Vitanza *et al. One Health Advances* (2025) 3:36
https://doi.org/10.1186/s44280-025-00103-0

One Health Advances

REVIEW

Open Access

Environmental sustainability of healthcare system in the era of One Health: a pharmaceuticals residues point of view

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Abstract

This study aims to investigate the environmental impact of pharmaceuticals across their life cycle—from production to disposal—in the context of increasing concerns about sustainability in healthcare systems. Utilizing a narrative review approach, data from recent scientific literature and policy documents were analyzed to assess the extent of pharmaceutical pollution, its ecological consequences, and the effectiveness of current mitigation strategies. The analysis revealed that pharmaceutical residues, particularly non-metabolized active pharmaceutical ingredients, have been shown to contribute to aquatic pollution and biodiversity loss in multiple studies, with evidence of effects on certain species and ecosystems. Emissions from pharmaceutical production account for approximately 4.4% of global carbon emissions, while inadequate disposal practices exacerbate environmental contamination. Moreover, specific drug classes, such as non-steroidal anti-inflammatory drugs, antibiotics, hormones, and anticancer agents, pose heightened ecotoxicological risks, including endocrine disruption and antimicrobial resistance. The study highlights promising mitigation strategies, including solvent recovery technologies, green packaging, advanced wastewater treatments, and innovations such as biodegradable drugs and AI-driven telemedicine. Case studies from companies such as Merck, Sanofi, and AstraZeneca demonstrate the feasibility of integrating sustainability into pharmaceutical operations. The findings underscore the urgent need for regulatory frameworks that incorporate environmental criteria into health technology assessments, in alignment with the EU Green Deal and Agenda 2030. These insights contribute to the One Health perspective, emphasizing the interdependence between environmental protection, public health, and pharmaceutical innovation.

Keywords Pharmaceutical pollution, One Health, Sustainable healthcare, APIs, Wastewater treatment, Antimicrobial resistance, Green packaging, Biodiversity loss, HTA, Telemedicine

Introduction

Pharmaceuticals play an indispensable role in safeguarding human health, supporting life expectancy, improving quality of life, and treating both chronic and acute conditions. However, in the face of escalating ecological degradation and climate change, the pharmaceutical sector must recognize a difficult paradox: while its products are designed to safeguard health, their entire life cycle from synthesis to consumption and disposal generates environmental burdens that ultimately undermine the health of both people and ecosystems. This contradiction becomes even more pressing in light of the One Health approach, which frames human, animal, and environmental health as interdependent [1]. In this context, the

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pharmaceutical industry cannot continue to externalize its environmental costs.

Some studies estimate that the pharmaceutical sector contributes roughly 4.4% of global carbon emissions, a figure comparable to or slightly higher than certain estimates for the automotive sector [2]. Carbon emissions arise not only from production facilities but also from energy-intensive supply chains, packaging, and even patient-level usage patterns. However, the environmental impact does not stop at carbon footprint. Increasing concentrations of active pharmaceutical ingredients (APIs) are being detected in freshwater bodies worldwide. These residues, often resulting from improper disposal, poor waste management, or unmetabolized excretion, can persist in aquatic environments and cause significant harm to biodiversity [3].

The consequences of such contamination are already known. Hormonal drugs have led to intersex conditions in fish, non-steroidal anti-inflammatory drugs (NSAIDs) such as diclofenac have contributed to the collapse of vulture populations in South Asia, and antibiotics are accelerating the global crisis of antimicrobial resistance by seeding resistance genes in waterborne bacteria. In short, pharmaceutical pollution is not a hypothetical future threat, but rather a measurable, present-day issue with impacts documented in specific species and locations, although the full global ecological consequences remain under investigation. Understanding and mitigating these impacts requires a systemic approach. Environmental concerns must be integrated into every phase of the pharmaceutical value chain, from drug design and manufacturing to drug distribution, use, and disposal.

This narrative review analyses the environmental impact of pharmaceuticals across their entire life cycle, with particular attention to the drug classes most commonly detected in environmental matrices. It further examines current mitigation strategies, technological innovations, and regulatory instruments proposed or implemented within the European Union (EU) framework, including those suggested by the European Commission and the European Parliament.

The literature considered includes peer-reviewed scientific publications and relevant policy documents issued between 2010 and 2025. The bibliographic search was performed using the PubMed database, with specific keyword combinations such as "pharmaceutical pollution", "API environmental impact", "green chemistry", "wastewater treatment", and "One Health". Eligible sources comprised English-language systematic reviews, case studies, and original articles reporting data on emissions, ecotoxicity, removal technologies, and mitigation approaches. Grey literature—such as documents from European Federation of Pharmaceutical Industries and Associations (EFPIA), the World Economic Forum (WEF), and European regulatory bodies—was also included to integrate scientific findings with policy and industry perspectives.

Throughout the text, a distinction is drawn between pharmaceuticals intended for widespread use—primarily dispensed through community pharmacies—and those used in hospital settings, such as antineoplastic agents, radiopharmaceuticals, and contrast media. Although the latter are associated with a considerable environmental impact, they will be addressed only briefly, with the aim of highlighting their specific characteristics. This distinction is warranted not only by differences in ecotoxicological risk profiles, but also by the specific analytical methods and wastewater treatment processes required for their detection and removal. The primary focus is placed on commonly used pharmaceuticals, due to their high consumption volumes, persistent detection in environmental matrices, and significant contribution to diffuse pharmaceutical pollution.

Environmental burdens throughout the pharmaceutical life cycle

The environmental burden of pharmaceuticals begins with the extraction of raw materials and continues throughout their production, packaging, distribution, and end-of-life [4]. The ecological footprint of medicines originates as early as the extraction and procurement of raw materials, which are often derived from non-renewable resources. The synthesis of APIs requires substances such as metal oxides, organic solvents, halogenated compounds, or natural derivatives, which are frequently extracted or produced in countries far from industrial sites. This results in additional emissions associated with the transportation and chemical processing of such materials.

The chemical synthesis phase of pharmaceuticals represents one of the most environmentally burdensome stages, involving high energy consumption, extensive use of organic solvents, and the release of toxic, poorly biodegradable by-products. Many reactions require metallic catalysts or chlorinated reagents that, if not properly managed, may contaminate air, water, and soil. Although some forward-thinking companies have implemented solvent recovery and recycling technologies [5], such practices remain limited, particularly in industrial contexts where environmental regulations are weak. Biocatalysis represents a promising alternative to traditional synthetic methods, employing enzymes as catalysts to achieve efficient transformations. Enzymatic synthesis demonstrates favorable green chemistry metrics, reducing energy consumption by 45% and achieving an atom

economy of 85–92%. Additionally, during the production of cardiac pharmaceuticals, biocatalytic processes result in a 50% reduction in CO_2 emissions compared to conventional synthesis [6].

Another significant source of impact stems from packaging and distribution.

Pharmaceutical packaging systems, such as the conventional polyvinyl chloride-aluminum blister packs, ensure impermeability and long product shelf life but are extremely difficult to recycle [7]. These materials, selected primarily for safety and cost-efficiency, fail to meet environmental sustainability criteria. In addition to recyclability issues, blister packs and plastic-coated pharmaceutical packaging represent a significant source of environmental microplastics, particularly during disposal and thermal degradation processes. These particles progressively fragment and are transported through atmospheric and aquatic systems, contributing not only to soil and water contamination but also to climate feedback mechanisms [8].

Microplastics originating from pharmaceutical packaging can adsorb and transport toxic substances, amplifying the environmental effects already associated with climate change including temperature rise, pH alteration, and decreased photosynthetic capacity in plants and algae.

According to several Life Cycle Assessment (LCA) studies, replacing conventional materials with biodegradable or recyclable alternatives could significantly reduce CO_2 emissions, industrial waste, and microplastic release [4]. However, large-scale adoption remains limited.

During the distribution and consumption phase, complexity further increases.

Overprescription or the dispensing of quantities exceeding therapeutic needs generates vast amounts of unused medicines. Many of these are improperly disposed of, for instance, by being thrown into general waste or flushed down toilets, thus contributing substantially to environmental contamination [9]. In Germany alone, an estimated 16,000 tons of pharmaceuticals are discarded annually, with nearly 80% disposed of incorrectly [10].

Another pathway for environmental release arises from metabolites excreted via urine and feces. After ingestion, a significant portion of active ingredients is not fully metabolized and is eliminated through sewage effluents. This category also includes topical formulations for skin and oral care, therapeutic cosmetics, and disinfectants, all of which increasingly contribute to the presence of pharmaceutical residues and emerging micro-pollutants in water bodies.

Wastewater treatment plants are not designed to remove such compounds. Conventional systems retain only a fraction of pharmaceutical molecules, allowing APIs such as ibuprofen, paracetamol, antibiotics, and steroid hormones to pass into surface waters [11]. Even at concentrations of just a few nanograms per liter, these substances can alter fish behavior, reproduction, and development, modify microbial community structures in sediments, and affect key water chemistry parameters such as pH, turbidity, and oxidative capacity.

The effects extend beyond aquatic ecosystems: accumulations in sediments and agricultural soils may propagate along the trophic chain, affecting plants, algae, and microorganisms. Several studies have identified synergistic interactions between pharmaceutical residues and climate change, which amplify pre-existing impacts, leading to biodiversity loss and disruptions in biogeochemical cycles [12, 13].

The environmental persistence of many compounds-combined with the presence of heavy metals, microplastics, and polycyclic aromatic hydrocarbons-produces cumulative effects that are difficult to predict and control. These contaminants, which are not readily biodegradable, can bioaccumulate and pose a significant ecotoxicological threat to entire ecosystems, representing one of the most urgent emerging challenges in the field of pharmaceutical sustainability.

Pharmaceuticals with elevated environmental impact

While all pharmaceuticals have some environmental cost, certain classes are particularly problematic due to their toxicity, volume of use, and long persistence [14]. In recent years, scientific interest in the removal of APIs from wastewater has increased significantly, both for municipal wastewater (MWW) and hospital wastewater (HWW) [15]. This trend is largely attributed to advances in analytical techniques, which now allow for the detection of emerging contaminants at very low concentrations (ng/L–µg/L) [16], as well as growing concern over the potential environmental and human health impacts associated with the presence of these substances in aquatic ecosystems. Some drug classes are more harmful than others. For example: NSAIDs, hormones, antibiotics, antidepressants, anticancer and contrast agents are frequently flagged in environmental monitoring efforts and the scientific literature [17].

Diclofenac, an NSAID, became emblematic of this problem when its use in livestock led to the catastrophic decline of vulture populations in South Asia [18]. Vultures that consume the carcasses of animals treated with diclofenac, in fact, suffer fatal kidney failure. This led not only to an ecological collapse but also to a public health crisis, as feral dogs filled the original ecological niche of vultures and contributed to the spread of rabies.

Table 1 Summary of pharmaceutical classes detected in municipal and hospital wastewater

Pharmaceutical Class	Main Compounds	Concentration in MWW	Concentration in HWW	Remarks
Antibiotics	CIP, NOR, OFL, SMX, SDZ, ENR	CIP: 27–4200 ng/L SMX: 12–7800 ng/L	NOR: up to 561,000 ng/L OFL: up to 198,000 ng/L CIP: 120–120,000 ng/L	HWW levels 3–10 × higher than MWW; frequent detection and persistence
Antiepileptics	CBZ	96–6500 ng/L	41.1–880 ng/L	CBZ shows high persistence; low biodegradability; difficult to remove with conventional treatments
Analgesics	NPX, DCF, ACE, IBU, KET	NPX: up to 1,370,000 ng/L ACE: 156–623,000 ng/L DCF: 6–410,000 ng/L	DCF: 590–166,000 ng/L ACE: 2660–119,500 ng/L	Most detected in MWW due to widespread OTC use; naproxen is most abundant
Hormones	E1, E2, E3, EE2	E1: 78–158 ng/L E2: 11–54 ng/L E3: 42–162 ng/L	EE2: up to 9833 ng/L E3: 27–1480 ng/L	Detected at lower concentrations but potentially harmful due to endocrine-disrupting effects, especially EE2

CIP ciprofloxacin, *NOR* norfloxacin, *OFL* ofloxacin, *SMX* sulfamethoxazole, *SDZ* sulfadiazine, *ENR* enrofloxacin, *CBZ* carbamazepine, *NPX* naproxen, *DCF* diclofenac, *ACE* paracetamol (acetaminophen), *IBU* ibuprofen, *KET* ketoprofen, *E1* estrone, *E2* 17β-estradiol, *E3* estriol, *EE2* ethinylestradiol, *MMW* municipal wastewater, *HWW* hospital wastewater, *OTC* over the counter

Hormonal drugs, especially synthetic estrogens used in contraceptives and hormone replacement therapies, are potent endocrine disruptors. For these drugs, no minimum safe dose has been established. Even at low concentrations, in fact, these compounds can feminize male fish and interfere with the reproductive systems of amphibians and other aquatic species [19, 20].

Antibiotics, which are the most urgent concern, contribute to the acceleration of antimicrobial resistance (AMR). The last report of the WEF flagged this as one of the top 10 global health threats [21]. Persistent residues in the environment promote the selection of resistant bacteria, which can spread across species and ecosystems [22]. This growing concern has been echoed by major international health organizations, which underline that the release of untreated or insufficiently treated hospital and municipal wastewater plays a critical role in driving the spread of AMR across environmental compartments [23]. These reports call for an integrated One Health approach, emphasizing that effective management of wastewater and sanitation systems is essential to limit the environmental dissemination of resistant microorganisms and to protect both human and animal health.

Complementary recommendations focus on emission control within the pharmaceutical production sector [24]. Inadequate treatment of effluents from antibiotic manufacturing facilities is identified as a potential point source for the selection and dissemination of resistance. To address this, the adoption of Best Available Techniques, improved on-site wastewater treatment, and stricter environmental monitoring of antibiotic residues are recommended as key strategies to minimize contamination and reduce AMR risks.

Antidepressants, whose use increased particularly in the post-pandemic era, are increasingly found in river and lake water. These drugs can alter the behavior of aquatic species, affecting predator–prey relationships and ecosystem dynamics [25].

As shown the Table 1, concentrations observed in HWW are generally higher than those found in MWW. For instance, norfloxacin and ofloxacin have reached maximum concentrations of 561 µg/L and 198 µg/L, respectively, in HWW, while in MWW the levels are significantly lower, typically in the ng/L range. A similar trend is observed for ciprofloxacin, with concentrations in HWW being 3 to 10 times higher than those in municipal effluents.

Among antiepileptic drugs, carbamazepin remains one of the most persistent compounds, with concentrations ranging from 96 to 6500 ng/L in MWW and from 41 to 880 ng/L in HWW. Its high chemical stability and low biodegradability make it difficult to remove through conventional treatment processes.

Analgesics such as naproxene, acetaminophen, and diclofenac show particularly high concentrations in MWW, with peaks up to 1.37 mg/L reported for naproxen, which is the most frequently detected. Their widespread occurrence is mainly attributed to their over-the-counter availability and extensive use without prescription.

Hormones generally occur at lower concentrations compared to other pharmaceutical classes. However, their environmental risk lies in their endocrine-disrupting effects on aquatic organisms, even at trace levels. 17a-ethinylestradiol, for example, has been reported at concentrations up to 9833 ng/L (range 881–9833 ng/L) in HWW, representing a potential threat to aquatic ecosystems [15].

The ubiquity of these compounds was mapped in an comprehensive study which reported that

pharmaceutical pollution is present in more than 1000 river sites across 104 countries, including remote areas such as the Arctic and the Amazon [26]. The global scale and uniformity of this phenomenon highlight the urgent need for policy and technological interventions.

Antineoplastic drugs and contrast agents

Antineoplastic drugs, widely used in cancer therapy, represent a class of pharmaceuticals with notable environmental concern due to their high toxicity, persistence, and low biodegradability [27]. According to [16] these compounds—often excreted unchanged or as active metabolites—are commonly detected in hospital wastewater and may reach municipal treatment systems, where standard processes are generally ineffective for their removal [28]. Recent studies have reported the presence of substances such as cyclophosphamide, ifosfamide, and bicalutamide in concentrations ranging from nanograms to micrograms per liter.

Analytical advancements have significantly improved detection capabilities: solid-phase extraction (SPE) combined with high-performance liquid chromatography tandem mass spectrometry (HPLC–MS/MS) now enables quantification at trace levels, with detection limits down to 0.5 ng/L. The use of isotope dilution further enhances accuracy by minimizing matrix effects, while enantioselective HPLC–MS/MS methods have been applied to increase specificity in the analysis of chiral compounds. Additionally, inductively coupled plasma mass spectrometry (ICP-MS) has shown potential for the detection of platinum-based cytostatics, though its application to real wastewater samples remains limited. Despite these methodological improvements, removal efficiencies in wastewater treatment plants remain highly variable, highlighting the need for targeted monitoring and the development of advanced, compound-specific treatment technologies. Similarly to antitumor pharmaceuticals, radiological contrast agents used in diagnostic imaging represent a significant group of emerging contaminants in wastewater, due to their persistence and resistance to conventional treatment processes. Iodinated compounds such as iopromide and iohexol have been detected in wastewater treatment plant effluents at concentrations up to 21 µg/L, with removal efficiencies often negligible or very low. Environmental analysis commonly relies on SPE followed by high-performance liquid chromatography coupled with HPLC–MS/MS, reaching limits of quantification below 50 ng/L. More recent approaches, including direct injection and ICP-MS, have improved both sensitivity and analytical throughput.

For gadolinium (Gd)-based contrast agents used in magnetic resonance imaging, studies on wastewater and surface waters have revealed limited removal during treatment, with effluent concentrations reaching up to 1500 pmol/L. Advanced techniques such as high-performance liquid chromatography–inductively coupled plasma sector–field mass spectrometry (HPLC–ICP–SFMS) and ion chromatography–inductively coupled plasma–mass spectrometry (IC–ICP–MS) have enabled detailed insights into chemical speciation, highlighting potential species transformation during sludge and water treatment processes. Anthropogenic Gd has also been found in natural environments, including rivers, lakes, and even marine waters, indicating widespread environmental dissemination.

Although acute toxicity at environmental concentrations appears to be low, sub-lethal and chronic effects—including endocrine disruption, genotoxicity, and behavioral changes—have been observed in preliminary studies involving aquatic organisms. Additionally, the continuous input of these agents may interfere with sediment microbial processes and contribute to cumulative ecotoxicological pressure in aquatic ecosystems.

Innovations and mitigation strategies

Responding to these complex challenges demands a multidimensional strategy, encompassing innovations in pharmaceutical design, improvements in wastewater treatment, and systemic changes in healthcare delivery. Green chemistry represents a promising and increasingly explored approach to reducing environmental impacts in pharmaceutical production. By rethinking synthetic pathways and employing less hazardous solvents and reagents, manufacturers can dramatically reduce emissions and waste [5]. Solvent recovery systems, process intensification, and continuous flow production are already demonstrating the viability of cleaner manufacturing [29].

In parallel, advanced wastewater treatment technologies—including membrane bioreactors (MBRs), ozonation and activated carbon filtration—are being tested and implemented. Among the most extensively investigated advanced treatment technologies for mitigating emerging contaminants, MBRs and ozonation have demonstrated considerable promise (Table 2). MBRs integrate conventional biological treatment with membrane filtration, achieving high removal efficiencies of suspended solids, nutrients, and organic pollutants. Several studies report removal rates exceeding 80–95% for pharmaceuticals such as analgesics, anti-inflammatory agents, antibiotics (e.g., ciprofloxacin, norfloxacin, trimethoprim), and cardiovascular drugs (e.g., propranolol). However, removal efficiency tends to be lower for more recalcitrant compounds, including psychiatric drugs (e.g., venlafaxine), iodinated contrast agents (e.g., iopromide), and certain antineoplastics.

Table 2 Ozonization vs. membrane bioreactor

Technique	Removal Efficiency	Successfully Treated Pharmaceuticals	Main Limitations
Ozonization	90–99%	(SMX), (CBZ), (DCF), (NPX), (E1), (E2), (EE2)	High operational costs; formation of potentially toxic transformation byproducts
Membrane Bioreactor	25–100% (variable)	(E1), (E2), (E3), (ACE)	Membrane fouling; high capital and maintenance costs; temperature-sensitive performance

SMX sulfamethoxazole, *CBZ* carbamazepine, *DCF* diclofenac, *NPX* naproxen, *E1* estrone, *E2* 17β-estradiol, *E3* estriol, *EE2* ethinylestradiol, *ACE* paracetamol

Ozonation, employed as an advanced oxidation process, leverages the strong oxidative potential of ozone (O_3) to degrade persistent organic contaminants and microorganisms. Its application as tertiary treatment for hospital wastewater has shown high efficacy, with removal efficiencies, refered to pilot-scale or controlled conditions, frequently exceeding 90% for various pharmaceuticals such as sulfamethoxazole, ciprofloxacin, erythromycin, and metoprolol. Nonetheless, the presence of dissolved organic carbon (DOC) in wastewater significantly impacts ozonation performance due to competitive consumption of ozone and hydroxyl radicals by DOC, necessitating high ozone doses (0.8–1.5 g O_3/g DOC) for effective oxidation. Consequently, direct ozonation of raw wastewater with elevated DOC concentrations (up to 500 mg/L) is generally not economically viable.

The combined use of MBR and ozonation represents a synergistic and high-performance approach for the removal of emerging contaminants. However, the considerable capital and operational costs associated with these technologies currently limit their widespread adoption. Further research is required to optimize process economics and assess treatment efficacy under full-scale operational conditions, particularly in systems with high flow rates and variable influent compositions [30]. Moreover, wastewater treatment improvements should be integrated into broader One Health strategies to minimize the environmental development and spread of antimicrobial resistance, linking technological innovation with surveillance and regulatory measures [31]. Enhanced hydrolysis processes have been shown to effectively degrade high concentrations of fermentative antibiotics in production wastewater, achieving removal efficiencies up to 99.9% for oxytetracycline, thereby significantly reducing the environmental impact of pharmaceutical residues [32].

High implementation costs and uncertain long-term performance remain barriers to widespread adoption of advanced treatment technologies [33]. Another frontier is the development of biodegradable drug compounds engineered to break down rapidly into nontoxic byproducts, although challenges remain in maintaining stability, efficacy and cost-effectiveness. While still in early development, this approach could transform the pharmaceutical industry by drastically reducing the persistence of harmful compounds in the environment. In the same way, nanotechnology offers promise in minimizing the dose of active ingredients while maintaining therapeutic efficacy, as evidenced by products such as Lipidil® 200, Lipidil 145 One®, and Ecocaps. As demonstrated by combining in vitro drug release studies with physiologically based biopharmaceutics modeling to estimate environmental emissions, the environmental impact of these three fenofibrate formulations differs significantly. The assessment focused on both metabolized and unmetabolized fractions, their respective toxicities, and the release of nanomaterials. Among the three, the Ecocaps formulation showed the most favorable environmental performance, with a 42.5% reduction in fenofibrate emissions, an 18% reduction in global warming potential, a 61% reduction in ecotoxicity, and a 15% reduction in human toxicity [34].

Digital health solutions, including telemedicine and AI-driven diagnostics, can also help reduce the environmental burden of healthcare. By reducing travel, minimizing unnecessary prescriptions, and optimizing treatment plans, these technologies contribute to more sustainable healthcare systems. Some modelling studies estimate potential emission reductions of up to 70% for routine consultations, although actual outcomes depend on local infrastructure and patient access [35]. Ultimately, a paradigm shift is needed that places environmental sustainability alongside efficacy and cost in healthcare decision-making [36]. The next section examines how regulatory frameworks are evolving to support this transition.

Regulatory and policy frameworks

Regulatory and policy frameworks represent one of the most strategic and potentially transformative arenas for reducing the environmental impact of pharmaceuticals.

While historically the focus of pharmaceutical regulation has centered on clinical efficacy, safety, and economic viability, environmental considerations have often remained peripheral or entirely absent [1]. This omission reflects a broader systemic issue: a fragmented and siloed approach to health governance that overlooks the deep interdependence of human, environmental, and animal health. As the urgency of environmental degradation becomes increasingly apparent, it is essential to reimagine, reform and re-write pharmaceutical regulation through the integrative lens of the One Health approach.

The European Union has made notable strides in this direction. Regulation (EU) 2021/2282 on Health Technology Assessment (HTA) established a pathway for evaluating new pharmaceuticals not only on the basis of therapeutic efficacy and cost-effectiveness but also with increasing consideration of environmental performance. While environmental metrics are not yet uniformly applied or required in all assessments, regulatory infrastructure now exists to support such integration. This regulatory evolution provides an opportunity—still in its early stages—to broaden the definition of value in health interventions not only in terms of patient outcomes, but also in terms of planetary sustainability.

Complementing the HTA Regulation are broader European policy instruments such as the European Green Deal, the Circular Economy Action Plan, and the Zero Pollution Action Plan. These initiatives collectively aim to decouple economic growth from environmental harm. In the pharmaceutical context, this could mean incentivizing greener manufacturing processes, supporting the development of biodegradable APIs, and prioritizing medications with lower life-cycle emissions in public procurement programs. Instruments such as the Ecodesign for Sustainable Products Regulation and the Packaging and Packaging Waste Directive 2025 also extend to pharmaceutical packaging, urging manufacturers to adopt recyclable, compostable, or reusable materials.

However, progress remains uneven across the globe. Many countries lack binding environmental standards for pharmaceutical production, distribution, and waste management. In some jurisdictions, environmental risk assessments (ERAs) are required for market authorization; however, these assessments rarely influence regulatory outcomes [37]. Moreover, ERAs are typically focused on the environmental fate of a compound, without fully considering cumulative exposure, ecosystem-level effects, or interactions with other pollutants.

To overcome these limitations, several measures should be considered. First, regulators could mandate LCAs as part of the drug approval process. LCAs provide a holistic picture of the environmental impacts across the entire pharmaceutical value chain from raw material extraction to postconsumer waste [38–42]. Second, public procurement policies should favour environmentally responsible options, thereby leveraging government purchasing power to drive industry-wide change. Third, regulatory agencies should adopt more rigorous post-market surveillance mechanisms to monitor the environmental behavior of pharmaceuticals under real-world conditions.

Equally important is the harmonization of international standards. Given the globalized nature of pharmaceutical supply chains, inconsistent regulations create loopholes that allow pollution to persist in less-regulated environments. International initiatives, such as the Strategic Approach to International Chemicals Management and the Global Leaders Group on Antimicrobial Resistance, could serve as platforms for aligning environmental objectives with global health governance.

Finally, regulatory transformation must be matched by institutional accountability and transparency. Environmental impact data should be made publicly available allowing researchers, civil society organizations, and consumers to hold manufacturers accountable. Environmental considerations should not be only part of the scientific and regulatory conversation but should also become a key component of pharmaceutical marketing, corporate responsibility, and investor relations.

By embedding environmental sustainability into the regulatory fabric of pharmaceutical governance, policymakers can shift the incentives that shape industrial behavior, guiding the sector toward innovation, resilience, and ecological responsibility. This shift is not only feasible but also essential to ensure that the health benefits delivered by pharmaceuticals are not offset by unintended harm to the ecosystems on which we all depend.

Industry best practices

The pharmaceutical industry, while often criticized for its environmental shortcomings, has also demonstrated that sustainable transformation is not only feasible but also can generate long-term value when it is embedded within strategic visions and operational frameworks. Increasingly, major industry players are embracing environmental responsibility not just as a compliance issue, but as an opportunity for innovation, leadership, and improved reputational standing. According to the most recent EFPIA report, several companies have already begun to implement a range of best practices [43].

Design and packaging

The design phase is crucial for preventing environmental impacts throughout the entire life cycle of a medicine.

Intervening at this early stage allows for reduced material use, simplified logistics, and improved recyclability.

An example is Merck, which redesigned the packaging of its fertility pens to produce the "Slim Pack." This new format led to a 40% reduction in volume, significantly lowering the use of plastic and aluminum. The benefits were not only environmental but also economic, thanks to lower transport-related emissions and reduced storage costs.

Manufacturing and resource use

Pharmaceutical manufacturing is one of the most environmentally impactful phases due to high energy, solvent, and material consumption. However, it also offers some of the greatest opportunities for improvement through recycling and process efficiency.

Novo Nordisk implemented an ethanol recycling program that reduced solvent usage by 89% and avoided the emission of approximately 175,000 tons of CO_2 per year. The initiative also yielded a 35% reduction in production costs.

Takeda Pharmaceuticals, through its BioLife Plasma Services, adopted circular economy practices in its supply chain, recycling over 10 tons of plastic annually and achieving a 30% reduction in greenhouse gas emissions. Moreover, the company has begun transitioning to low-emission production methods for biologics and vaccines.

Sanofi embraced a circular model at its Val-de-Reuil production site, converting waste eggs from vaccine manufacturing into compost and biogas. This strategy enables the production of renewable energy on site and enhances soil quality in the local agricultural area.

Water and energy management in production

Optimizing water and energy use in production facilities significantly reduces operational environmental impact while improving internal efficiency.

AstraZeneca installed advanced water recycling systems at its Swedish sites. These interventions led to a 40% reduction in potable water consumption and a 15% decrease in site-level CO_2 emissions.

Distribution

The distribution phase can have a considerable impact, particularly due to transport emissions and packaging use. Targeted interventions can improve sustainability across the supply chain.

The new Slim Pack by Merck, in addition to its design-stage benefits, also contributed positively during distribution by reducing transport volume and required storage space.

Use and end-of-life

The end-of-life phase of pharmaceutical products and medical devices presents a critical environmental challenge. Implementing recovery and recycling systems can prevent harmful emissions and foster circularity.

Chiesi Farmaceutici addressed inhaler waste with its "Take AIR" (Action for Inhaler Recycling) initiative. In collaboration with pharmacies, the company collected and recycled more than 24,000 used inhalers, avoiding the release of 144 tons of CO_2. This program is part of a broader strategy to develop next-generation inhalers with low-global-warming-potential propellants.

What distinguishes these examples is not only the scale of environmental benefit but also the way sustainability has been integrated into core business models. These are not isolated Corporate Social Responsibility projects, but part of deliberate and long-term strategies. In each case, environmental stewardship is linked to product innovation, process optimization, risk mitigation, and market positioning. The cross-cutting nature of these initiatives underscores a powerful insight: environmental sustainability in the pharmaceutical sector is not merely compatible with competitiveness; it is becoming a prerequisite for it.

Moreover, many of these companies have achieved success through multistakeholder collaboration. Partnerships with universities, Non-Governmental Organizations, local municipalities, and specialized technology providers have enabled knowledge transfer, shared infrastructure, and social legitimacy. These networks are essential for the scalability of sustainable practices and can accelerate the diffusion of innovation across the industry.

Despite these successes, widespread implementation remains uneven. Smaller pharmaceutical firms and manufacturers in emerging markets often lack the resources, incentives, or regulatory pressure to replicate these practices. To close this gap, best practices must be actively disseminated through international forums, professional associations, and governmental agencies. Regulatory systems should evolve to include preferential procurement programs and environmental certifications that reward companies with verifiable sustainability commitments. In parallel, global reporting standards such as those developed by the International Sustainability Standards Board should be adopted to enhance transparency and comparability.

Conclusions and call for action

The pharmaceutical sector stands at a pivotal juncture. As this narrative review has demonstrated, the environmental impact of pharmaceuticals extends across the

entire value chain from energy-intensive production and unsustainable packaging to improper disposal and environmental persistence. The consequences are both acute and chronic, ranging from local ecotoxicological effects to global threats such as antimicrobial resistance and climate change. However, despite the complexity and scale of the challenge, the path forward is not only necessary but also achievable.

What emerges from the analysis is a twofold imperative: systemic transformation and shared responsibility. First, sustainability must be embedded as a core criterion in the development, approval, and use of therapeutic options. This means that environmental impact should no longer be treated as an afterthought in pharmaceutical regulation or clinical decision-making, but rather as a central factor on par with efficacy, safety, and cost. Regulatory tools such as Health Technology Assessments must evolve to incorporate comprehensive environmental metrics, while should become standard practice across the industry. Similarly, the adoption of environmental labelling for pharmaceuticals similar to energy efficiency ratings on appliances could empower consumers and healthcare providers to make more informed choices.

Second, no single actor can resolve this crisis alone. The pharmaceutical industry must continue to innovate and scale up green chemistry, biodegradable formulations, and sustainable packaging. Healthcare professionals must be trained to prescribe drugs responsibly and educate patients on appropriate drug disposal methods.

Policymakers must harmonize environmental standards across borders, promote green procurement, and invest in wastewater infrastructure capable of filtering pharmaceutical residues. Researchers must explore the environmental fate of APIs with greater precision and propose scalable mitigation technologies. Civil society organizations must keep environmental justice at the forefront, advocating for the protection of vulnerable ecosystems and communities most affected by pharmaceutical pollution. Finally, citizens must be empowered to understand their role, but are limited in safeguarding ecological and public health.

There is also a generational element to this transition. As younger professionals enter the fields of medicine, pharmacy, public health, and environmental science, sustainability can become a shared professional ethic; that prioritizes long-term planetary health over short-term convenience. Integrating sustainability modules into medical and pharmaceutical education could institutionalize this shift from the ground up, cultivating a culture of care that extends beyond the individual patient to the broader biosphere.

Success stories already exist and should serve as blueprints, not outliers. Industry leaders have demonstrated that sustainability and profitability are not mutually exclusive, whereas policy innovations in the EU have provided replicable models for broader adoption. Telemedicine and artificial intelligence are not only revolutionizing healthcare delivery but also reducing its carbon footprint. Wastewater treatment innovations and drug take-back programs have proven effective at the local level and await expansion. However, these isolated successes need to be scaled, systematized, and sustained through coherent governance frameworks and international cooperation.

In conclusion, the pharmaceutical industry already possesses the tools, knowledge, and precedents to embrace a new paradigm of responsible production and stewardship. These industry best practices, while encouraging, must be scaled and institutionalized if they are to reshape the sector at large. Only through widespread adoption and systemic support can sustainability transition from a pioneering aspiration to a foundational norm.

The transition to environmentally sustainable pharmaceutical systems is not a utopian vision. It is a practical, evidence-based pathway grounded in One Health principles.

By recognizing the interconnectedness of human, animal, and environmental well-being, and by aligning economic incentives with ecological imperatives, we can redefine what it means to deliver healthcare in the twenty-first century. This transition is a moral, scientific, and strategic necessity, that demands bold, coordinated, and immediate action to secure a livable and healthier future for all species that share this planet.

Limitations of the study

This narrative review is subject to certain limitations, including potential selection bias in the choice of sources, heterogeneity in the methodologies adopted across studies, and the limited availability of standardized environmental indicators. Despite these constraints, the work provides a comprehensive synthesis of current evidence, technological innovations, and emerging regulatory trends.

Abbreviations

APIs	Active pharmaceutical ingredients
NSAIDs	Non-steroidal anti-inflammatory drugs
HTA	Health technology assessment
EU	European Union
EFPIA	European Federation of Pharmaceutical Industries and Associations
WEF	World Economic Forum
MWW	Municipal wastewater
HWW	Hospital wastewater
NOR	Norfloxacin
OFL	Ofloxacin
CIP	Ciprofloxacin
CBZ	Carbamazepine
NPX	Naproxen

ACE	Acetaminophen
DCF	Diclofenac
EE2	Ethinylestradiol
MBR	Membrane bioreactor
DOC	Dissolved organic carbon
LCA	Life cycle assessment
HPLC–MS/MS	High-performance liquid chromatography tandem mass spectrometry
ICP–MS	Inductively coupled plasma mass spectrometry
IC–ICP–MS	Ion chromatography inductively coupled plasma mass spectrometry
Gd	Gadolinium
SPE	Solid-phase extraction

Acknowledgements
The authors wish to express their sincere gratitude for the opportunity to present and discuss this review in a multidisciplinary setting. We also thank the researchers and professionals whose work is cited throughout this paper and whose contributions to the fields of enviromental science, pharmacology and public health have been invaluable to this analysis.

Authors' contributions
A.M.V. Conceptualization, Writing-Reviewing, and Editing; G.O.C. Formal analysis and Editing; M.F. Supervision and Validation. All authors read and approved the final manuscript.

Funding
No funding was received for this study.

Data availability
No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare no competing interests. Author Gea Oliveri Conti is a member of the Editorial Board for *One Health Advances*, and she was not involved in the journal's review of, or decisions related to this manuscript.

Received: 14 June 2025 Revised: 26 October 2025 Accepted: 19 November 2025
Published online: 22 December 2025

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