RESEARCH PAPER

Eco-Friendly Contrast Agents and Sustainable Radiology: A Pharmacy-Integrated Review of Science, Technology, and Environmental Stewardship

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Abstract

The growing need for environmentally friendly pharmaceutical processes, especially in the creation and application of imaging agents, has been brought to light by the rising need for diagnostic imaging. This study integrates ideas from pharmacokinetics (PK), pharmacodynamics (PD), environmental pharmacology, green chemistry, and biotechnology to examine recent developments in environmentally friendly biopharmaceutical approaches for medical imaging. Despite their clinical efficacy, conventional iodinated and gadolinium-based contrast agents cause environmental contamination due to their persistence, insufficient clearance of wastewater, and creation of hazardous transformation products. Promising options with less of an impact on the environment include hydroxypyridinone (HOPO)-based ligands, biodegradable chelators, and green synthesis methods. The article goes on to address how nanotechnology is used in sustainable imaging, Biotechnology innovations including plant cell culture, fermentation-based production, and AI-assisted manufacturing are emphasized as ecologically friendly and scalable production methods. An important method for assessing the environmental impact of imaging agents throughout the course of their lifecycle is life cycle assessment, or LCA. Furthermore, as essential elements for advancing sustainable healthcare, changing legal frameworks, green pharmacy concepts, sustainable packaging, waste management, and health economics are analysed.

Keywords: Pharmacokinetics, Environmental pharmacology, Iodinated contrast media, Waste management

How to cite this article: Padmaja T, Wagdevi P, Nagaraj B, Busi SK, Indira P. Eco Friendly Contrast Agents and Sustainable Radiology: A Pharmacy-Integrated Review of Science, Technology, and Environmental Stewardship. Int J Drug Deliv Technol. 2026;16(69s): 569-575. DOI: 10.25258/ijddt.16.69s.62

1. Introduction

The scientific foundation for comprehending how medications function in the body is provided by the closely connected fields of pharmacokinetics (PK) and pharmacodynamics (PD). Pharmacodynamics studies the drug's physiological and biochemical effects as well as its mode of action at the target site, whereas pharmacokinetics concentrates on the drug's passage through the body as characterized by absorption, distribution, metabolism, and excretion (ADME). When combined, PK and PD provide a thorough understanding of drug behaviour that helps optimize pharmacological therapy in both clinical and research contexts. Designing sensible dosage schedules that minimize toxicity and produce the intended therapeutic effects requires the combination of PK and PD data. PK/PD analysis is now much more accurate and applicable thanks to developments in computational modelling and bioanalytical technologies. (Gorakshnath GV and Rangnath DB, 2025)

2. Environmental Burden of Current Contrast Agents

Scientists have been paying more attention to Perfluorinated and Polyfluorinated Alkyl

Compounds (PFAS) in recent years. Thousands of commercially produced chemicals are used in many products and technical processes. Because of these compounds' remarkable environmental stability, humans and all other life forms are consequently exposed to them.

The most notable characteristic of all PFAS is their extraordinary persistence—they barely break down in the natural world. The non-fluorinated portion of partially fluorinated hydrocarbons is known to degrade slowly through microbial transformation processes, but the perfluorinated residue that remains will last for a very long time. (Brunn, H et al.,2023)

2.1. Iodinated Contrast Agents

Iodine-based Contrast Agents (ICMs) are essential materials in medical imaging because of their strong X-ray properties and chemical stability. However, there is growing environmental concern due to their persistence and inadequate removal in conventional wastewater treatment. Despite the low acute toxicity of ICMs, their transformation during water disinfection can produce iodine-based disinfection by-products (I-DBPs), such as iodo trihalomethanes, which have significant ecotoxic, genotoxic, and cytotoxic effects and lower the quality of drinking water. Due to their environmental durability and insufficient removal by traditional wastewater treatment methods, iodinated contrast agents which are frequently used in medical imaging are becoming more prevalent in aquatic settings. Iodinated disinfection by-products with cytotoxic and genotoxic qualities can arise during water disinfection, despite the fact that ICMs themselves have little acute toxicity.(Wrzesińska, et al., 2026)

2.2 Gadolinium-Based Contrast Agents (GBCAs)

By enabling the use of contrast-enhanced MRI to enable crucial clinical diagnosis in a variety of diseases that would otherwise go undiagnosed, Gadolinium-Based Contrast Agents (GBCAs) have revolutionized magnetic resonance imaging (MRI). Despite the fact that Globally, studies have shown that gadolinium can remain in tissues long after exposure and that patients with reduced renal function can develop nephrogenic systemic fibrosis, a disease linked to GBCA. Understanding the pharmacokinetics of both people and animals is essential to comprehending the distribution, excretion, and, eventually, potential retention of gadolinium and GBCAs. Every GBCA exhibits quick extravascular and blood distribution, followed by quick renal clearance. Gadoxetate and gadobenate, which contain a percentage of hepatobiliary excretion that permits liver imaging, are the exceptions. (Davies, J et al.,2022)

2.3 Plastic Consumables in Radiology

Medical imaging agents, such as radiopharmaceuticals and contrast agents for magnetic resonance imaging (MRI), are essential for illness diagnosis. However, the majority of them contain dangerous and non-biodegradable materials like radionuclides, heavy metals, and per- and polyfluoroalkyl substances (PFAS). These chemicals are entering different water bodies and soil due to their growing clinical use, endangering both human health and the environment. The main imaging techniques' impacts on the environment are described here, along with a link between the chemistry of the contrast agents and their effects on the environment. The 3Cs of imaging agents—control, change, and combine as well as new methods for more environmentally friendly imaging techniques are presented as suggestions for the creation and use of contrast agents. This combination of actions should stimulate an open dialogue, provide ideas for ways to lessen imaging agent pollution, and raise awareness of the effects of imaging agent-related toxic waste. (Pichler, et al.,2025)

3.Pharmaceutical Chemistry of Eco-Friendly Chelates

3.1 HOPO (Hydroxypyridinone)-Based Chelators

The pharmaceutical industry is increasingly employing green solvents as eco-friendly alternatives to conventional solvents in response to growing environmental concerns and regulatory constraints. This paper examines the advancements in green chemistry in the pharmaceutical industry, with a focus on the use of bio-based solvents, water-based solvents, supercritical fluids, and deep eutectic solvents. Dimethyl carbonate, limonene, and ethyl lactate are examples of bio-based solvents with low toxicity, biodegradable qualities, and reduced emission of volatile organic molecules. Water-based solvents that are non-toxic and non-flammable alternatives include aqueous solutions of acids, bases, and alcohols.(Bibhas Pandit and Projesh Saha,2025)

3.2 Green Synthetic Chemistry Approaches

A green chemistry practice is mostly driven by the catalytic method. The science of utilizing catalysts to improve or sustainably facilitate a chemical reaction is known as catalysis. A catalyst is a material that speeds up a chemical reaction without changing chemically over time. There are two types of catalysts: homogeneous and heterogeneous. When a catalyst is heterogeneous, its state differs from that of the reactants.(Sageer et al., 2024)

4. Pharmaceutical Nanotechnology for Sustainable Imaging

Science and technology, which are only used to create new tools and goods that range in size from micro to nanoscale, have always been essential to humankind's battle. Because of its many uses in biomedicine, especially in relation to medication delivery and bioimaging, nanotechnology has attracted a lot of attention. Numerous nanomaterials and nanodevices have been created for the diagnosis and treatment of various illnesses. The two main facets of nanomedicine—drug administration and in vivo imaging—have been discussed here, with an emphasis on current developments and upcoming research. Recent years have seen tremendous breakthroughs in nanotechnology techniques for imaging, especially of cancer cells. A appropriate medium for performing molecular level alterations, such as site-specific imaging and targeting, is provided by nanoparticles. The development of radionuclides, quantum dots, magnetic nanoparticles, carbon nanotubes, and the use of gold nanoparticles in biosensors have transformed imaging, making it easier to comprehend the pathophysiology of disease and improving therapeutic delivery. Because of the significance of nanomedicine's great specificity and selectivity, recent developments in this area must be comprehended for a better present and a more prosperous future.(Mir et al.,2017)

5.Pharmacokinetics, Toxicology & Environmental Pharmacology

5.1 Human PK/PD of Eco-Friendly Agents

The study of how medications pass through the body is known as pharmacokinetics. It entails comprehending how medications are absorbed, distributed, metabolized, and excreted (ADME), which together define the drug's concentration in the body over time. The process by which a medication leaves the site of administration—such as the digestive tract or muscle tissue—and enters the bloodstream is known as absorption. The drug's transfer from the bloodstream to other body tissues and organs is referred to as distribution. The process by which the body chemically transforms a medication into a metabolite that is simpler to eliminate is known as metabolism, or biotransformation. Excretion is the process by which a medication or its metabolites are removed from the body, typically by the liver or kidneys. Determining the proper dosage schedule for a medication, comprehending drug interactions, and forecasting how physiological changes (such liver or kidney illness) may impact drug levels in the body all depend on pharmacokinetic principles. (Abhishek Kumar, 20024_)

In order to conduct successful pharmacokinetics/pharmacodynamics (PK/PD) research during the drug discovery and development phases, the pharmaceutical industry needs scientific professionals from complementary fields. Pharmacology labs within a particular disease area often carry out the pharmacodynamic aspect of PK/PD investigations (e.g., animal dosing and response measurement), while DMPK measures concentrations and evaluates pharmacokinetics.(Balaji et al.,2007)

5.2 Environmental Pharmacokinetics (E-PK) and Eco-Toxicology

Drug elimination pathways may be influenced by environmental conditions. According to research (Li et al. 2019), environmental stressors including exposure to high temperatures or pollution can change hepatic enzyme activity and renal function, which may have an impact on drug clearance rates. Drug excretion may also be impacted by dietary and fluid changes brought on by environmental factors. Customizing medication regimens to particular environmental contexts requires an understanding of the environmental factors that impact drug excretion. (Vikas Sahu, and Bhisham Sahu.2020).

Erythromycin has recently been found in a number of aquatic systems due to its widespread use. Erythromycin resistance and its detrimental impact on a variety of aquatic organisms have been documented in numerous investigations. As a result, erythromycin's possible effects on environmental health have drawn more attention. Fish have been the focus of many publications about the bioaccumulation and negative consequences of erythromycin since they are an essential part of aquatic ecosystems.(Alam,et al.,2025)

6. Sustainable Pharmaceutical Consumables in Radiology

The necessity for sustainable and environmentally friendly procedures is highlighted by the radiopharmaceutical sciences' explosive growth, which is fueled by the regulatory approval of theranostic drugs and the growing use of PET imaging. Despite the fact that radiopharmaceuticals provide very precise, focused therapy with low systemic toxicity, the industry has difficulties with waste management, energy consumption, and rising demand. With the nuclear medicine business expected to grow to $30 billion by 2030, radiopharmaceutical development must incorporate sustainability concepts like green chemistry and green engineering. These ideas offer methods for lessening the environmental impact of radiochemical processes, which are energy-intensive..(Verena Pichler et al.,2025)

6.1 Reusable and Recyclable Imaging Kits and Packaging Innovations

The issues with waste management for disposable, non-recyclable, and non-biodegradable materials as well as environmental sustainability when plastic items or components are used in medical equipment and supplies. Syringes, tubing, intravenous (IV) bags, packaging, and more are examples of medical plastic waste. Although it is not yet a top priority, creating biodegradable substitutes for petroleum-based plastics in medical equipment is a significant undertaking. A number of important topics are involved in the examination of alternatives, such as material selection, testing, validation, and regulatory approval.(Moshkbid, et al., 2024)

7. Biotech Manufacturing & Scalable Production

7.1 Fermentation-Based Chelator Production

Manufacturing is the foundation of national economies and a major factor in international competition. Artificial intelligence and other innovative technologies have played a major role in recent biotechnology advancements. Artificial intelligence (AI) has played a significant role in the biotech industry's advancement in recent years. New AI biotech products must, however, abide by laws controlling the use, disclosure, sales, and marketing of personally identifiable information. It has revolutionized the manufacturing sector.

Optimizing fermentation is crucial for the industrialization of biological manufacturing and has been extensively used in a variety of industries, including food, medicine, cosmetics, and bioenergy, all of which have significant financial advantages. Since strain creation directly affects the product yield and overall success of the fermentation process, it is regarded as the fundamental component of fermentation technology. (Zhen-Zhi et al.,2025)

7.2 Plant Cell Culture for Natural Agents

Plants have been used as a sustainable source of food, tastes, colors, agrochemicals, medicinal proteins, bioactive substances, and stem cells. However, due to numerous environmental conditions and human disturbances, plant habitats are rapidly disappearing. This calls for the development of a workable substitute technology for the ongoing manufacturing of substances used in food and medicine. Because they accumulate in little amounts, high-value natural products and bioactive chemicals are frequently difficult to chemically produce. The process of isolating and purifying bioactive chemicals from plants is labor-intensive, time-consuming, and requires difficult extraction techniques. Alternative solutions are therefore required, and the plant cell culture method provides simple downstream processes. Some of the benefits for the synthesis and accumulation of the targeted metabolites and the development of high-yielding cell factories include the preservation of the metabolic cues of natural plants, scale-up facilities, use as stem cells in the cosmetics industry, and metabolic engineering (particularly the rebuilding of the pathways in microbes). Plant cell suspension cultures for the in vitro modification and synthesis of plant bioactive chemicals are covered in this article.(Bapat, VA et al., 2023)

7.3 Life-Cycle Assessment (LCA)

Life Cycle Assessment (LCA) is a method of scientific analysis that measures the environmental impact of a technology, product, or process at every stage of its life cycle, from the extraction of raw materials to processing, manufacturing, distribution, usage, and disposal. The conventional technique for evaluating the biophysical and socioeconomic effects of goods and services throughout their life cycles is life cycle assessment, or LCA. using Life Cycle Assessment (LCA) to measure and examine the environmental impacts of the pharmaceutical industry, including medication formulation, packaging and transportation, end-of-life disposal, and active pharmaceutical ingredients (APIs).(Zhengyun et al., 2024)

The inventory analysis results are allocated to several impact categories throughout the LCA's impact assessment phase. The computed inventory emissions and resources are converted into indicators that may represent resource scarcity or environmental or health risks using impact assessment methodology. Equivalency factors, which show the anticipated contribution to an impact per unit of emission or resource consumption, serve as the foundation for this "translation." Models are typically used to calculate the factors.(Kristi et al., 2022)

8. Regulatory Science & Pharmacy Practice Implications

8.1 Regulatory Pathways

With effect from September 2024, the European Medicines Agency (EMA) has released a new Environmental Risk Assessment (ERA) Guideline that will change how pharmaceutical companies assess and reduce the environmental effects of their medicines. More scientific rigor, openness, and pharmaceutical sustainability are prioritized in the new framework, which guarantees that each human medicinal product (HMP) is subjected to a methodical assessment of its possible ecological dangers. This upgrade is a crucial step in bringing the pharmaceutical industry into line with the larger objectives of the European Green Deal and the rising standards for environmental responsibility.

A pharmaceutical substance's possible effects on the environment, including surface water, groundwater, soil, and biodiversity, are assessed through an Environmental Risk Assessment (ERA). As agencies expedited vaccine assessments while battling coordination gaps, the COVID-19 pandemic exposed both agility and fragility in regulatory processes. Many regulators deal with resource constraints, such as inadequate infrastructure and technological capability, particularly in low- and middle-income nations. (George et al.,2026)

8.2 Waste Management & Green Pharmacy

The pharmaceutical sector has grown rapidly at the same time that environmental concerns have grown. A new idea called "green pharmacy" incorporates sustainable management techniques into pharmaceutical operations to lessen the negative environmental effects of drug discovery, manufacturing, distribution, and disposal. The important aspects of sustainable practices in the pharmaceutical sector are examined in this book, which also looks at how innovation, legal frameworks, environmental stewardship, and economic viability interact. (Arpitha, 2025). This bibliometric evaluation provides a thorough summary of the evolution and current status of research on the use of sustainable medicines. In addition to highlighting the research field's interdisciplinary and collaborative nature, we have recognized the most significant contributions, publications, and emerging research trends. (Ammar et al., 2025)

9. HEOR Perspective: Cost, Value, and Sustainability

Accurately showing the product's value, health economics and outcomes research, or HEOR (Health Economics and Outcomes Research), has become a crucial component of healthcare systems. Healthcare stakeholders can use HEOR's valuable insights to make well-informed decisions about the provision of healthcare. The purpose of this review is to emphasize the importance of integrating HEOR activities throughout the different stages of drug development and the critical role that HEOR plays throughout the product lifecycle. Pharmaceutical firms are becoming more aware of how important it might be for their product's ongoing commercial success to integrate HEOR efforts from the early stages of product development through product launch, as well as during the postmarketing period, in order to provide real-world evidence (RWE). A pharmaceutical product's success in various regulatory and health technology assessment (HTA) environments across different regions is made possible by HEOR's assistance in validating the product's worth. Technological developments provide chances to increase the value of HEOR despite a number of difficulties in data gathering and processing. HEOR will become even more important in determining the long-term value of a pharmaceutical product for all stakeholders, including regulators, patients, prescribers, and payers, given the growing expectations for solid clinical evidence by international regulators and economic evidence by HTA agencies and payers.

Conclusion

A big step in lessening the environmental impact of contemporary diagnostic imaging while preserving therapeutic efficacy is the creation of environmentally friendly contrast agents and sustainable radiology. Although conventional iodinated and gadolinium-based contrast agents have revolutionized medical diagnostics, there is an urgent need for sustainable alternatives due to their persistence in aquatic habitats, limited removal during wastewater treatment, and potential toxicological effects. Current developments in biodegradable chelators. Additionally, biotechnology-driven manufacturing techniques, including as plant cell culture, microbial fermentation, and AI-assisted process optimization, offer scalable and resource-efficient production strategies that are consistent with green pharmacy principles. Evidence-based decision-making for sustainable healthcare is supported and a thorough assessment of the environmental impact of imaging agents is made possible by the incorporation of Life Cycle Assessment (LCA) into their design, manufacture, usage, and disposal. The next generation of imaging agents can provide high diagnostic performance while preserving ecosystem health and

promoting the long-term viability of healthcare systems by fusing scientific innovation with environmental stewardship.

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