenous paracetamol supplied in glass vials results in notably higher CO_2 emissions compared with oral tablet formulations. This comparison underscores the importance of prioritizing low-carbon dosage forms in clinical settings. When clinically suitable, replacing IV therapy with oral formulations can substantially decrease healthcare-associated carbon emissions and advance sustainable pharmacy practices [2].

Future Perspectives

Future developments in green pharmaceutical and healthcare practices will focus on the use of renewable energy, digital health innovations, and sustainable manufacturing methods. Combining biocatalysis, environmentally benign solvents, and waste-minimization strategies will strengthen overall environmental performance. Policy support, educational initiatives, and technological innovation will accelerate the adoption of environmentally friendly processes. These measures will improve sustainability while maintaining efficiency and cost-effectiveness in healthcare and pharmaceutical production [14].

Conclusion

Green pharmacy offers sustainable approaches to reduce the environmental impact of pharmaceutical manufacturing and healthcare delivery. The adoption of green chemistry, environmentally friendly manufacturing technologies, and circular waste management practices helps lower carbon emissions, decrease solvent use, and minimize waste generation. Regulatory support and technological innovation further encourage sustainable pharmaceutical development. Overall, the integration of green pharmacy principles is crucial for achieving environmentally responsible and sustainable healthcare systems.

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