SYSTEMATIC REVIEW

GREEN PHARMACEUTICS AND GREEN PHARMACY: ADVANCING SUSTAINABLE MEDICINES FOR HUMAN AND ENVIRONMENTAL HEALTH

Amrute Bhavesh B.[1], Surana Srushti N.[2], Surana Leena N.[3], Surana Rashmi S.[4], Dhadiwal Harsh A.[5], Jain Ronak P.[6], Chordiya Nayan R.[7], Deshmukh Yash S.[8], Kumat Vinit S.[9], Bhandare Nitish S.[10], Upasani Chandrashekhar D.[11]

[1-11]S.N.J.B.'s Shriman Sureshdada Jain College of Pharmacy, Neminagar, Chandwad, Nashik, Maharashtra, India.

***Corresponding Author**: Mr. Amrute Bhavesh B.*
***Email ID**: bhaveshamrute@gmail.com*

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ABSTRACT
Medicines are essential to modern healthcare, yet their benefits are accompanied by an environmental footprint that begins with raw-material selection and continues through synthesis, formulation, packaging, distribution, patient use and disposal. Pharmaceutical manufacturing can generate substantial quantities of solvent-rich waste and may require significant energy and water inputs. At the other end of the life cycle, active pharmaceutical ingredients and their transformation products may enter wastewater and aquatic systems through excretion, inappropriate disposal and manufacturing discharges. Green pharmacy provides a life-cycle framework for reducing these impacts while maintaining medicine quality, efficacy and patient safety. Green pharmaceutics represents an important formulation-focused component of this approach, covering excipient selection, dosage-form design, and processing, packaging and manufacturing operations. This review discusses the concepts and relationship between green chemistry, green pharmacy and green pharmaceutics; the application of the twelve principles of green chemistry to pharmaceutical development; and emerging approaches including biocatalysis, safer solvents, continuous-flow processing, microwave-assisted synthesis, mechanochemistry and greener extraction. Particular attention is given to formulation and packaging, environmental occurrence of pharmaceutical residues, measurement of process greenness, and the role of pharmacists and other healthcare professionals. The review also considers practical barriers, including regulatory requirements, cost, skills, incomplete environmental data and possible trade-offs between different sustainability indicators. Future opportunities include life-cycle thinking at the molecular-design stage, solvent recovery, continuous manufacturing, improved environmental risk assessment and digital or AI-assisted route selection. A sustainable medicine should therefore be considered not only in terms of therapeutic performance and patient safety, but also in terms of how responsibly it is produced, delivered and returned to the environment.

Keywords: green pharmacy; green pharmaceutics; green chemistry; sustainable pharmaceutical manufacturing; biocatalysis; green extraction; pharmaceutical waste; environmental sustainability; life-cycle assessment.

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1. INTRODUCTION

Pharmacy has traditionally focused on the quality, efficacy, safety and stability of medicines. These remain non-negotiable requirements, but the environmental consequences of pharmaceutical production and use have become an additional consideration. A medicine has a life cycle: materials are sourced, chemicals are transformed, the active ingredient is purified, a dosage form is manufactured, the product is packaged and transported, the patient uses it, and the remaining material or metabolites ultimately enter waste streams or the

environment. Each stage can consume resources or create environmental burdens.

The pharmaceutical sector is unusual because many products are manufactured in relatively small quantities but through multi-step processes that use substantial amounts of solvents, reagents, water and energy. The E-factor concept introduced by Sheldon expresses the mass of waste generated per mass of product and has demonstrated that fine chemicals and pharmaceuticals can have particularly high waste intensities[1,2]. Pharmaceutical sustainability is therefore not simply a question of reducing the quantity of final product packaging; process chemistry, purification and solvent management can have a major influence on overall impact.

Environmental exposure does not end at the factory gate. Following administration, many medicines and metabolites are excreted. Unused medicines can also be discarded into household waste or flushed into wastewater. Conventional wastewater treatment was not originally designed to remove every pharmaceutical compound, and residues have been reported in surface water, groundwater and other environmental compartments[4,5]. Manufacturing discharges can be particularly important at locations where untreated or insufficiently treated effluent contains high concentrations of active pharmaceutical ingredients[6].

The consequences can extend beyond direct chemical contamination. Antibiotics present in environmental compartments may contribute to selection pressure for antimicrobial resistance, while endocrine-active substances can interfere with biological processes in aquatic organisms. A striking example of unintended ecological harm is the decline of vulture populations in South Asia associated with veterinary diclofenac exposure[7]. Such examples demonstrate why environmental performance should be considered alongside therapeutic benefit.

Green pharmacy has emerged as a broader way of thinking about these challenges. Rather than representing one manufacturing technology, it applies sustainability principles across the medicine life cycle. Green pharmaceutics can be viewed as the dosage-form and formulation dimension of this framework, where excipients, processing conditions, solvents, energy demand, packaging and product design are considered together. The objective is not to compromise therapeutic performance, but to obtain the required pharmaceutical quality with less environmental burden.

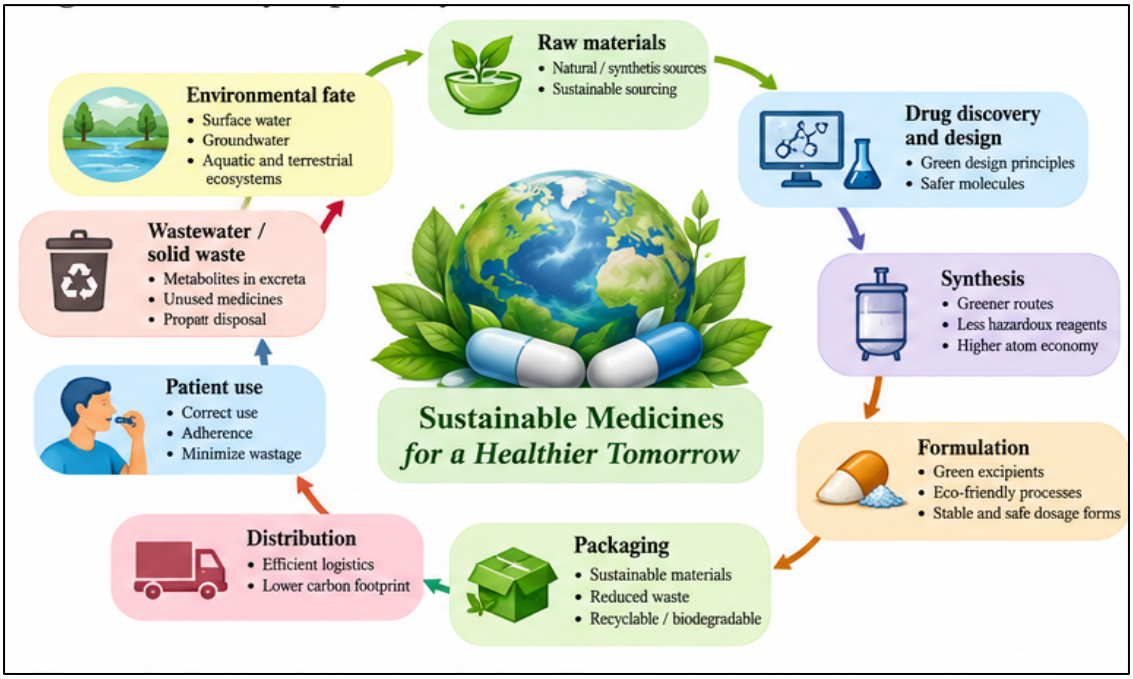


Figure 1. Life-cycle pathway of a medicine, from raw-material sourcing and drug design to environmental fate.

2. SCOPE AND OBJECTIVES OF THE REVIEW

This review brings together concepts relevant to the pharmaceutical life cycle and examines how green chemistry principles can be translated into pharmaceutical development and pharmacy practice. It specifically aims to:

i. clarify the terms green chemistry, green pharmacy and green pharmaceutics;
ii. explain the major principles that guide sustainable pharmaceutical design;
iii. discuss greener synthetic and manufacturing technologies;
iv. examine formulation and packaging opportunities;
v. describe routes by which pharmaceutical residues reach the environment;
vi. compare commonly used metrics for assessing greenness;
vii. highlight the contribution of pharmacists and healthcare providers; and
viii. identify barriers and future directions for implementation.

3. GREEN CHEMISTRY, GREEN PHARMACY AND GREEN PHARMACEUTICS

3.1 Green chemistry

Green chemistry is commonly defined as the design of chemical products and processes that reduce or eliminate the use and generation of hazardous substances[8]. The concept moves beyond end-of-pipe waste treatment: instead of producing a waste stream and then attempting to manage it, the process itself is designed to avoid unnecessary waste and hazards. In pharmaceutical development, this may involve selecting reactions with high atom economy, replacing hazardous reagents, reducing the number of synthetic steps, improving catalytic efficiency and choosing safer solvents.

3.2 Green pharmacy

Green pharmacy extends the sustainability discussion across the complete life cycle of medicines. It includes drug discovery and molecular design, manufacturing, formulation, packaging, distribution, dispensing, patient use and disposal[9]. This broader perspective is important because a process that appears green during synthesis may still create a significant environmental burden during formulation, packaging or end-of-life management.

3.3 Green pharmaceutics

Green pharmaceutics focuses more specifically on pharmaceutical formulation and dosage-form development. Opportunities include selecting excipients with appropriate environmental profiles, reducing solvent consumption during granulation and coating, choosing energy-efficient unit operations, minimizing processing steps, optimizing batch sizes and reducing unnecessary packaging. The concept can also influence dosage-form selection: a formulation that delivers the required dose efficiently and minimizes unused product may reduce downstream waste.

3.4 Relationship between the three concepts

Concept	Primary focus	Examples
Green chemistry	Chemical design and synthesis	Atom economy, catalysis, safer reagents, safer solvents
Green pharmacy	Whole medicine life cycle	Manufacturing, dispensing, use, disposal, environmental risk
Green pharmaceutics	Formulation and dosage-form stage	Excipients, coating, granulation, energy, packaging

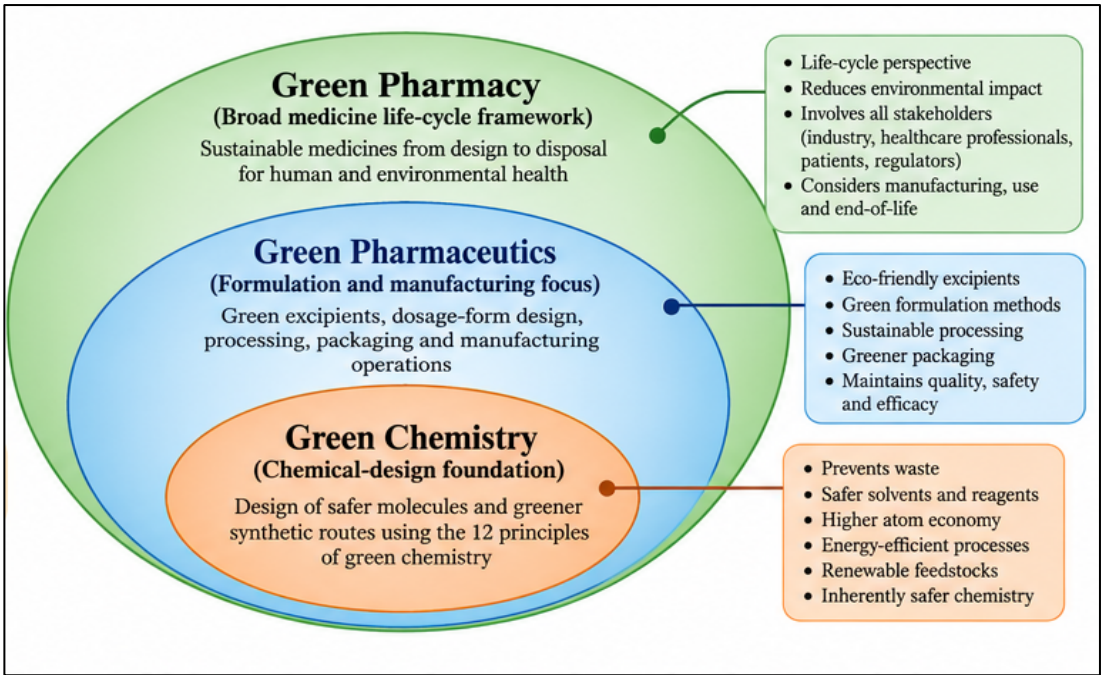


Figure 2. Conceptual relationship among green chemistry, green pharmacy and green pharmaceutics.

4. PRINCIPLES OF GREEN CHEMISTRY APPLIED TO PHARMACEUTICALS

The twelve principles developed by Anastas and Warner provide a useful conceptual foundation[8]. Their value in pharmacy lies in translating broad sustainability ideas into specific decisions during drug development and manufacturing.

Principle	Application in pharmaceutical practice
Prevent waste	Redesign routes and processes so waste is avoided rather than treated after generation.
Atom economy	Select reactions in which a larger proportion of starting-material atoms become part of the final active ingredient[10].
Less hazardous synthesis	Replace hazardous reagents, intermediates and process conditions where feasible.
Design safer chemicals	Balance therapeutic activity with reduced toxicity to humans and ecosystems.
Safer solvents and auxiliaries	Prefer water, ethanol or other better-performing solvents when scientifically appropriate[11,12].
Energy efficiency	Use lower temperatures and pressures and efficient technologies such as continuous or microwave-assisted processing where suitable.
Renewable feedstocks	Use renewable or bio-derived materials where their complete life-cycle performance is advantageous.
Reduce derivatives	Avoid unnecessary protection/deprotection or temporary chemical modifications.
Catalysis	Use catalytic or biocatalytic reactions rather than stoichiometric reagents where possible.
Design for degradation	Consider whether molecules and excipients can transform into less harmful substances after use[9].
Real-time analysis	Monitor processes to prevent failed batches, off-specification material and avoidable waste.
Inherently safer chemistry	Reduce fire, explosion, toxicity and accidental-release hazards through process and material selection.

5.GREENER TECHNOLOGIES IN DRUG SYNTHESIS AND MANUFACTURING

5.1 Biocatalysis

Biocatalysis uses enzymes or whole biological systems to perform chemical transformations. Enzymes can provide high selectivity under relatively mild conditions, potentially reducing side products and simplifying purification[13]. The manufacture of sitagliptin is a frequently discussed example: an engineered transaminase was incorporated into the route to the chiral amine intermediate, demonstrating how enzyme engineering can replace a less desirable conventional transformation and improve process performance[14].

The environmental value of biocatalysis is not automatic. Enzyme production, cofactor requirements, solvent choice, downstream purification and enzyme recovery should also be considered. Nevertheless, continued progress in protein engineering is expanding the range of transformations that can be performed efficiently with biological catalysts.

5.2 Alternative and Safer Solvents

Solvents often account for a large proportion of the mass used in pharmaceutical processes, making solvent selection one of the most influential opportunities for improvement[1, 15]. A solvent should not be selected solely on the basis of whether it is bio-derived or familiar. Toxicity, flammability, volatility, worker exposure, water demand, energy required for recovery and end-of-life treatment all contribute to its overall profile. Solvent-selection guides such as CHEM21 provide structured approaches for comparing solvent options[12].

Water, ethanol and selected bio-based solvents can sometimes replace problematic organic solvents. Solvent-free reactions may offer another route, although they must still meet the required yield, purity, and scalability and process-safety requirements. Recovery and recycling can further reduce solvent consumption when complete substitution is not practical.

5.3 Continuous-Flow Chemistry

Continuous-flow chemistry moves reactants through relatively small reaction channels rather than processing the entire quantity in one large vessel. Improved heat and mass transfer can provide better process control, while smaller inventories of hazardous intermediates may improve safety[17]. Continuous operation may also provide more consistent product quality and can be integrated with inline monitoring and automated control.

5.4 Microwave-Assisted Processing

Microwave-assisted synthesis can accelerate suitable reactions by providing rapid and controlled heating. In some applications, reactions that conventionally require long heating periods can be completed much faster, potentially reducing energy demand and increasing throughput[18]. However, energy savings should be assessed across the complete process rather than assumed from shorter reaction time alone.

5.5 Mechanochemistry

Mechanochemistry uses mechanical energy, commonly through grinding or milling, to promote chemical transformations. Because some reactions can proceed with little or no solvent, the approach is attractive from a waste-reduction perspective[19].

Pharmaceutical applications include the preparation of salts and cocrystals. Scale-up, equipment design, heat management and process reproducibility remain important practical considerations.

5.6 Green Extraction of Natural Products

Natural products are important sources of pharmaceutical and nutraceutical ingredients, but conventional extraction may consume substantial quantities of organic solvents and energy. Green extraction approaches include supercritical carbon dioxide, ultrasound-assisted extraction, microwave-assisted extraction and selected bio-based solvents[20]. These approaches can improve extraction efficiency while reducing solvent use, although the choice of technology should be based on the material, target compound, required purity and total energy demand.

5.7 Solvent Recovery and Process Intensification

Even when a solvent cannot be eliminated, recovery can reduce fresh-solvent requirements and waste generation. Distillation, membrane-based separation and other recovery systems may be incorporated where technically and economically appropriate. Process intensification—achieving the same pharmaceutical output with smaller equipment, shorter residence times or fewer unit operations—can further reduce resource requirements.

5.8 Digital and Data-Driven Process Design

Digital tools can support greener pharmaceutical development by comparing synthetic routes, estimating material and energy requirements, monitoring process variability and identifying opportunities for waste reduction. Emerging AI-assisted approaches may eventually optimize synthetic pathways using multiple objectives such as yield, cost, safety, waste generation and environmental impact rather than optimizing yield alone. Such tools should support, rather than replace, experimental validation and professional judgement.

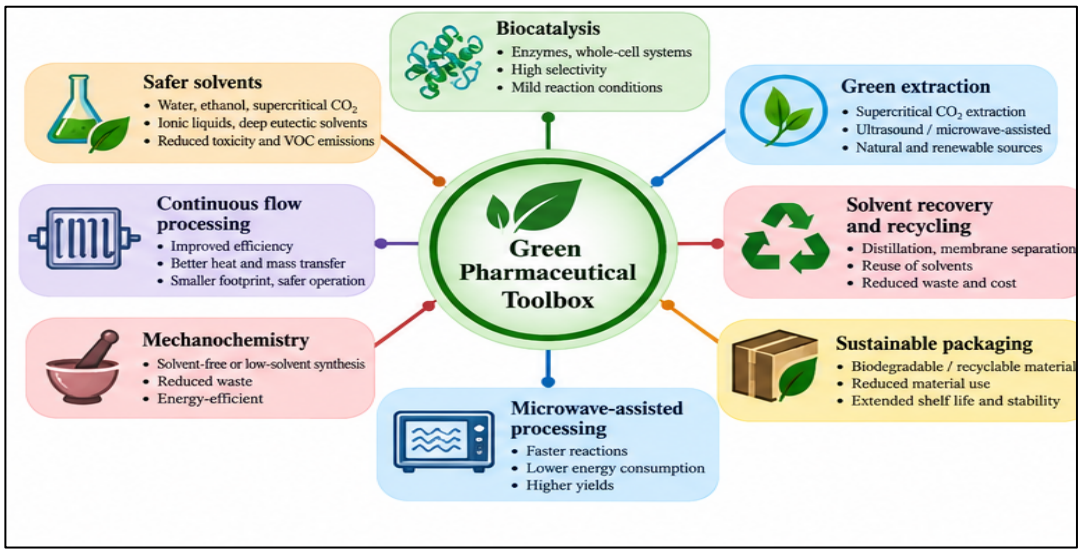


Figure 3. Green pharmaceutical toolbox for sustainable synthesis, processing, recovery and packaging.

6. GREEN PHARMACEUTICS: MAKING THE DOSAGE FORM MORE SUSTAINABLE

Formulation development is sometimes overlooked when pharmaceutical sustainability is discussed. However, dosage-form manufacturing can involve wet granulation, coating, drying, milling, compression, sterilization and packaging, each with its own material and energy requirements. A green formulation should therefore be considered from the beginning of product development rather than only after the formulation has been finalized.

6.1 Excipient selection

Excipients are selected primarily for functionality, safety, stability and regulatory acceptability. Environmental considerations can complement these criteria. Where alternatives provide equivalent performance, formulators can consider renewable sourcing, manufacturing footprint, biodegradability, toxicity and availability. Such choices must not compromise dose uniformity, stability, bioavailability or patient acceptability.

6.2 Direct compression and process simplification

Direct compression can avoid some of the wetting, drying and milling steps required in wet granulation. Where the powder blend possesses suitable flow and compression properties, this can reduce water or solvent use, drying energy and processing time. It is not universally applicable; the final decision

must depend on material properties and product performance.

6.3 Aqueous coating

Aqueous film coating can reduce reliance on organic solvent systems. The approach may still require substantial drying energy because water must be removed, so the sustainability assessment should include both solvent hazard and energy demand. Optimized spray rates, inlet-air conditions and coating thickness can help reduce processing time and energy consumption.

6.4 Solvent-free and low-solvent technologies

Hot-melt processing and other solvent-free approaches can eliminate or reduce liquid solvents in selected formulations. Their feasibility depends on the thermal stability of the drug and excipients and on the required dosage-form characteristics.

6.5 Sterile products and special dosage forms

Sterile manufacturing presents a particular challenge because microbial control, product quality and patient safety require validated processes. Sustainability efforts may include optimized water-for-injection use, efficient clean-room operation, appropriate sterilization strategies, reduced rejected batches and carefully designed single-use systems. These measures should be introduced without weakening sterility assurance.

6.6 Packaging

Packaging protects medicines from moisture, oxygen, light, contamination and mechanical damage, so reduction cannot simply mean using less material. Green packaging involves selecting the minimum material necessary to provide the required protection, reducing unnecessary secondary packaging, improving recyclability and considering transport weight. Packaging design should also support accurate dosing and patient adherence so that product protection and environmental performance are considered together.

Formulation area	Potential green approach	Important consideration
Granulation	Direct compression or dry processing	Powder flow, compressibility and content uniformity
Tablet coating	Aqueous coating	Drying-energy requirement
Solvent use	Safer/low-solvent or solvent-free processing	Drug and excipient stability
Manufacturing	Process intensification and automation	Validation and reproducibility
Packaging	Lightweight, recyclable, optimized packs	Protection and stability
Product sizing	Pack sizes matched to expected use	Avoid excess and unused medicines

7. PHARMACEUTICALS IN THE ENVIRONMENT

Pharmaceutical residues can reach the environment through several pathways. The most direct route for human medicines is excretion after administration. Depending on the compound, metabolites may be transformed further during wastewater treatment or environmental processes. Unused and expired medicines represent another avoidable source, particularly when they are flushed or placed in general household waste. Manufacturing effluents can contribute concentrated releases if treatment and discharge controls are inadequate[4–6].

Source	Environmental pathway	Potential response
Patient excretion	Urine/faeces → sewage → wastewater treatment → receiving water	Environmental risk assessment; improved treatment; design for degradation where appropriate
Unused/expired medicines	Flushing or disposal with household waste	Take-back systems, counselling, suitable pack sizes

Manufacturing	Industrial effluent and accidental releases	Effluent standards, monitoring, closed-loop processes and containment
Veterinary medicines	Excretion, runoff, carcass contamination	Controlled use, environmental assessment and safer alternatives where available

7.1 Antibiotics and antimicrobial resistance

Antibiotic residues in environmental compartments are a concern because exposure to low concentrations can contribute to selective pressure on microbial populations. The environmental dimension of antimicrobial stewardship therefore complements clinical efforts to preserve antibiotic effectiveness. Responsible prescribing, adherence, appropriate disposal and effective wastewater management can all contribute to reducing unnecessary environmental exposure.

7.2 Endocrine-active pharmaceuticals

Some pharmaceutical compounds interact with hormonal pathways by design. When released into aquatic environments, such biological activity can become an unintended ecological effect. Reported concerns include changes in aquatic physiology, behaviour and reproduction[4,5]. This reinforces the importance of considering environmental activity during molecular design and environmental risk assessment.

7.3 Ecological consequences of veterinary pharmaceuticals

The diclofenac-associated decline of vultures in South Asia is a particularly well-known example of pharmaceutical exposure causing an ecological consequence[7]. It illustrates that a compound may be safe and effective for its intended veterinary use while still producing severe effects in non-target species through exposure pathways that were not fully considered at the time.

7.4 Wastewater treatment

Conventional wastewater treatment can remove many contaminants, but removal efficiency varies substantially among pharmaceutical compounds and treatment configurations. Advanced processes such as ozonation, activated carbon adsorption and membrane technologies may improve removal for selected contaminants, but they can also require additional energy and generate secondary waste streams. Therefore, upstream prevention and source reduction should complement downstream treatment rather than relying on treatment alone.

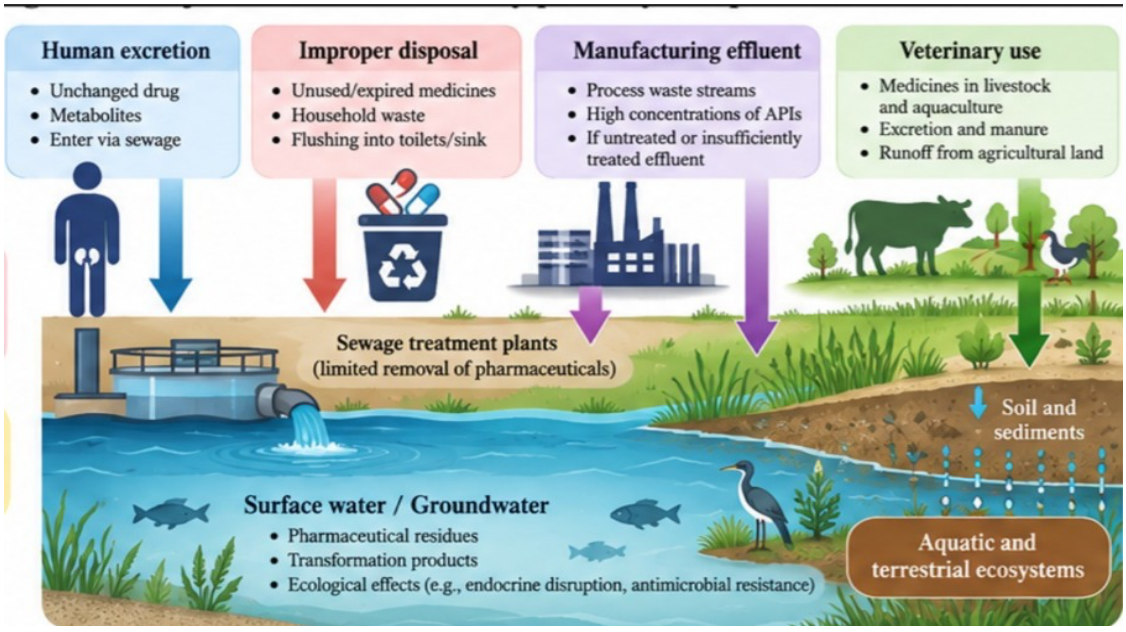


Figure 4. Major environmental entry pathways for pharmaceutical residues and their environmental destinations.

8. MEASURING PHARMACEUTICAL SUSTAINABILITY

The term 'green' is meaningful only when environmental performance can be evaluated using transparent criteria. Several metrics are useful, but no single number captures every aspect of sustainability[15, 21].

Metric	What it measures	Strength	Limitation
Atom economy	Fraction of reactant mass incorporated into product	Useful during route design	Does not account for yield, solvents or energy
E-factor	Mass of waste per mass of product	Simple and intuitive[1,2]	Does not distinguish waste toxicity
Process Mass Intensity (PMI)	Total mass of inputs per mass of product	Useful for industrial tracking[21]	Primarily mass-based
Solvent-selection guides	Relative solvent hazard/profile	Practical for process decisions[11,12]	Different guides may rank differently
Life Cycle Assessment (LCA)	Environmental impacts across a life cycle	Holistic approach	Data-intensive and time-consuming
Energy/carbon indicators	Energy use or greenhouse-gas emissions	Highlights climate-related burden	May overlook toxicity and resource depletion

8.1 Why multiple metrics are necessary

A process can perform well according to one metric and poorly according to another. For example, a route may have a low E-factor but rely on a hazardous reagent, or a bio-based solvent may appear attractive by feedstock origin while requiring substantial energy for recovery. Combining mass-based, hazard-based and life-cycle indicators gives a more balanced picture[15,21].

9. ROLE OF PHARMACISTS AND HEALTHCARE PROFESSIONALS

Green pharmacy cannot be achieved by pharmaceutical manufacturers alone. Pharmacists interact directly with medicines, patients and healthcare systems and can therefore influence what happens after a medicine leaves the manufacturing site. Practical actions include educating patients about appropriate disposal, supporting medicine take-back programs, reducing unnecessary dispensing, encouraging adherence and considering environmental information when therapeutically equivalent options are available.

Pharmacy education also has an important role. Students who understand pharmaceutical waste, environmental fate, sustainable formulation and green manufacturing can carry these principles into community pharmacy, hospital practice, industry, research and regulatory work. Sustainability can therefore become a professional habit rather than a separate specialist topic.

Pharmacy setting	Possible sustainability contribution
Community pharmacy	Patient counselling, take-back participation, appropriate dispensing
Hospital pharmacy	Inventory control, formulary considerations, waste segregation
Industrial pharmacy	Process optimization, solvent recovery, green formulation
Academic/research pharmacy	Green synthesis, sustainable formulation research, environmental assessment
Regulatory practice	Encouraging evidence-based environmental considerations in development

10. CHALLENGES AND BARRIERS

10.1 Regulatory inertia

Manufacturing processes for approved medicines are highly controlled. A change in synthetic route, excipient, process parameter or manufacturing site can trigger additional validation and regulatory work. As a result, companies may hesitate to alter established processes even when a greener alternative is available[9].

10.2 Cost and infrastructure

Continuous-flow equipment, enzyme development, solvent-recovery systems and

life-cycle assessment can require capital investment and specialist expertise. For smaller organizations, the initial cost may be a significant barrier even when long-term savings are possible.

10.3 Data gaps

Environmental fate and ecotoxicity information is not equally available for every active pharmaceutical ingredient, metabolite or excipient. This makes comparative decision-making difficult and can limit accurate life-cycle assessment[4,5].

10.4 Sustainability trade-offs

Environmental decisions often involve trade-offs. A change that reduces solvent toxicity may increase energy demand; a lightweight package may provide less protection and increase product loss; and a renewable feedstock may not automatically have a lower total environmental footprint. Green decisions therefore require a whole-system perspective rather than a single-attribute approach.

10.5 Green washing

Environmental claims can become misleading when they are based on one favourable characteristic without considering the entire process. Transparent metrics, defined boundaries and evidence-based comparisons are necessary to distinguish genuine improvement from marketing language.

10.6 Skills and awareness

Green pharmaceutical development requires interdisciplinary understanding. Chemists, formulators, engineers, pharmacists, environmental scientists, toxicologists and regulatory specialists may each see a different part of the problem. Education and cross-functional collaboration are therefore central to implementation.

11. FUTURE PERSPECTIVES

The next phase of green pharmacy is likely to move from isolated process improvements toward sustainability-by-design. Instead of asking whether an established product can be made greener after development, researchers can consider environmental performance during the earliest stages of molecular and formulation design.

11.1 Benign-by-design medicines

Kümmerer's concept of designing molecules to be sustainable from the beginning emphasizes the possibility of retaining therapeutic activity while encouraging transformation into less persistent substances after environmental release[9]. This approach requires careful balancing of pharmacology, stability, metabolism and environmental fate.

11.2 Continuous manufacturing

Continuous manufacturing offers opportunities for improved control, smaller equipment footprints, reduced hold-up volumes and integration of monitoring systems[17]. As regulatory and technical experience increases, continuous approaches may become more common for suitable pharmaceutical processes.

11.3 Solvent recycling and circular approaches

Solvent recovery, material reuse and circular resource strategies can reduce the demand for virgin materials. Their feasibility depends on purity requirements, contamination risk, energy consumption and economics.

11.4 AI-assisted green route selection

Computational tools may help researchers compare synthetic routes using multiple sustainability objectives. A future route-selection system could consider yield, number of steps, solvent profile, waste, energy, safety and estimated life-cycle impact simultaneously. Experimental validation and transparent assumptions will remain essential.

11.5 Stronger environmental risk assessment

Environmental considerations can increasingly become part of pharmaceutical development rather than a late-stage compliance activity. Better information on persistence, bioaccumulation, ecotoxicity and degradation products can improve the design of medicines and manufacturing processes.

11.6 Education and professional practice

Embedding green pharmacy into pharmacy curricula can prepare future professionals to recognize environmental considerations in formulation, manufacturing, dispensing and disposal. The long-term objective is a pharmaceutical culture in which sustainability is treated as one component of quality rather than an optional addition.

12. PRACTICAL FRAMEWORK FOR DEVELOPING A GREEN PHARMACEUTICAL PRODUCT

A practical sustainability workflow can help convert broad principles into decisions during development. The following framework is adapted from the concepts and metrics discussed in the source review and its cited literature.

Stage	Questions to ask	Possible action
Molecular design	Can therapeutic activity be retained while reducing environmental persistence or hazard?	Consider benign-by-design concepts and environmental fate early.
Route selection	Which route uses fewer steps, safer reagents and less material?	Compare atom economy, PMI, E-factor and hazard.
Solvent selection	Can hazardous or high-impact solvents be replaced or recovered?	Use solvent guides and recovery systems.
Process design	Can energy, water and processing time be reduced?	Evaluate flow, direct compression, microwave or mechanochemistry where appropriate.
Formulation	Can the same performance be achieved with fewer processing steps?	Optimize excipients and manufacturing method.
Packaging	What is the minimum material needed to protect product quality?	Reduce unnecessary layers and improve recyclability.
Distribution	Can transport burden be reduced?	Optimize pack dimensions, weight and supply-chain efficiency.
Use	How can unnecessary medicine waste be avoided?	Improve adherence, pack sizing and patient counselling.
End of life	What happens to unused medicine and metabolites?	Promote take-back and assess environmental fate.
Verification	Has improvement been demonstrated quantitatively?	Use multiple sustainability metrics and, where possible, LCA.

13. RESEARCH GAPS AND OPPORTUNITIES

Despite rapid interest in sustainable pharmaceuticals, several questions remain open. More comparable environmental data are needed across active pharmaceutical ingredients and excipients. Standardized approaches for comparing formulation alternatives would help researchers distinguish genuine improvements from changes that simply shift the burden from one environmental category to another. There is also a need for more practical methods that smaller pharmaceutical organizations can use without extensive specialist infrastructure.

Future research could investigate biodegradable drug candidates, lower-impact excipients, solvent-free processing, recyclable or lower-impact packaging, decentralized manufacturing, and digital tools for real-time sustainability monitoring. Greater collaboration between pharmaceutical scientists and environmental researchers could also improve understanding of transformation products and ecological effects.

Importantly, sustainability should not be separated from medicine quality. Any green intervention must preserve identity, strength, purity, stability, bioavailability, sterility where required, and patient safety. The strongest approaches are therefore those that achieve environmental improvement while maintaining or improving pharmaceutical performance.

14. CONCLUSION

Green pharmacy represents a shift in how pharmaceutical quality is understood. A medicine must continue to be effective, safe, stable and acceptable to patients, but its environmental footprint is increasingly

relevant to responsible pharmaceutical development. Green pharmaceutics provides a practical route for addressing this challenge through sustainable excipient selection, process simplification, safer solvent systems, efficient manufacturing and improved packaging. At the manufacturing level, biocatalysis, continuous-flow chemistry, mechanochemistry, microwave-assisted processing, green extraction and solvent recovery offer promising opportunities.

The environmental life cycle does not end when a medicine is dispensed. Pharmaceutical residues can enter water and soil through excretion, disposal and manufacturing effluent, making environmental risk assessment, appropriate wastewater management and patient education important parts of the solution. Pharmacists can contribute through counselling, medicine take-back, and rational dispensing and sustainability education.

No single technology or metric can make the pharmaceutical sector sustainable. Meaningful progress requires life-cycle thinking, transparent measurement and collaboration across pharmaceutical science, engineering, environmental science, regulation and clinical practice. The central principle is straightforward: future medicines should be designed to heal patients while minimizing avoidable harm to the ecosystems on which human health ultimately depends.

15. Key Takeaways

- Green pharmacy considers the entire life cycle of a medicine, not only its synthesis.
- Green pharmaceutics applies sustainability principles specifically to formulation, manufacturing and packaging.
- Solvents, purification steps and process complexity can strongly influence pharmaceutical waste.
- Biocatalysis, continuous flow, mechanochemistry, microwave-assisted processing and green extraction are important enabling technologies.
- Environmental exposure can occur through patient excretion, unused medicines, manufacturing effluent and veterinary use.
- Metrics such as atom economy, E-factor, PMI and LCA should be interpreted together.
- Pharmacists can influence medicine waste through dispensing practices, patient counselling and take-back initiatives.
- Sustainable pharmaceutical development requires environmental improvement without compromising pharmaceutical quality or patient safety.

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