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Green Pharmacy Practices: Progress in Sustainable Drug Synthesis and Waste Mitigation

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Abstract: The increasing environmental challenges caused by medicines have led to the creation of green and sustainable pharmacy, which promotes eco-friendly methods throughout the entire process of creating and using medical products. Medicines can enter the environment during their creation, use, and disposal, often leading to pollution of land and water, which can harm other living things. This article looks into environmentally friendly methods for making and disposing of medicines, aiming to cut down on pollution while ensuring that important medicines remain effective and available. The ideas of green chemistry provide the basis for creating drugs that are better for the environment, focusing on using safer solvents, renewable materials, energy-saving methods, and materials that break down naturally. Using techniques like catalysts, biotransformation, enzyme-driven reactions, and nanotechnology in making medicines shows great promise for reducing harmful waste and cutting down energy use. Besides creating medicines in a green way, managing the end-of-life disposal of drugs is vital to lessen their impact on nature. Safe disposal initiatives, like programs for returning unused medicines, educating homes about not flushing drugs down the toilet, and using safe burning methods and advanced water treatment technologies, are crucial to stop active pharmaceutical ingredients from contaminating water sources. New wastewater treatment techniques such as advanced oxidation, activated carbon filters, and membrane systems provide better efficiency than traditional treatment plants. A comprehensive and cooperative effort involving industries, regulators, healthcare professionals, pharmacists, and consumers is necessary to aid the global move toward sustainable pharmacy. By embracing eco-friendly production methods and responsible disposal practices, the pollution from pharmaceuticals can be greatly reduced, ultimately safeguarding human health and maintaining ecological balance.

Keywords: *Green Pharmacy, Sustainable Drug Synthesis, Eco-Friendly Pharmaceuticals, Waste Mitigation, Green Chemistry.*

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I. INTRODUCTION

The growing global need for medicines has raised worries about the impact they have on the environment during their making, use, and disposal. Green and sustainable pharmacy focuses on using eco-friendly methods throughout the life of a drug from getting raw materials, making the drug, its formulation, distribution, use, and finally, how it is disposed of to lessen harm to nature and reduce risks to human health[1]. Traditional pharmaceutical production often uses harmful chemicals, non-renewable solvents, and requires a lot of energy, all of which add significantly to pollution[2]. In addition, throwing away unused drugs incorrectly and the constant release of active pharmaceutical ingredients (APIs)

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through waste or industrial runoff have caused pollution in both water and land ecosystems[3]. This has resulted in problems like antibiotic resistance, interference with wildlife hormones, and the buildup of harmful substances[4]. Sustainable methods include green chemistry ideas such as choosing safer solvents, maximizing atom usage, improving catalytic efficiency, and using materials that can break down naturally. They also promote programs that allow the return of unused medicines, advanced technologies for waste treatment, and educating the public on how to dispose of drugs responsibly[5]. Therefore, shifting to greener pharmacy methods is crucial to lessening the environmental impact of medicines while ensuring that they remain effective and accessible.

II. ECO-FRIENDLY DRUG SYNTHESIS: PRINCIPLES OF GREEN CHEMISTRY

Green chemistry refers to creating chemical products and processes that aim to cut down or eliminate harmful substances. It offers guidelines for environmentally friendly pharmaceutical production by following its twelve main principles. These principles encourage reducing waste, improving atom use, using safer solvents, utilizing renewable resources, saving energy, and employing non-harmful materials and methods[6]. In the pharmaceutical sector, this approach has introduced reactions without solvents, chemistry in water, synthesis using microwaves, and flow reactors to enhance atom efficiency while lowering emissions[7]. The use of enzymes and whole-cell systems in biocatalysis is now common, replacing older methods that relied on metals. This change allows for better selectivity under gentler conditions while producing fewer toxic by-products[8]. Additionally, using renewable raw materials, like those derived from biomass, supports circular economy practices and lessens dependence on petrochemical resources[9]. All these improvements help create cleaner methods for making drugs, prioritizing care for the environment while maintaining the quality and effectiveness of pharmaceuticals.

➢ *Nanotechnology and Catalysis*

The use of nanotechnology and better catalytic systems in drug production has greatly improved how sustainable and efficient these processes are. Heterogeneous nanocatalysts, like metal nanoparticles placed on reusable surfaces, have a large surface area relative to their volume, which boosts their catalytic performance and precision[10]. This approach also lessens the amount of catalysts needed and the use of harmful chemicals. Additionally, their ability to be reused decreases chemical waste and lowers production costs. Nanostructured materials in continuous-flow reactors help to speed up mixing, reduce reaction times, and allow for synthesis methods that do not need solvents or can use water[11]. Enzymatic catalysis, especially using lipases, oxidoreductases, and other biological catalysts, offers eco-friendly options for specific chemical transformations at low temperatures and nearly neutral pH levels. This helps to lower energy use and reduce the creation of dangerous by-products[12]. Altogether, these advancements promote more environmentally friendly methods in drug manufacturing that generate less wastewater and enhance production efficiency[13].

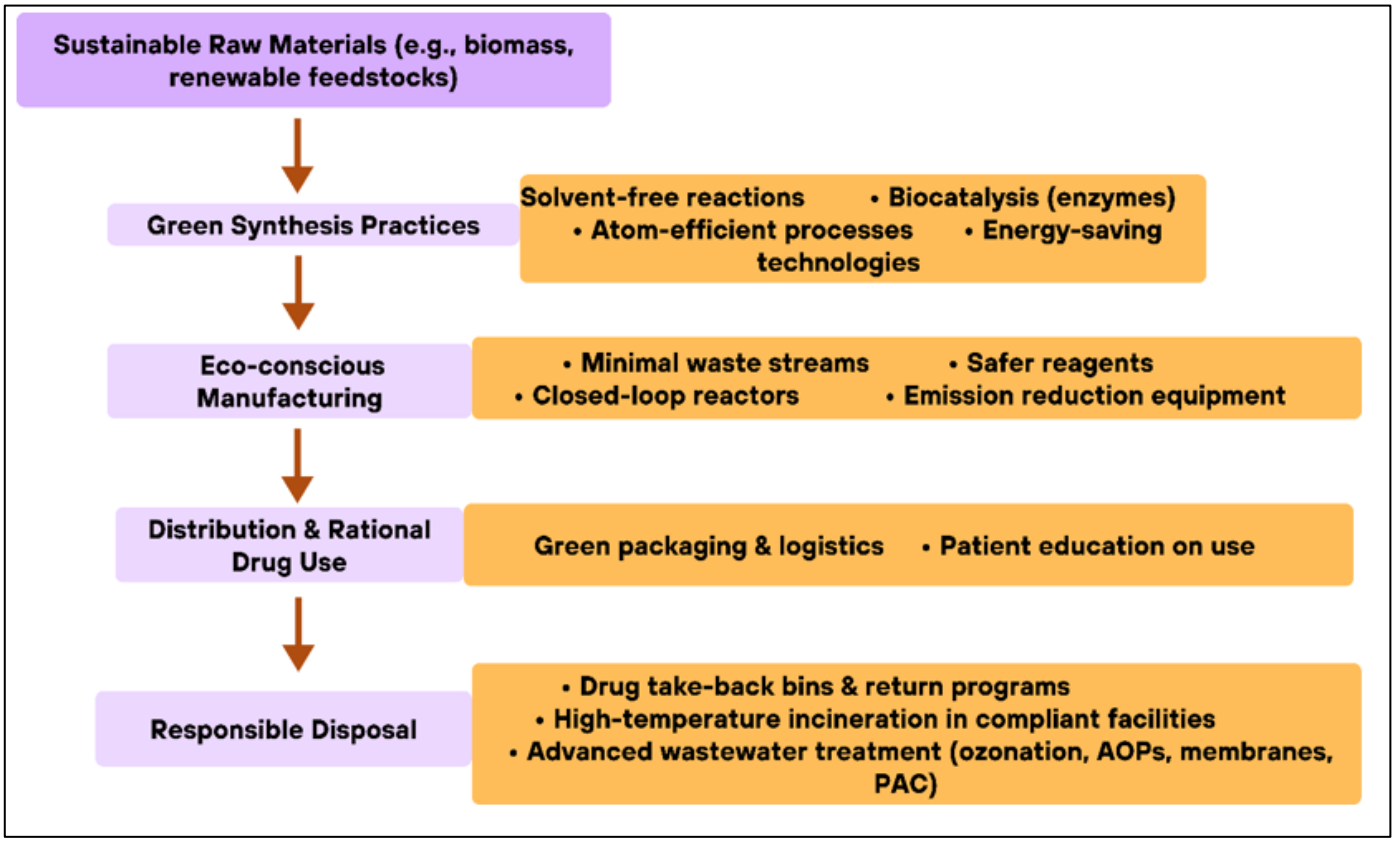

Fig 1 Sustainable Drug Manufacturing[14].

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III. SUSTAINABLE PHARMACEUTICAL DISPOSAL

➢ *Household Medication Waste*

Improper disposal of leftover or outdated medications, like flushing them down toilets or throwing them in regular trash, leads to the direct release of active ingredients into sewage systems and garbage dumps, where they can seep into surface water and groundwater[15]. These long-lasting chemicals can create ongoing harm, disrupt hormones, and lead to drug resistance in aquatic life, even in very small amounts. To tackle this problem, health organizations promote programs for returning medications, secure drop-off boxes at drugstores, mail-back options, and local collection events. These alternatives provide safe ways to get rid of medications and help keep harmful ingredients out of nature[16]. Raising public awareness and providing clear guidelines for disposal are essential for boosting involvement and making these programs successful over the long term.

➢ *Hospital and Community Pharmacies*

Healthcare facilities such as hospitals, clinics, and local pharmacies generate large amounts of medication waste from expired stock, unused drugs, harmful substances, and residue from spills[17]. If not disposed of properly, this waste can lead to a significant amount of active pharmaceutical ingredients entering our surroundings. Implementing strict sorting rules making clear differences among dangerous, non-dangerous, infectious, and harmful pharmaceutical waste helps ensure that each type is handled using the best treatment method available[18]. Incinerating waste at very high temperatures, especially in rotary kiln systems that meet strict environmental emission standards, is now seen as the most effective way to get rid of active ingredients and prevent harmful emissions[21]. Regular checks on emissions, staff education, and careful buying choices also improve sustainability efforts in managing healthcare waste systems[19].

➢ *Advanced Wastewater Treatment Methods*

Standard town wastewater treatment facilities are not meant to fully remove complex small contaminants like active pharmaceutical ingredients (APIs), which results in their ongoing discharge into nearby water sources[20]. To address this issue, new advanced tertiary treatment methods have been created to improve the ability to remove these substances. Ozonation and other advanced oxidation methods produce highly reactive particles that quickly break down a variety of pharmaceuticals into safer substances[21]. Using activated carbon, both in powdered and granular forms, provides a large surface area for capturing hydrophobic APIs, which lowers their levels in water[22]. Furthermore, filtration techniques that rely on membranes, such as nanofiltration and reverse osmosis, effectively separate APIs, but they might need additional processing for the concentrated waste[23]. Merging these advanced methods with traditional treatment approaches can greatly reduce the environmental dangers posed by pharmaceutical pollution in water bodies[24].

IV. DISCUSSION

Integrating eco-friendly methods throughout the pharmaceutical supply chain from initial research to production, shipping, and waste disposal is essential for ensuring ongoing sustainability and safeguarding public health[25]. Using green chemistry in drug design can lower risks later on and make waste management easier, while cleaner production methods and processes without solvents can significantly lessen the carbon impact of industrial activities[26]. Likewise, it's crucial to think about how to safely dispose of products at the end of their life, including programs for returning medications and effective wastewater treatment systems, to avoid harming the environment. To speed up the adoption of green pharmacy practices throughout the industry, it is necessary for governments to enforce stricter environmental laws, encourage cleaner technologies, and enhance education for both the public and professionals[27]. Creating a circular pharmaceutical economy that focuses on eco-friendly innovation, openness, and responsibility will be vital for meeting sustainable development targets.

V. CONCLUSION

Green and sustainable pharmacy is a new way of making medicines that focuses on caring for the environment while also creating effective treatments. By using environment-friendly methods at every stage of drug making—from designing the molecules and using energy-saving ways to create them, to safely distributing, using, and getting rid of them the medicine industry can significantly lessen its impact on the planet. Ongoing improvements in eco-friendly chemistry, using sustainable raw materials, and using cleaner manufacturing processes will be key to reducing harmful emissions and conserving resources. It is also very important to have strong programs for returning unused medications, educating the public, and using advanced systems to treat wastewater to stop active drug ingredients from being released into nature. As more people become aware of medicine-related pollution, cooperation between different groups like businesses, lawmakers, healthcare workers, and consumers will be vital to creating sustainable and circular medicine systems that protect both people's health and delicate ecosystems for generations to come.

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