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IP International Journal of Comprehensive and Advanced Pharmacology

Journal homepage: https://ijcap.in/

Review Article

Green and sustainable pharmacology: Integrating environmental responsibility into drug discovery, development, and practice

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Abstract

Pharmaceuticals are indispensable for modern healthcare, yet their development, production, use, and disposal have unintended consequences for ecosystems and public health. The persistence of active pharmaceutical ingredients (APIs) in the environment, their contribution to antimicrobial resistance, and the carbon and chemical footprint of manufacturing processes are increasingly recognized as critical sustainability challenges. Green and sustainable pharmacology has emerged as an interdisciplinary paradigm that integrates green chemistry principles, sustainable manufacturing, eco-directed prescribing, green analytical chemistry, and ecopharmacovigilance (EPV) to minimize environmental impacts across the entire pharmaceutical life cycle. This review synthesizes recent advances in green chemistry approaches for drug synthesis, greenness assessment metrics for analytical procedures, sustainable supply-chain strategies, EPV frameworks, and eco-directed pharmacy practice. Industry initiatives, policy drivers, and One Health perspectives are also considered. Key barriers include economic trade-offs, regulatory gaps, and risks of greenwashing. Practical recommendations are provided for researchers, prescribers, pharmacists, regulators, and industry stakeholders. Looking forward, digital technologies, artificial intelligence, predictive ecotoxicology, and circular-economy models are expected to accelerate the integration of sustainability principles into pharmacology. Green pharmacology represents not only an ethical imperative but also an opportunity to align healthcare innovation with global sustainability goals.

Keywords: Green pharmacology, Sustainable chemistry, Ecopharmacovigilance, Lifecycle assessment, Green analytical chemistry, Eco-directed prescribing, Pharmaceuticals in the environment

Received: 19-09-2025; **Accepted:** 29-10-2025; **Available Online**: 19-11-2025

1. Introduction

Pharmaceuticals are central to improving quality of life and extending human longevity. However, over the past two decades, their unintended impacts on ecosystems and human health have become more visible. Numerous studies have documented the presence of pharmaceutical residues in surface waters, sediments, soils, and even drinking water at concentrations ranging from nanograms to micrograms per litre.[1] Compounds such as antibiotics, non-steroidal anti-inflammatory drugs (NSAIDs), anti-epileptics, and hormones have been shown to affect aquatic organisms, disrupt endocrine systems, and contribute to antimicrobial resistance (AMR).[2] At the same time, the pharmaceutical industry contributes significantly to global carbon emissions, solvent waste, and chemical consumption. A comparative analysis revealed that the sector's carbon intensity is often higher than that of the automotive industry.[3] Addressing these challenges requires reimagining pharmacology through a sustainability lens.

Green and sustainable pharmacology is an emerging discipline that integrates the principles of green chemistry, sustainable manufacturing, green analytical chemistry, eco-directed prescribing, and Eco pharmacovigilance (EPV) to minimize the environmental footprint of medicines. It reflects a "One Health" approach, linking human, animal, and environmental health in a unified framework.[4] This review explores recent developments in green pharmacology, highlights tools for assessing greenness, discusses industry and regulatory drivers, and proposes pathways for embedding sustainability into drug discovery, development, and clinical

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https://doi:10.18231/j.ijcaap.13328.1761800153

practice. **Table 1** summarises environmental "hot spots" across the pharmaceutical lifecycle.

Table 1: Environmental "hot spots" across the pharmaceutical lifecycle

Stage	Environmental Impacts	Green Solutions
Drug design	Persistent metabolites; poor biodegradability	Early biodegradability screening; Greener framework
Synthesis	High solvent use, toxic reagents	Solvent substitution, biocatalysis, flow chemistry
Manufacturing	Energy-intensive processes; emissions	Continuous manufacturing, renewable energy, waste heat recovery
Formulation & packaging	Plastic and excipient waste	Biodegradable polymers, recyclable packaging
Distribution	Cold-chain energy demand	Optimized logistics, renewable-powered transport
Use	Over-prescription, poor adherence	Eco-directed prescribing, adherence support
Disposal	Improper discarding into sewage/landfills	Drug take-back programs, patient education

2. Drivers of Green Pharmacology

1. **Environmental contamination of pharmaceuticals:** Pharmaceuticals enter the environment via multiple pathways: excretion of unmetabolized drugs, improper disposal of unused medicines, wastewater effluents from manufacturing plants, and agricultural runoff from veterinary drugs. A global monitoring study across 104 countries reported detectable levels of pharmaceuticals in more than 50% of sampled rivers, with antibiotics and analgesics being the most prevalent.[5] These residues are not inert. For example, diclofenac has been linked to mass mortality in vulture populations in South Asia, while estrogenic compounds cause feminization of fish.[6] The persistence of carbamazepine and sulfamethoxazole in wastewater underscores the need for eco-directed drug design.
2. **Regulatory and policy frameworks:** Regulatory agencies have begun integrating environmental considerations. The European Medicines Agency (EMA) requires an environmental risk assessment (ERA) for new active substances.[7] The U.S. FDA has issued guidance on environmental assessments, although post-market monitoring remains limited. At a global level, the WHO has identified pharmaceutical pollution and AMR as major threats to sustainable health systems.
3. **Industry commitments:** Pharmaceutical companies are responding to stakeholder pressure by adopting sustainability targets. AstraZeneca, for instance, has published an EcoPharmacoVigilance dashboard that monitors environmental discharge and supports mitigation programs.[8] Similar initiatives have emerged from Johnson & Johnson, Pfizer, and Novartis, which are exploring green chemistry metrics in manufacturing.
4. **One health and public awareness:** The One Health concept emphasizes interconnectedness between human, animal, and ecosystem health. Public campaigns about improper disposal of medicines, coupled with national take-back programs, reflect growing awareness of pharmaceuticals as environmental pollutants.[4]

3. Discussion

Green pharmacology is an integrative discipline that embeds environmental sustainability across the entire pharmaceutical life cycle, from molecular design and synthesis to clinical use and post-market management (**Figure 1**). It is based on the principle of designing drugs and processes that minimize ecological persistence and toxicity while sustaining therapeutic efficacy. Modern approaches prioritize biodegradable scaffolds and metabolic pathways that limit the formation of persistent or bioactive transformation products, reducing long-term ecological burden. Synthetic strategies in green pharmacology embrace the long-established principles of green chemistry: atom economy, hazard reduction by replacement of hazardous reagents and solvents, and catalytic (including bio-catalysis) vs stoichiometric transformations. Bio-catalysis has become among the most impactful tools of sustainable synthesis, enabling highly selective transformations under mild conditions, improvement of stereo-selectivity, and low volume of hazardous wastes, a trend accelerated by introduction of enzymes into continuous-flow systems for industrial scalability. Complementarily, adoption of solvent- and energy-efficient extraction and formulation techniques, e.g., supercritical CO_2 extraction, microwave-assisted extraction, has lowered solvent waste in natural-product sourcing and phyto-pharmacology.

Analytical greenness has now become a formal consideration in the development of methods: tools such as AGREE, GAPI, and their derivatives provide a systematic scoring framework to quantify the environmental impacts of analytical methods and to guide selection of greener alternatives. These metrics support method optimization and can be incorporated into validation protocols in order to assure that routine quality-control practices do not inadvertently increase environmental risk. LCA is an increasingly applied approach for quantifying the cradle-to-grave environmental footprints of pharmaceutical products, informing choices from raw-material sourcing to end-of-life disposal. The results of LCA studies often indicate that one

or more non-intuitive stages-such as solvent manufacture, packaging, or patient-level excretion-dominate environmental impacts, and LCA therefore plays an important role in identifying high-leverage interventions.

Post-market stewardship has advanced under the umbrella of ecopharmacovigilance, which extends traditional pharmacovigilance to monitor and mitigate adverse environmental effects of medicinal products. EPV encompasses environmental risk assessment in regulatory submissions, monitoring of pharmaceutical residues in water and soil, and development of take-back and safe-disposal programs to reduce inputs of APIs into ecosystems. EPV contributes to the goals of One Health by linking patterns of human pharmaceutical use to the downstream ecological and animal-health effects. Early-stage prediction of environmental fate and ecotoxicity through digital tools and in-silico modelling enables computational prioritization of candidate molecules with lower predicted ecological impacts before expensive synthesis. These in-silico approaches, when combined with experimental green metrics and LCA, accelerate the selection of safer and more sustainable candidates. Despite significant advances, some challenges persist: the need to incentivize green redesign within commercial portfolios, to mainstream EPV into global regulatory frameworks, and to ensure the economic scalability of green technologies for generic and small-molecule producers. Overcoming such barriers requires integrated action across academia, industry, regulators, and healthcare systems, coupled with the adoption of standardized metrics and reporting standards for environmental performance. Overall, green pharmacology reframes the objective of drug development-not only to deliver clinical benefit but to do so with minimal and measurable harm to ecosystems, thereby supporting long-term human and planetary health.

Figure 1: Key aspects of green pharmacology

The Principles of Green & Sustainable Pharmacology thus integrate molecular, process, analytical, lifecycle, and ecological considerations into a holistic framework. Together, these principles represent a paradigm shift — from pharmacology that focuses solely on patient outcomes, to one that also safeguards planetary health. The key pillars include:

1. Designing biodegradable and eco-safe drugs.
2. Employing green chemistry in synthesis.
3. Applying sustainable analytical methods.
4. Monitoring via Eco pharmacovigilance.
5. Promoting rational prescribing and use.
6. Embedding lifecycle and circular economy principles.
7. Adopting a One Health perspective.

4. Principles of Green & Sustainable Pharmacology

The emerging discipline of Green and Sustainable Pharmacology builds on the foundational concepts of green chemistry[9] and green analytical chemistry,[10] extending them to the entire pharmaceutical lifecycle — from drug design and synthesis to use, disposal, and environmental monitoring. The goal is to minimize the ecological footprint of pharmaceuticals without compromising their therapeutic efficacy. Unlike conventional pharmacology, which primarily emphasizes efficacy, safety, and pharmacokinetics, sustainable pharmacology introduces ecotoxicological and lifecycle considerations into every decision-making step.[1] The principles can be categorized into design-oriented, process-oriented, analytical, and use-phase principles, complemented by ecopharmacovigilance (EPV).

5. Green Drug Design and Molecular Optimization

One of the core principles is designing drugs with inherent biodegradability and reduced persistence in the environment. Traditional pharmaceuticals are often optimized for long half-life and metabolic stability to improve dosing compliance. However, these same attributes can lead to accumulation in the environment, creating ecological hazards.[11]

1. **Benign-by-design drugs:** Compounds are engineered to degrade into non-toxic metabolites after therapeutic action.[12]
2. **In silico modelling:** Predictive algorithms incorporating QSAR (quantitative structure–activity relationships) and AI-driven biodegradability models are now applied to drug development pipelines.
3. **Case study:** Recent work on biodegradable NSAID analogues shows promising reductions in persistence while maintaining anti-inflammatory activity.[13]

Thus, molecular optimization becomes a balance between pharmacological potency and ecological safety.

6. Sustainable Synthesis and Green Chemistry Integration

Pharmaceutical manufacturing is highly resource-intensive, generating significant solvent waste, greenhouse gas emissions, and toxic by-products.[3] Green pharmacology emphasizes eco-efficient synthesis routes, guided by the 12 principles of green chemistry. The key strategies may include:

1. **Catalysis and bio-catalysis:** Using enzymes or metal catalysts to reduce reaction steps and energy consumption.[14]
2. **Flow chemistry:** Continuous-flow reactors enhance atom economy and minimize hazardous intermediates.[15]
3. **Solvent substitution:** Replacing halogenated solvents with greener alternatives such as supercritical CO_2, ionic liquids, or water-based systems.[16]
4. **Process intensification:** Coupling synthesis with purification in one step reduces waste streams.

This principle recognizes that sustainability must be built into industrial scale-up, not retrofitted after discovery.

7. Green Analytical Pharmacology

Pharmacological research, drug quality control, and toxicological assessment all depend on analytical techniques. Traditional methods, however, often rely on hazardous solvents, energy-intensive processes, and large sample requirements. Green analytical pharmacology seeks to minimize these impacts.

1. **Metrics and tools:** The Analytical GREEnness Metric (AGREE) and Green Analytical Procedure Index (GAPI) provide structured frameworks to assess the sustainability of analytical workflows.[17]
2. **Miniaturization:** Microfluidic and lab-on-chip systems significantly reduce sample and solvent use.[18]
3. **Automation and AI:** Machine learning optimizes chromatographic separations and reduces trial-and-error waste.
4. **Spectroscopic techniques:** FTIR, Raman, and NMR spectroscopy allow non-destructive, solvent-free analyses.
5. **Recent studies** Yin et al.[19] highlight the trend toward holistic greenness assessment, ensuring that pharmacological research itself aligns with environmental responsibility.

7.1. Eco pharmacovigilance (EPV)

Analogous to pharmacovigilance, which monitors adverse drug reactions in humans, ecopharmacovigilance (EPV) tracks and manages the environmental effects of pharmaceuticals.[20] It forms a central pillar of sustainable pharmacology. EPV aligns with the One Health approach by linking human, animal, and environmental health. For example, antibiotic discharge into rivers can foster resistant bacterial strains that eventually threaten human therapeutics.

7.2. Concept and scope

EPV extends traditional pharmacovigilance by monitoring environmental risks associated with pharmaceutical use. It involves detection, evaluation, and prevention of adverse environmental effects caused by APIs.[4] Key steps may include:

1. **Detection:** Monitoring pharmaceuticals in water bodies, soils, and sludge using advanced analytical tools.
2. **Assessment:** Evaluating ecological risks with standardized ERA (Environmental Risk Assessment) models.[21]
3. **Management:** Regulatory frameworks and mitigation strategies to limit pharmaceutical discharge.
4. **Public awareness:** Engaging prescribers and patients in safe disposal and rational use of medicines.

7.3. Monitoring approaches

1. **Targeted monitoring:** Focusing on high-risk APIs (e.g., antibiotics, hormones, NSAIDs).
2. **Non-targeted monitoring:** Using advanced LC-HRMS for broad-spectrum screening of pharmaceuticals in environmental matrices.
3. **Wastewater-based epidemiology (WBE):** Tracking population-level drug consumption and excretion trends.

7.4. Integration with policy

The EMA has proposed enhanced ERA requirements for new APIs, while national environmental agencies are piloting EPV networks.[20] However, standardized global frameworks remain under development. A notable example is the diclofenac-vulture crisis,[6] which catalysed global recognition of EPV as a public health and biodiversity necessity.

7.5. Rational and responsible use of medicines

Sustainability extends to the prescribing and consumption stages. The principle emphasizes:

1. *Rational prescribing:* Avoiding overmedication, particularly of antibiotics and psychiatric drugs, which often persist in aquatic systems.[5]
2. *Dose optimization:* Formulations that minimize excess excretion (e.g., controlled-release designs).
3. *Green pharmacy practice:* Encouraging pharmacists to provide guidance on environmentally safe disposal, drug take-back schemes, and eco-friendly packaging.[22]

This human-cantered principle links pharmacological responsibility with public health education.

8. Lifecycle and Circular Economy Integration

The pharmaceutical lifecycle — from raw material extraction to disposal — offers multiple entry points for sustainability interventions.[23] Principles include:

1. *Sustainable sourcing*: Using renewable feedstock and plant-based APIs.
2. *Circular packaging*: Biodegradable blister packs and recyclable materials.[24]
3. *Waste valorization*: Recovery of APIs or solvents from expired or unused medications.

4. *Carbon foot printing*: Evaluating and reducing CO_2 emissions at each lifecycle stage.[25]

Circular economy principles ensure that pharmaceutical development does not simply shift the environmental burden downstream.

8.1. Interdisciplinary integration and one health

Finally, sustainable pharmacology rests on the One Health principle — recognizing the interconnectedness of human, animal, and environmental health.[4]

1. *Veterinary pharmacology*: Restricting ecotoxic drugs (e.g., diclofenac in livestock).
2. *Environmental toxicology*: Incorporating ecotoxicological endpoints in preclinical studies.
3. *Policy harmonization*: Aligning national and international regulatory frameworks.[26]

This principle underscores that pharmacology must transcend disciplinary silos to address global sustainability challenges.

9. Green Chemistry in Pharmaceutical Synthesis

1. **Solvent substitution and solvent-free approaches:** Solvents account for up to 80% of the waste generated in pharmaceutical synthesis.[16] Replacement with greener alternatives (e.g., water, ethanol, ionic liquids, supercritical CO_2) or solvent-free methods (mechano-chemistry) has shown promise.
2. **Catalysis and biocatalysis:** Enzyme-mediated transformations and metal catalysis allow selective reactions under mild conditions, reducing energy demand and hazardous by-products. For example, lipase-catalysed esterification in API synthesis eliminates toxic reagents.[27]
3. **Flow chemistry and continuous manufacturing:** Continuous manufacturing reduces solvent consumption, energy use, and reaction times compared to batch processing.[15] The FDA has approved several APIs produced via continuous processes, paving the way for mainstream adoption.
4. **Design for degradation:** Designing APIs with controlled biodegradability ensures they break down into non-toxic metabolites in the environment. While challenging, computational chemistry and predictive ecotoxicology are enabling early-stage screening for environmentally benign drug candidates.[28]

10. Green Analytical Chemistry (GAC)

1. **Importance of green analytical approaches:** Analytical chemistry is indispensable to the pharmaceutical lifecycle, ensuring drug quality, stability, and regulatory compliance. Yet, conventional methods consume large amounts of toxic solvents, reagents, and energy. Green Analytical Chemistry (GAC) aims to minimize these impacts while preserving method robustness and accuracy.[10]
2. **Greenness assessment tools:** Table 2. summarizes several standardized tools have been developed to evaluate the environmental friendliness of analytical methods:

Table 2: Comparison of greenness metrics in analytical chemistry.[17,19]

Metric	Features	Strengths	Limitations
Agree (Analytical GREEnness Metric)	Software tool scoring 0–1	Comprehensive, covers 12 principles	Requires detailed data inputs
GAPI (Green Analytical Procedure Index)	Color-coded pictogram	Visual, holistic	Qualitative, less quantitative
Eco-Scale	Numeric (out of 100)	Simple calculation	Focuses mainly on hazards, less on energy
NEMI (National Environmental Methods Index)	Quadrant-based	Easy to use	Oversimplified, less nuanced

11. Practical Interventions

1. **Miniaturization of methods:** Capillary electrophoresis and microfluidics significantly reduce solvent consumption.
2. **Greener solvents:** Ethanol, propylene carbonate, and ethyl lactate can replace acetonitrile and methanol in chromatography.
3. **High-efficiency techniques:** UHPLC and UPLC minimize run times and solvent use compared to traditional HPLC.
4. **Automated sample preparation:** Techniques such as solid-phase microextraction (SPME) reduce reagent consumption**.**

Recent studies report widespread application of AGREE and GAPI tools in developing stability-indicating HPTLC, LC-MS, and spectroscopic methods.[29] Publishing greenness scores alongside method validations is increasingly seen as best practice.

12. Sustainable Manufacturing and Supply Chains

12.1. Environmental footprint of manufacturing

Pharmaceutical manufacturing is resource-intensive. Studies show that solvent use accounts for most of a drug's carbon and chemical footprint (Jiménez-González et al., 2011). Energy consumption during synthesis, purification, and formulation adds to emissions, while improper wastewater management leads to API discharges.

12.2. Strategies for sustainable manufacturing

1. Solvent recycling and recovery systems reduce hazardous waste.

2. Continuous manufacturing improves yield and reduces energy use.
3. Renewable energy adoption in production facilities cuts carbon emissions.
4. Process intensification (telescoping multiple steps) avoids intermediate isolations.

12.3. Supply-chain transparency

Hospitals and health systems are demanding greener procurement, requiring suppliers to disclose chemical footprints and sustainability practices (Wilburn et al., 2021). Several pharmaceutical companies now publish annual sustainability reports aligned with the Global Reporting Initiative (GRI).

12.4. Green pharmacy practice and prescribing

1. **Eco-directed prescribing:** Eco-directed prescribing involves choosing drugs and formulations with lower environmental footprints when clinically appropriate. For instance, selecting APIs with shorter environmental half-lives or formulations with reduced excipient toxicity.[30]
2. **Take-back and disposal programs:** Improper disposal (e.g., flushing medicines down sinks) is a significant contamination source. National drug take-back programs, such as those in Sweden and the U.S., have reduced pharmaceutical waste entering landfills and water systems.
3. **Role of pharmacists:** Pharmacists are critical in counseling patients about proper disposal and adherence. In Sweden, community pharmacies integrate sustainability assessments into their daily operations, setting an example for other countries.[22]
4. **Patient engagement:** Promoting adherence reduces unused medicines, thereby minimizing waste. Mobile health (mHealth) tools can remind patients of dosing schedules, indirectly supporting sustainability.

12.5. Metrics and lifecycle assessment

1. *Lifecycle assessment (LCA):* LCA quantifies carbon, water, and toxicological footprints across the pharmaceutical lifecycle. It identifies hotspots where intervention yields the greatest sustainability benefits.[23]
2. *Greenness evaluation:* Analytical and synthetic greenness metrics (AGREE, GAPI, Eco-Scale, E-factor) are increasingly integrated into research publications and regulatory submissions.
3. *Corporate reporting:* Some companies have adopted pharmaceutical foot printing — measuring emissions, solvent use, and wastewater discharges for each product. However, reporting lacks standardization, making comparisons across firms difficult.

13. Barriers and Challenges

1. **Economic and supply-chain inertia:** Transitioning to greener methods often requires significant capital investment. Small and medium-sized enterprises may lack resources to upgrade facilities.
2. **Therapeutic–environmental trade-offs:** Optimizing a drug for biodegradability can compromise pharmacokinetics or therapeutic efficacy. Balancing these aspects is a major design challenge (Moermond et al., 2022).
3. **Regulatory and analytical gaps:** Not all regions mandate ERAs for pharmaceuticals. Moreover, monitoring APIs in environmental matrices requires advanced and costly instrumentation, limiting widespread adoption.
4. **Greenwashing risks:** Without standardized metrics, companies may exaggerate sustainability claims. Independent verification of greenness metrics is essential to build trust.

Table 3: Key Barriers vs. solutions in green pharmacology

Barrier	Examples	Potential Solutions
Economic costs	High investment in new manufacturing systems	Tax incentives, public-private partnerships
Therapeutic trade-offs	Biodegradability may reduce half-life	Computational optimization, balanced design
Regulatory gaps	ERA not mandatory in many countries	Global harmonization, WHO-led frameworks
Greenwashing	Inflated sustainability claims	Independent certification, transparent LCA reporting

14. Recommendations

14.1. For researchers and developers

1. Integrate biodegradability and ecotoxicity screening into early drug design.
2. Report greenness metrics alongside synthetic and analytical methods.

14.2. For manufacturers

1. Adopt continuous manufacturing, solvent recycling, and renewable energy.
2. Publish transparent chemical footprint reports.

14.3. For pharmacists and prescribers

1. Practice eco-directed prescribing when alternatives exist.
2. Educate patients on safe disposal of medicines.

14.4. For regulators and policymakers

1. Mandate ERAs for new APIs.
2. Incentivize green procurement in healthcare systems.

3. Establish global EPV networks to monitor pharmaceutical pollution.

14.5. Outlook

1. The future of green pharmacology will be shaped by technological, regulatory, and societal trends.
2. Artificial intelligence (AI) and machine learning will accelerate green drug design by predicting biodegradability and toxicity of candidate molecules.
3. Organs-on-chip and microfluidic systems will reduce reliance on animal testing and minimize resource consumption in preclinical studies.
4. Digital twins and personalized medicine may reduce overall pharmaceutical consumption by optimizing dosing regimens.
5. Circular economy models will promote recycling of solvents, reagents, and packaging materials.
6. Global policy frameworks integrating One Health principles will harmonize environmental standards for pharmaceuticals.
7. Ultimately, embedding sustainability into pharmacology is not only an environmental necessity but also an opportunity to align healthcare innovation with the United Nations Sustainable Development Goals (SDGs).

15. Conclusion

Green pharmacology is a novel paradigm that unites pharmacological innovation with ecological sustainability. It places emphasis on the design, synthesis, and application of pharmaceuticals with minimal environmental toxicity or consumption of vital resources. With the employment of green chemistry principles in drug manufacturing, the focus has shifted to atom economy, renewable feedstock, and the usage of green solvents. Green extraction techniques, like supercritical CO_2 and microwave-assisted extraction, have been developed to decrease the dependency on hazardous chemicals in phytopharmacological research. Biocatalysis and enzyme-catalyzed synthesis provide cleaner and efficient ways of producing drugs, while green analytical methodology, quantified by tools like GAPI and AGREE, provides environmentally benign testing protocols. Life cycle assessment (LCA) has been increasingly applied to gain better insight into the overall ecological footprint of pharmaceuticals, from synthesis to disposal, contributing to eco-pharmacovigilance and regulatory compliance. Moreover, AI-based modelling underpins predictive assessment of environmental impacts, aligning digital pharmacology with sustainable drug discovery. Green pharmacology, therefore, contributes to the One Health vision by protecting human well-being, ecological stability, and biodiversity through these combined efforts.

Table 4 summarizes the main domains of green pharmacology and emphasizes how sustainable innovations are being integrated into pharmaceutical science. Each of the elements involved, from the design and synthesis of drugs to waste management and digitalization, illustrates the application of eco-friendly methodologies that cumulatively reduce environmental burdens. The table provides representative examples such as supercritical CO_2 extraction, enzyme-catalyzed synthesis, AGREE-based analytical evaluation, and AI-driven ecotoxicity prediction. Collectively, these examples show how the field is shifting toward a more circular and sustainable model of the pharmaceutical industry that fits within the One Health framework, incorporating human well-being with ecological safety and economic feasibility.

Table 4: Key Aspects of green pharmacology with representative innovations and examples

Aspect	Green Innovation / Approach	Representative Examples (2020–2025)	Outcome / Impact
Drug Design	Development of biodegradable and eco-friendly drug molecules	Example: Ibuprofen and naproxen analogues redesigned for rapid biodegradation; biodegradable polymers in drug carriers (PLA, PCL-based)	Reduced environmental persistence and aquatic ecotoxicity
Synthesis Methods	Adoption of green chemistry principles (atom economy, solvent substitution, catalysis)	Example: Use of water or ethanol as reaction media; Pd/C or enzyme-based catalysis replacing stoichiometric reagents	Lower hazardous waste, improved process efficiency
Extraction Techniques	Supercritical CO_2, microwave-assisted, ultrasound-assisted extraction	Example: Supercritical CO_2 extraction of curcumin and resveratrol; microwave extraction of alkaloids and flavonoids	Reduced solvent use, higher yield, faster extraction
Phytopharmacology	Sustainable sourcing of plant bioactives under GACP and organic cultivation	Example: Cultivation of *Withania somnifera* and *Curcuma longa* using organic farming; traceability under WHO GACP	Conservation of biodiversity and renewable sourcing
Analytical Chemistry	Implementation of green analytical metrics	Example: AGREE assessment for HPLC of antihypertensives; ethanol-water mobile phases replacing acetonitrile	Improved environmental compliance and laboratory safety

	(GAPI, AGREE) and greener solvents		
Bio-catalysis	Enzyme-mediated synthesis using lipases, oxidases, or transaminases	Example: Lipase-catalyzed esterification for statin intermediates; oxidase-catalyzed synthesis of chiral amines	Mild conditions, high stereoselectivity, reduced toxic waste
Waste Management	Safe collection, recycling, and degradation of pharmaceutical residues	Example: Activated carbon filtration for antibiotic residues; UV-assisted photocatalytic degradation of diclofenac and carbamazepine	Prevention of drug accumulation in soil and water
Nanopharmacology	Biosynthesized nanocarriers from plant or microbial extracts	Example: Silver nanoparticles synthesized from *Azadirachta indica* and *Aloe vera* extracts for antimicrobial formulations	Reduced chemical waste, high biocompatibility
Life-Cycle Assessment (LCA)	Quantifying total environmental footprint from synthesis to disposal	Example: LCA of paracetamol and amoxicillin production highlighting solvent and packaging emissions	Identification of key stages for emission reduction
Regulatory Oversight	Eco-pharmacovigilance (EPV) and environmental risk assessment inclusion	Example: EMA's inclusion of EPV guidelines in pharmaceutical submissions; FDA's green chemistry initiatives	Enhanced post-market environmental monitoring
Digital Integration	Use of AI, QSAR, and in-silico ecotoxicology tools	Example: AI-driven biodegradability prediction for new APIs; in-silico QSAR models for aquatic toxicity prediction	Early screening of low-impact drug candidates
Public Health and Ethics	One Health approach linking human, animal, and environmental health	Example: WHO One Health initiatives; integration of EPV into hospital waste management programs	Balanced human and ecosystem health protection

Green and sustainable pharmacology represents a paradigm shift in how medicines are designed, produced, prescribed, and monitored. By embracing green chemistry principles, sustainable manufacturing, green analytical methods, Eco pharmacovigilance, and eco-directed prescribing, the pharmaceutical sector can minimize its ecological footprint without compromising therapeutic efficacy. Despite challenges such as economic barriers, regulatory gaps, and risks of greenwashing, progress is evident in both academia and industry. The integration of AI, lifecycle assessment, and One Health frameworks offers promising pathways. Moving forward, cross-disciplinary collaboration between chemists, pharmacologists, clinicians, policymakers, and patients will be essential to achieve a truly sustainable pharmaceutical future.

16. Source of Funding

None.

17. Conflict of Interest

None.

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Cite this article: Dube S. Green and sustainable pharmacology: Integrating environmental responsibility into drug discovery, development, and practice. *IP Int J Comprehensive Adv Pharmacol*. 2024;10(3):125-133.