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Pharmacoenvironmentology: Assessing the Impact of Pharmaceutical Residues on the Environment and Public Health

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Abstract

An integral part of environmental pharmacology is the emerging field of Eco pharmacology, which addresses the ecological consequences of drug consumption and improper medication disposal. As the number of pharmaceuticals consumed by people in the global world has increased, drug residues are becoming sources of emerging concern, caused by their ability to linger in the aquatic and land flourishing systems. Knowledge, attitudes, and disposal practices are emphasized in this review to ratify the imperative role of pharmacy students in reducing pharmaceutical pollution. Research has shown that the perceived knowledge of the concept of eco-pharmacology connotes a knowledge gap, where a small section of students has some understanding of the term eco-pharmacology and its environmental applicability. Even though a positive attitude toward safe disposal and environmental protection among pharmacy students is widespread, improper ways of disposal (disposal of medications into domestic waste or flushing them down the toilet) still appear to be a prevalent phenomenon. The absence of national pharmaceutical take-back programs in most regions adds to this unsafe practice, as there is limited curricular focus on it. Additionally, the level of awareness of antimicrobial residues as the root cause of resistance is quite low. Learning programs in pharmacies, introduction of take-back systems, and intervention to improve awareness and surveillance to encourage sustainable practices through policy interventions are

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vital. Finally, becoming ecologically literate in the way pharmacology is being handled is essential to both protecting ecosystems and reducing the impact on human and animal health.

Keywords: Eco pharmacology, medication disposal, pharmaceutical waste, pharmacy education

Introduction

Another emerging area in pharmacology is *pharmacoenvironmentology*, which focuses on understanding how drugs interact with the environment and the implications this has for both human health and ecosystems [1]. With population growth, improved access to healthcare, and increased use of veterinary medicines, there has been a noticeable rise in pharmaceutical residues in the environment. These substances are now being detected in soil, water bodies, and even drinking water sources [2]. Such residues include active pharmaceutical ingredients (APIs), their breakdown products, and other chemical derivatives that can persist long after the drug has served its therapeutic purpose [3].

What makes this issue particularly important is that pharmaceuticals are designed to be biologically active. Unlike many conventional pollutants, they are intended to produce specific physiological effects. When released into the environment, however, they can affect non-target organisms and disrupt ecological balance. Understanding these unintended consequences often involves examining gene–environment interactions, as well as broader pharma–environment and toxin–environment relationships [4].

Scientific interest in this field dates back to the 1970s, when early studies first detected traces of pharmaceuticals in wastewater treatment systems. Since then, research has consistently shown the widespread presence of drugs such as antibiotics, hormones, analgesics, beta-blockers, and antidepressants in rivers, lakes, groundwater, and even treated drinking water across the globe [5]. Some findings have been particularly striking, including the detection of cocaine in the River Thames and the widespread presence of analgesics and anti-inflammatory drugs in Indian rivers, underscoring the global scale of the issue [6].

One of the most pressing concerns in pharmacoenvironmentology is the rise of antibiotic-resistant microorganisms, driven by continuous low-level exposure to antibiotics in wastewater. In addition, endocrine-disrupting compounds, such as synthetic estrogens used in oral contraceptives, have been shown to cause feminization in male fish by inducing the production of egg yolk proteins like vitellogenin [7]. Similarly, the sharp decline in vulture populations in the Indian subcontinent has been linked to diclofenac-contaminated carcasses, highlighting the severe ecological consequences of veterinary pharmaceuticals [8]. These examples demonstrate that even low concentrations of pharmaceutical pollutants can lead to significant and sometimes irreversible effects on biodiversity and ecosystem stability.

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Pharmaceutical residues enter the environment through several pathways, including human and animal excretion, improper disposal of unused medications, agricultural runoff, and waste from hospitals and pharmaceutical manufacturing plants [9]. Unfortunately, conventional wastewater treatment plants are not specifically designed to remove these compounds, allowing them to persist in aquatic systems. Some of these substances, known as environmentally persistent pharmaceutical pollutants (EPPPs), resist biodegradation and can accumulate over time, posing long-term risks to both ecosystems and human health [10].

Even at trace levels, chronic exposure to pharmaceutical residues has been associated with a range of biological effects, including genetic, developmental, immune, and hormonal disruptions in various species. Emerging evidence also suggests possible implications for human health, such as endocrine disorders and carcinogenesis. This issue is particularly challenging because pharmaceuticals are biologically active even at very low concentrations [11].

Despite these concerns, pharmaceutical pollutants often fall outside strict regulatory oversight. While agencies such as the European Medicines Agency (EMA) and the U.S. Food and Drug Administration (FDA) have introduced environmental risk assessment guidelines for new drugs, these assessments are largely predictive. Monitoring of real-world, post-marketing environmental impacts remains limited, and long-term ecological and health data are still scarce [12].

The situation is further complicated in many low- and middle-income countries, where the lack of proper drug disposal systems and increasing reliance on medications contribute to higher levels of environmental contamination. Addressing this issue requires a more integrated and interdisciplinary approach, often referred to as *environmental pharmacovigilance*. This framework emphasizes monitoring and minimizing the environmental impact of pharmaceuticals at every stage, from drug design and production to consumption and disposal [13].

In all, pharmacoenvironmentology lies at the intersection of pharmacology, environmental science, and public health, and plays a crucial role in addressing the growing problem of pharmaceutical pollution [12]. As the use of pharmaceuticals continues to expand, it becomes increasingly important to understand how these substances enter the environment, how they affect ecosystems, and what their presence may indicate about human health. Strengthening monitoring systems, improving risk assessment strategies, and promoting sustainable practices will be essential in reducing the risks posed by pharmaceutical residues to both the environment and human populations [14].

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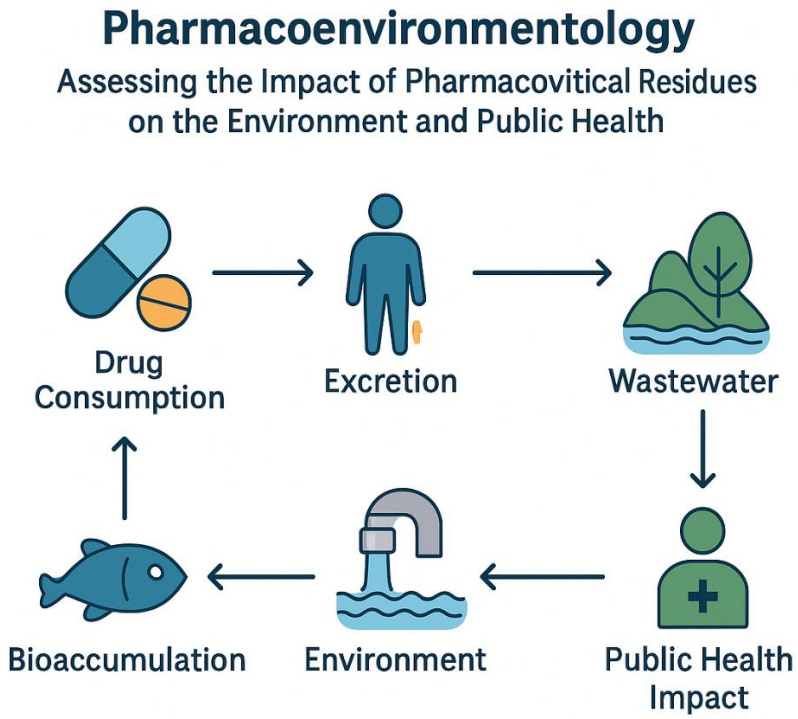

Historical background and evolution

Pharmacoenvironmentology developed out of the increasing acknowledgement that even though pharmaceuticals are very important to the health of humans and animals, they can develop unintentional and detrimental effects on the environment.[15] This field has its historical background in the research of environmental pharmacology, the interactions of drugs with the ecological systems. In the beginning, environmental issues were dominated by the concern of chemicals and pesticides produced by industries; pharmaceuticals were not a big focus due to the belief that they were not dangerous at low environmental levels.[16] This eventually changed when evidence in the science world started questioning this assumption in 1976, when scientists at the Big Blue River treatment plant discovered drug debris present in sewage. This finding served as the starting point for a methodical study of the presence of pharmaceuticals in the environment.[17]

In subsequent decades, the development of analytical procedures enabled the identification of traces of pharmaceutical substances in surface water and adjacent groundwater and drinking water sources, ranging from nanograms to micrograms per liter, worldwide.[18] These results showed that pharmaceutical contamination was not regional but a global phenomenon. The accumulating evidence showed devastating environmental effects. For example, the sharp decline in vulture populations in India

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during the late 20th century was traced to the use of diclofenac in veterinary medicine.[19] Vultures feeding on carcasses of livestock treated with this non-steroidal anti-inflammatory drug (NSAID) developed fatal renal failure. Similarly, synthetic estrogens like ethinyl estradiol, a common ingredient in contraceptives, were found to cause feminization of male fish through endocrine disruption, leading to reproductive failures in aquatic species. Antidepressants such as fluoxetine (Prozac) were observed to alter behavior in aquatic organisms, including triggering spawning in shellfish. These incidents highlighted the ecological consequences of pharmaceutical residues, even at extremely low concentrations.

The growing concerns prompted the evolution of terminology and concepts. [20] Initially, the term ecopharmacology was used to describe the study of pharmaceuticals in ecosystems. However, as the scope broadened to include pharmacovigilance and post-therapy drug elimination from living organisms, the term pharmacoenvironmentology was introduced in 2006[21]. This specialized discipline focuses on the environmental impact of pharmacological agents after their excretion and disposal, emphasizing their journey beyond therapeutic use. Later, related concepts such as eco-pharmacovigilance and pharmacoecology emerged, reinforcing the integration of environmental monitoring into pharmacovigilance frameworks [21].

Regulatory bodies gradually began addressing these issues. The European Medicines Agency (EMA) introduced guidelines for environmental risk assessment of pharmaceuticals, and similar initiatives followed in the United States. These frameworks aimed to predict the environmental concentration of pharmaceuticals and their potential ecological effects. [22] However, most assessments remain predictive, and there is a lack of robust post-marketing surveillance for environmental hazards. Today, pharmacoenvironmentology represents a critical intersection of pharmacology, ecology, and public health. Its evolution reflects an increasing awareness of the complex life cycle of pharmaceuticals and their unintended consequences in the environment. This discipline continues to grow, driven by the urgent need for sustainable strategies to minimize pharmaceutical pollution and protect ecosystems and human health.[15, 23]

Importance in the present scenario

The significance of pharmacoenvironmentology in the present scenario cannot be overstated. With the exponential growth in pharmaceutical production and consumption, environmental contamination by pharmaceutical residues has emerged as a global concern. [18] Modern healthcare practices, widespread use of medications for chronic diseases, and the extensive application of veterinary drugs in livestock and aquaculture contribute to the continuous release of active pharmaceutical ingredients (APIs) into the environment. These compounds enter water bodies, soil, and even the food chain primarily through human and animal excretion, improper disposal of unused medicines, and industrial effluents. [24] What makes this issue particularly critical today is the

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persistent and bioactive nature of pharmaceuticals, even at trace concentrations. Pharmaceuticals, in contrast to most industrial chemicals, are meant to interact with biological systems at low concentrations, and this implies that their presence within the environment will interfere with non-target organisms.[25] An example offered is in hormonal birth control, which causes endocrine disruption in aquatic life, and antibiotic residues that facilitate the emergence of antimicrobial resistancespreading a significant epidemic against later identified as a major health threat by the World Health Organization.

There is also a comparable worry about the nature of health exposures caused by chronic exposure to low doses of pharmaceuticals in drinking water, particularly long-term effects of exposure on human health, such as endocrine, developmental toxicity, and carcinogenicity. [26] Pharmaceutical use has escalated, especially in urbanizing countries with aging populations and growing healthcare needs, and further due to the poor waste management systems in most developing countries. Moreover, climate change and water scarcity also add to the risks by intensifying the contaminants in the scarce water sources. Pharmacoenvironmentology in this regard is critical in terms of risk evaluation, mitigating measures, and incorporating environmental pharmacovigilance in terms of drug regulatory and healthcare policy. Through monitoring and the safer design of drugs as well as creating awareness among the people, pharmacoenvironmentology is playing a vital role in protecting the environment in the form of the ecosystem, besides human health, in the interconnected world of today.[27, 28]

Sources of Pharmaceutical Residues in the Environment

The entry of pharmaceuticals into the environment occurs in a number of ways, and in many cases, human actions, medical care, and agricultural tasks bring them to the environment. These residues, along with active drug ingredients and their products of breakdown, may linger on in water, soil, and even food chains, resulting in ecological and health complications[29]. The most important sources are defined as follows:

Pharmaceutical Manufacturing Units

Pharmaceutical manufacturing plants are significant contributors to environmental contamination. Effluents from drug production facilities often contain high concentrations of active ingredients, which are discharged into surface waters or soil. In countries with lax environmental regulations, untreated or inadequately treated wastewater from manufacturing plants has been linked to contamination of rivers and groundwater[30]. For example, studies in India have detected extremely high levels of antibiotics downstream from manufacturing sites, resulting in the proliferation of antibiotic-resistant bacteria. Even after standard treatment, many compounds remain in effluent due to their complex chemical structures, making industrial discharge a critical

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point of concern.[31]

Hospitals and Healthcare Facilities

Hospitals, clinics, and diagnostic centers generate large volumes of pharmaceutical waste, including expired medicines, patient excreta containing drug metabolites, and chemicals used in diagnostic imaging (e.g., X-ray contrast media). Inadequate disposal systems in healthcare facilities often lead to direct release of these substances into sewage systems[32]. Localized hotspots of contamination frequently occur near hospital effluent discharge points, where concentrations of antibiotics, analgesics, and cytotoxic drugs have been detected. These residues contribute to environmental hazards and the potential emergence of drug-resistant microorganisms in sewage and aquatic environments.[33]

Improper Drug Disposal Practices

One of the most widespread sources of pharmaceutical residues is improper disposal of unused or expired medicines. In many households, unused drugs are discarded in household trash or flushed down toilets and sinks, leading to direct entry into sewage systems and landfills. Unlike industrial pollutants, pharmaceuticals are rarely subjected to proper waste segregation and destruction protocols.[34] In developed countries, “take-back programs” exist but are underutilized, while in developing regions, the absence of such initiatives exacerbates contamination risks. Over time, landfill leachate and sewage overflow transport these chemicals into surface and groundwater, creating long-term environmental persistence.[35]

Human and Veterinary Excretion

A substantial proportion of ingested drugs is excreted as parent compounds or active metabolites through urine and feces. These residues enter sewage systems and, ultimately, water bodies. Since most wastewater treatment plants are not designed to remove pharmaceuticals, significant quantities pass through treatment processes and persist in rivers, lakes, and even drinking water supplies.[36] Veterinary drug excretion adds to the burden, as livestock treated with antibiotics, anti-parasitics, and hormonal agents deposit residues in soil through manure. This not only affects terrestrial ecosystems but also introduces pharmaceutical residues into the food chain.[37]

Agricultural Practices and Livestock Treatment

The agricultural sector contributes to pharmaceutical contamination through the use of veterinary medicines in livestock, poultry, and aquaculture. Antibiotics, growth promoters, and anti-parasitic drugs are routinely administered to animals to improve productivity and prevent disease. The leftovers of these chemicals are discharged into the environment and may fall into rivers and soil systems when manure has been applied as a fertilizer or the discharge of the farm runoffs are discharged into

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waterways.[38] Also, chemicals exist in the form of some pharmaceuticals used by farm owners to make the crop healthy, making the situation of contamination even more complex in farming matters. The practices were associated with a significant risk of antibiotic resistance in soil and aquatic microbiota, which could be a significant threat to the ecology and health of people.[39]

Types of Pharmaceutical Residues and Their Environmental Persistence

The sources of pharmaceutical residues in the environment are of diverse classes of therapeutic properties, which help define their stability and impact on the ecological system. The compounds are specifically and specially used in terms of stability and bioactivity in biological systems, which causes them to have a long persistence once they have made entry into the environmental compartments.[40] According to the literature reviewed, there are significant groups:

Antibiotics

The most common pharmaceutical contaminants that are often detected in environmental matrices include antibiotics. Not only do they have a large application in human therapy, veterinary medicine, and grazing production, which contribute to their concentration in surface water, groundwater, and sediment. [41] The issue with these residues is powerful because they contribute to antimicrobial resistance (AMR), which is considered the significant health issue of the global threat. Research has demonstrated that antibiotics such as sulfonamides, fluoroquinolones, and tetracyclines usually bypass the regular wastewater treatment procedures and can stay longer, endangering the environment and health.[42]

Hormones and Endocrine Disruptors

Hormonal drugs, including synthetic estrogens such as ethinyl estradiol, are potent endocrine-disrupting compounds (EDCs). Even at nanogram concentrations, these substances interfere with endocrine functions in aquatic species, leading to feminization of male fish and disruption of reproductive physiology. [43]Hormonal residues originate primarily from human contraceptive use and veterinary applications. Due to their chemical stability and lipophilic nature, they persist in aquatic environments and bioaccumulate in organisms, causing long-term ecological effects.[44]

Analgesics and Anti-inflammatory Drugs

Analgesics, particularly non-steroidal anti-inflammatory drugs (NSAIDs) like diclofenac, ibuprofen, and naproxen, are highly prevalent environmental contaminants. These drugs have been detected in sewage, surface waters, and sediments globally.[45] Diclofenac is of special concern because its veterinary use caused catastrophic declines in vulture populations in the Indian subcontinent. Many NSAIDs display moderate degradation in wastewater treatment but remain in

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the environment through transformation products or adsorption to sediments.[46]

Anticancer and Cytotoxic Drugs

Anticancer agents, particularly cytotoxic drugs, represent one of the most hazardous pharmaceutical groups due to their mutagenic, genotoxic, and carcinogenic properties. These compounds are used in chemotherapy and are excreted in active form by patients, entering hospital effluents and subsequently aquatic environments. Due to their structural complexity, these drugs resist conventional wastewater treatments, resulting in environmental persistence and potential risks to non-target species, including genotoxic effects.[47]

Psychotropic Drugs and Others

Psychotropic drugs, such as antidepressants (e.g., fluoxetine) and antipsychotics, are emerging contaminants of concern. These compounds have been detected in aquatic environments and are known to alter the behavior of aquatic organisms, including changes in feeding and reproduction.[48]Other pharmaceuticals, including beta-blockers, lipid regulators, and antiepileptic drugs like carbamazepine, are also commonly reported. Carbamazepine, in particular, is considered a marker of wastewater contamination due to its strong persistence and resistance to biodegradation in both wastewater treatment systems and natural environments.[49]

Table 1. Major Types of Pharmaceutical Residues, Their Sources, Environmental Impacts, and Human Health Risks

Category	**Primary Sources**	**Environmental Impact**	**Public health concern**
Antibiotic	Human & veterinary excretion, hospital effluents, agriculture	Alteration of microbial communities; persistence in soil and water	Development of antimicrobial resistance (AMR); transfer of resistant genes to pathogens
Hormones & Endocrine Disruptors	Contraceptive pills, hormone therapies, and livestock treatment	Feminization of fish; disruption of aquatic reproductive systems	Endocrine disruption in humans: fertility issues, hormone-related cancers, altered puberty

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NSAIDs (e.g., Diclofenac, Ibuprofen)	Over-the-counter use; hospital discharge; improper disposal	Vulture mortality; toxicity to fish and amphibians	Gastrointestinal & renal risks in humans via exposure; indirect impacts through food chain
Cytotoxic/Anticancer Drugs	Hospital effluents, oncology wards	Mutagenic and carcinogenic to aquatic species; persistence in water	Potential mutagenicity, genotoxicity, and long-term cancer risks in humans
Psychotropic Drugs	Psychiatric medication use, municipal sewage	Altered fish behavior (feeding, reproduction, predator avoidance)	Unknown long-term risks; potential neurological impacts at low doses
Veterinary Pharmaceuticals	Livestock treatment, aquaculture	Accumulation in manure and runoff; soil contamination	Human exposure via crops, meat, and milk

Pathways of Pharmaceutical Contamination in the Environment

Pharmaceutical residues enter and move through the environment via multiple interconnected pathways. These routes determine the distribution and persistence of contaminants across different environmental compartments, including water, soil, sediments, and living organisms. Understanding these pathways is crucial for risk assessment and mitigation strategies[9]. The major pathways include:

Wastewater Discharge and Sewage Systems

One of the most significant pathways for pharmaceuticals into the environment is municipal and industrial wastewater discharge. After consumption, a large fraction of drugs is excreted as active compounds or metabolites through urine and feces, which then enter sewage systems. [50]Wastewater from households, hospitals, and pharmaceutical manufacturing facilities flows to wastewater treatment plants (WWTPs). However, most WWTPs are not designed to remove pharmaceutical compounds effectively. Consequently, significant amounts of these residues pass through treatment processes and are discharged into surface waters, such as rivers and lakes, or infiltrate into groundwater through soil percolation.[51]

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Effluents from Hospitals and Healthcare Facilities

Hospitals contribute concentrated pharmaceutical loads to sewage systems. Diagnostic agents, antibiotics, cytotoxic drugs, and other medications excreted by patients or discarded during treatments directly enter hospital wastewater. When this wastewater is not pre-treated before mixing with municipal sewage, it becomes a major source of contamination, particularly for highly potent and hazardous compounds like anticancer drugs.[52]

Discharge from Pharmaceutical Manufacturing Units

Pharmaceutical production facilities release substantial quantities of active pharmaceutical ingredients (APIs) into the environment, especially in regions with inadequate effluent treatment standards. These discharges often lead to localized "hotspots" with very high concentrations of drug residues in adjacent water bodies and soils. Antibiotics released from manufacturing plants have been associated with the emergence of multidrug-resistant bacterial strains in nearby aquatic ecosystems.[53]

Improper Disposal of Unused or Expired Medicines

Inappropriate disposal of leftover or expired medicines by households, hospitals, and pharmacies represents another critical pathway. Common practices such as flushing drugs down toilets or discarding them in regular trash lead to pharmaceutical residues entering sewage systems and landfills. In landfills, leachate containing these chemicals can contaminate groundwater and nearby surface waters.[54]

Runoff from Agricultural Fields and Animal Farming

Veterinary pharmaceuticals and feed additives used in livestock farming and aquaculture contribute significantly to environmental contamination. Drugs administered to animals are excreted in active form, and manure containing these residues is often applied to agricultural fields as fertilizer. During rainfall, runoff carries these residues into rivers, lakes, and groundwater. Similarly, aquaculture operations discharge water rich in antibiotics, antiparasitic agents, and other chemicals directly into aquatic environments.[24, 55]

Sludge Application on Agricultural Land

Sewage sludge from wastewater treatment plants is commonly applied to agricultural fields as a soil conditioner. However, this sludge often contains high concentrations of pharmaceutical residues and their transformation products. When applied to soil, these contaminants can persist, undergo leaching, or enter crops, posing a risk of bioaccumulation in the food chain.[56]

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Atmospheric Deposition (Minor Pathway)

Although less studied, certain pharmaceuticals and their metabolites can volatilize during manufacturing or disposal processes and subsequently deposit onto soil and water through atmospheric transport. This pathway is relatively minor compared to aquatic routes, but it still contributes to the environmental dissemination of some compounds.[57]

Environmental Impact of Pharmaceutical Residues

Pharmaceutical residues have become contaminants of emerging concern in terrestrial and aquatic environments. These compounds, designed to be biologically active and stable, often persist for extended periods in environmental matrices such as water, soil, and sediments.[58] Their continuous input from multiple anthropogenic sources has led to a condition known as pseudo-persistence, where concentrations remain relatively constant due to ongoing replenishment. The environmental impact of these residues is diverse, encompassing toxicological effects on aquatic organisms, disruption of ecological processes, alteration of microbial communities, and bioaccumulation across food chains.[59]

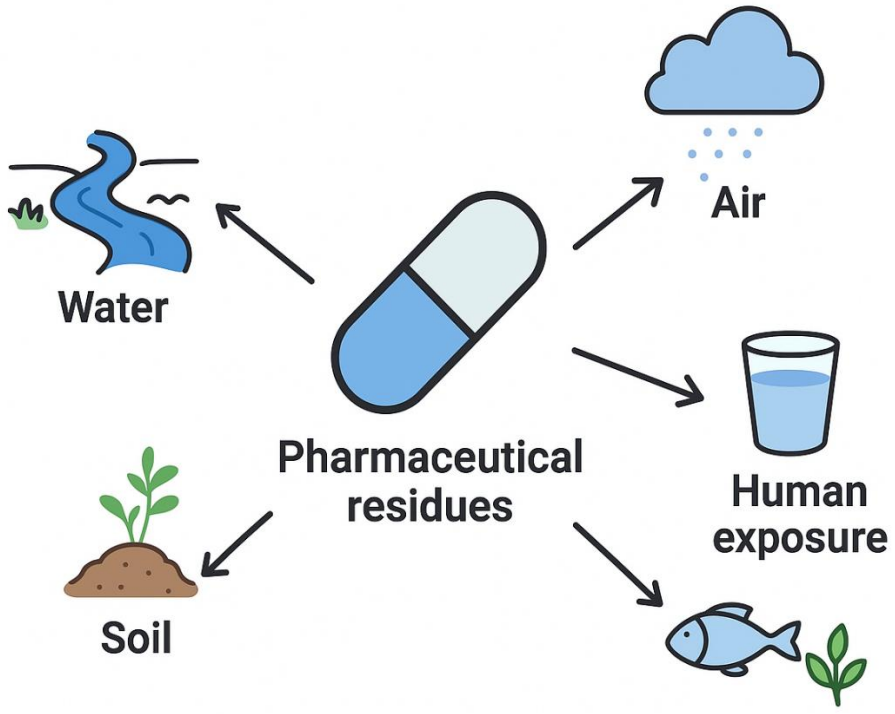

Fig. 2: Pharmaceutical residues disperse into water, soil, and air, affecting ecosystems and leading to human exposure through drinking water and the food chain.

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Impact on Aquatic Ecosystems

Aquatic environments are the primary sinks for pharmaceutical pollutants because of direct discharge of treated and untreated wastewater, hospital effluents, and agricultural runoff. Studies have detected numerous pharmaceuticals, including antibiotics, analgesics, beta-blockers, hormones, and psychotropic drugs, in surface waters and sediments. Although the concentrations are typically in the nanogram to microgram per liter range, these compounds can exert chronic effects on aquatic organisms because they are biologically active at very low levels.[58, 60]

Key impacts on aquatic systems include:

Endocrine Disruption: Synthetic estrogens such as ethinyl estradiol and natural hormones interfere with the endocrine systems of fish and amphibians. Feminization of male fish, reduced fertility, and altered sex ratios have been widely documented. These changes threaten the reproductive success of species and can lead to population decline.[61]

Behavioural Alterations: Psychotropic drugs such as fluoxetine (Prozac) have been found to alter behaviour in aquatic species, affecting feeding, mating, and predator avoidance. For example, fluoxetine exposure in shellfish can induce premature spawning.[62]

Toxicity and Mortality: A famous example is the disastrous reduction in the number of vultures in India due to veterinary use of diclofenac, a nonsteroidal anti-inflammatory. When vultures ate the carcasses of treated cattle, they died with fatal renal failure. On the same note, NSAIDs have also been shown to cause nephrotoxicity and physiological impairments in fish and amphibians.[63]

Disruption of Food Web: When pharmaceuticals find their way into water bodies, the primary producers such as algae and phytoplankton are harmed, causing slower growth and photosynthetic rates, thus affecting creatures up the food webs, disrupting complete ecosystems.[64]

2. Soil Contamination and Plant Uptake

Pharmaceutical residues reach soils primarily through:

- **Application of sewage sludge** as fertilizer
- **Use of manure** from medicated livestock
- **Irrigation with contaminated water**

Once in the soil, many pharmaceuticals persist for long periods because of their chemical stability and adsorption to soil particles. Antibiotics such as sulfonamides and tetracyclines strongly bind to soils, reducing their mobility but prolonging their presence.[65] Some pharmaceuticals, notably carbamazepine, can

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be absorbed by plants and translocated into edible tissues, creating a potential pathway for human exposure through the food chain. Moreover, antibiotics in soil alter microbial diversity by inhibiting sensitive bacteria and promoting resistant strains, which can affect nutrient cycling and soil fertility.[66]

Development of Antimicrobial Resistance (AMR)

One of the most significant consequences of pharmaceutical contamination is the development and spread of antimicrobial resistance in environmental bacteria. Constant exposure to low concentrations of antibiotics in soil and water creates selective pressure, favoring resistant strains. [67]These resistance genes can be transferred horizontally among microbial communities and eventually reach pathogenic bacteria, posing severe threats to public health. This environmental reservoir of resistance is now recognized as a critical factor in the global AMR crisis.[67, 68]

Bioaccumulation and Trophic Transfer

Persistent pharmaceutical compounds, particularly lipophilic drugs, can bioaccumulate in aquatic organisms. For example:

- Fish and shellfish exposed to contaminated water have been shown to accumulate residues of antidepressants, beta-blockers, and anti-inflammatory drugs.
- Bioaccumulation can lead to trophic transfer, where contaminants move through the food chain, ultimately reaching humans who consume contaminated fish or crops irrigated with polluted water.[69]

Ecotoxicological Impact of Specific Drug Classes

- **NSAIDs (e.g., Diclofenac):** Associated with organ toxicity in fish and catastrophic effects on scavenging birds.
- **Hormonal Drugs:** Responsible for endocrine disruption in fish and amphibians, leading to reproductive failure.
- **Cytotoxic Drugs:** Exhibit genotoxic and mutagenic effects in non-target species, increasing ecological risks.
- **Beta-blockers and Cardiovascular Drugs:** Interfere with metabolism and cardiac physiology in aquatic organisms.
- **Psychotropic Drugs:** Alter behavior and ecological interactions among aquatic fauna.[70, 71]

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Public Health Implications

Human Exposure Pathways

Individuals may be exposed to trace drugs in a number of common pathways. Water consumption is one of the most important routes: numerous active substances (antihistamines, antibiotics, antidepressants, and many more) have been observed in treated supplies and tap water, and even in potable reuse, and all of that in relatively simple reuse, in urban wastewater treatment.[72] Some residues in the environment (water, soil, sludge) have a half-life that is reported to be longer than a year; thus, chronic exposure, albeit low, is feasible even when the individual dose is minute. [73] Additionally, rivers affected by wastewater, bank filtration, and aquifer recharge can also absorb wastewater mixtures, which are subsequently used as drinking water.[74] Food-chain exposure occurs when crops absorb persistent compounds from reclaimed water or sludge-amended soils, and when aquatic organisms accumulate residues; fish often share drug targets with humans, raising concerns about sub-therapeutic but biologically active doses in edible tissues. [75] Occupational and consumer-product contact (e.g., handling medications, detergents, plastics) provides further routes, alongside inhalation or dermal contact with contaminated air, water, or soil.[76] Notably, mixtures, rather than single drugs, are the norm; experiments show that complex blends at environmental levels can affect human embryonic cells, underscoring the risks associated with mixtures at low concentrations. [29]

Antibiotic Resistance and Global Health Threat

Environmental reservoirs of antibiotics and co-occurring stressors create selective pressure that enriches resistance genes, the "environmental resistome."[77] Hospitals and wastewater systems are the areas of focus because they are places where the resistance is acquired, amplified, and distributed via mobile genetic elements, thus leading to the horizontal transfer between species. [78] This is often co-selected: within the same mobile elements that carry the antibiotic resistance, the resistance to metals exists, and is, therefore, being selected by the one edifice carrying the other. [79] The outcome is a liquid, mobile meta-genome floating along with water, animals, crops, and humans that disperses resistant organisms across the earth.[80] Field observations are reinforcing the danger: very high concentrations of antibiotics and pan-resistant bacteria have been found down- river of treatment plants, and there are even reports of various pharmaceuticals in the drinking water of major cities all over the world. [81]Taken together, environmental antibiotic exposure contributes to reduced clinical efficacy, complicates infection control, and represents a transboundary public-health challenge.[82]

Endocrine Disruption and Chronic Health Issues

Endocrine-active pharmaceuticals (e.g., synthetic estrogens) and other endocrine-disrupting chemicals (EDCs)

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can interfere with hormone signaling. While definitive human cause-and-effect links are difficult to establish, the biological plausibility is strong: EDCs interact with steroid and thyroid receptor systems found across tissues (brain, cardiovascular, skeletal, urogenital), meaning wide-ranging effects are possible.[83] Animal and wildlife studies demonstrate outcomes relevant to human risk assessment feminization of fish, reproductive organ changes, and population-level effects near effluent sources, indicating that environmental levels can be biologically active. In humans, potential associations discussed include impaired semen quality, testicular disorders, certain hormone-related cancers and gynecologic conditions, as well as developmental concerns in children (neurobehavioral, immune, thyroid, growth, and timing of puberty). Because exposure is often chronic and via mixtures, low-dose effects over long durations are a central concern for public health. [84, 85]

Long-Term Health Risks and Knowledge Gaps

Despite expanding monitoring and ecotoxicology, major uncertainties remain about long-term human health impacts of continuous, multi-decadal exposure to complex pharmaceutical mixtures at trace levels. The literature highlights knowledge gaps on cumulative and interactive effects, sensitive windows (e.g., fetal and early-life stages), and links to chronic diseases, including immune dysregulation and possible autoimmune pathways triggered by environmental xenobiotics.[86] Evidence from environmental persistence (e.g., legacy metabolites such as clofibric acid still found years after drug withdrawal) and repeated detection of pharmaceuticals in food and water suggests sustained, low-dose exposure is likely; yet dose–response relationships, mixture interactions, and real-world epidemiology are incompletely characterized. Furthermore, most data derive from sentinel species or cell systems, with limited longitudinal human studies capturing lifetime exposure. Accordingly, precautionary management, reducing inputs at source, improving removal in treatment, and promoting safe disposal have been advocated while research resolves these gaps. [87, 88]

Current Strategies for Risk Mitigation

The pharmaceutical residues have environmental and health impacts that should be mitigated using a multi-pronged approach. Good plans extend to technological improvements in wastewater treatment, as well as preventive measures, such as designing green drugs that are supported by strict regulations and community-based disposal schemes.[81]

Table 3. Current Strategies for Mitigating Pharmaceutical Pollution and Their Effectiveness

Strategy	Description	Advantages	Limitations	References

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Advanced Wastewater Treatment (AOPs, Ozonation, Membranes, GAC)	Uses ozonation, activated carbon, photocatalysis, and membrane bioreactors to degrade or remove APIs	High removal efficiency; effective against persistent compounds	High operational costs; energy-intensive; risk of toxic by-products	[89]
Drug Take-Back Programs	Collection of unused/expired medicines from households and hospitals for safe disposal	Reduces direct disposal into sewage/landfills; raises public awareness	Limited public participation; logistical challenges in low-resource settings	[90]
Safe Disposal Guidelines (WHO, EPA)	Incineration, encapsulation, or secure landfilling of pharmaceutical waste	Minimizes environmental leakage; globally applicable framework	Incineration is costly; improper adherence in many countries	[91]
Regulatory Frameworks (EU ERA, FDA, National Policies)	Environmental risk assessment during drug approval: monitoring frameworks	Systematic oversight encourages greener prescribing	Often limited to the pre-market phase, the weak enforcement of post-market surveillance	[92]
Green Pharmacy (Eco-Drug Design)	Designing APIs with faster biodegradability, lower persistence, and reduced ecotoxicity	Prevents pollution at source; aligns with sustainability	Requires strong R&D investment; may reduce drug stability	[93]
Ecopharmacovigilance (EPV)	Continuous monitoring of	Detects emerging risks; supports	Still under development;	[94]

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	pharmaceutical residues and effects post-marketing	evidence-based regulation	lacks global implementation	
Public Awareness & Education	Campaigns to inform consumers and healthcare workers about proper drug disposal	Low-cost; community engagement; complements take-back systems	Behavior change is slow; it requires continuous effort	[95]

Wastewater Treatment and Advanced Removal Technologies

Most APIs are not fully removed by conventional activated-sludge treatment, such that the remaining may be discharged into receiving waters. According to your papers, polishing processes, most notably ozonation and activated carbon, improve removal significantly over thermal classes, and membrane operations restrict particulate-bound material. [96]As an extension of this, full-size European experience demonstrates that post-ozonation and then biologically active or granular activated carbon (BAC/GAC) is reliable in reducing both parent drugs and mixture toxicity in secondary effluent. According to field tests in the Swiss WWTPs, ecotoxicological impacts decrease 66-93 percent in post-ozonation treatments, and national regulations have upgraded a few of the plants (including ozonation and/or GAC) to reduce the emission of micropollutants. The hybrid type (e.g., MBR + AOPs, or ozonation + BAC) is becoming popular as well since AOPs degrade recalcitrant molecules, whereas BAC recovers by-products as well as polishing biodegradable fractions that need to be considered where disinfection and toxicity necessity are competing. [97, 98]The utilization of biological or subsequent treatment of the effluent in pharmaceutical effluents reviews also indicates the role of biological routes (MBR, anaerobic, and hybrid systems) or adsorption as the most effective therapy with optimized, site-specific combinations based on the life-cycle of the effluent and trade-offs in energy use.[99]

Drug Take-Back Programs and Safe Disposal Practices

One of the inputs that can be prevented is improper disposal at home. According to your sources, an organized type of collection and destruction is advisable to prevent unused medicines from going into the sewers and landfills, particularly after emergencies where high amounts may build

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up.[100] Practically, national take-back programs like the U.S. DEA regulation that allows pharmacies, hospitals/clinics, and other registrants to receive controlled substances back in mass, and a regular, semi-annual Take Back Day, provide easy and safe returns and provide a set of controlled drug destruction of an unparalleled standard. WHO's operational guidance (originally for emergency contexts) details practical options high-temperature incineration preferred, with controlled landfilling or encapsulation as last resort procedures still widely cited in contemporary health-sector waste plans.[101]

Regulatory Frameworks and International Guidelines

At the authorization stage, environmental risk assessment (ERA) of human and veterinary medicines is required in the EU and many other jurisdictions; your papers note ongoing efforts to close data gaps and strengthen post-approval oversight where use-phase emissions dominate. The EU Strategic Approach to Pharmaceuticals in the Environment (2019) sets actions spanning the life cycle, improving ERA and monitoring, promoting prudent use, reducing emissions at source (healthcare and manufacturing), and fostering green design, followed by continuing implementation work and Parliament resolutions urging faster delivery. Several countries pair authorization-level controls with infrastructure policy, for example, Switzerland's national program to retrofit WWTPs for micropollutants, illustrating how environmental objectives can be embedded into water law and funded at scale. Meanwhile, sector guidance (e.g., health-care waste rules drawing on WHO) codifies segregation, storage, and destruction steps to minimize leakage from care facilities [102].

Green Pharmacy and Sustainable Drug Design

Mitigation increasingly starts upstream. Your sources discuss "eco-pharmacovigilance" and the push for APIs/formulations with lower persistence, bioaccumulation, and toxicity, paired with rational prescribing and patient-adherence strategies that reduce unused stock. Policy directions in Europe explicitly call for greener design, applying "benign-by-design" principles, degradability screening, and improved labelling /classification to steer prescribers and procurement toward environmentally preferable options without compromising efficacy or safety. On the manufacturing side, process intensification, solvent substitution, and closed-loop water systems reduce point-source releases, while supply-chain transparency frameworks and periodic reporting are being explored to verify performance.[103]

Role of Pharmacoenvironmentology in Modern Healthcare

Pharmacoenvironmentology has emerged as a critical interdisciplinary field that bridges pharmacology, environmental science, toxicology, and public health. It aims at exploiting, tracking, and reducing the effect on the surroundings of the pharmaceutical products throughout their life cycle. As

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the consumption of pharmaceuticals grows exponentially with modern medicine, a longer lifespan, and access to healthcare around the globe, this science becomes significantly involved in ensuring the advantages of therapeutics are not dispersed onto the environment and the health of industrial populations.[15]

Integrating Environmental Safety into Drug Development

Conventionally, clinical efficacy and patient safety have been the goals of pharmaceutical development, and little consideration of the impact on the environment has been allowed. Pharmacoenvironmentology changes the paradigms since it applies the environmental risk assessments (ERA) in drug development at smaller stages.[12] Current regulatory systems, including those put in place by the European Medicines Agency (EMA) demand the use of predictive models to determine their possible concentration in the environment (PEC) and ecotoxicologically evaluate active pharmaceutical ingredients (APIs). Through this proactive process, manufacturers are able to identify compounds that are highly persistent or bioaccumulative and greener alternatives are put into consideration prior to commercialization. Also, the field of pharmacotechnology promotes and advances the so-called Green Pharmacy to develop medications that are therapeutically efficient and environmentally blameless. This involves the creation of APIs that have short half-lives, biodegradable metabolites, and low ecotoxicity and do not affect the outcome of patients.[104, 105]

Monitoring Pharmaceutical Footprints in Healthcare Systems

Pharmaceutical emission sources are determined by hospitals, clinics, and long-term care facilities to a great extent. Pharmacoenvironmentology offers the frameworks of monitoring adverse drug reactions in the environment, but also the drug-related unintended/adverse effects on the environment. [106] These will entail monitoring of hospital effluents, sewage discharges, and treatment plant effluents in order to monitor such contaminants as antibiotics, cytotoxic drugs, and diagnostic agents. By pharmacoenvironmentology, health care facilities are implementing friendly waste management systems where fumes of the hazardous pharmaceutical waste are separated, high-risk effluents are pre-treated using technologies, and the facilities are enrolling in drug take-back programmes. Such practices contribute to the prevention of environmental contamination at its origin and correspond to the objectives of green healthcare.[107]

Addressing Antimicrobial Resistance as a Healthcare Priority

Antimicrobial resistance (AMR) is the global crisis that is the most urgent issue related to the sphere of public health, and pharmacoenvironmentology can take a central role in resolving it. Anamorphic exposition of microorganisms in the environment to the residues of anti-bacterial drugs as a result of hospital sewage, pharmaceutical plants, and runoff soils increases the development of

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resistance genes. Those genes might be reintroduced to clinical pathogens that might hydrolyze antibiotics with life-saving effects. Pharmacoenvironmentology is another critical aspect that is increasingly incorporated in modern healthcare policies. Rational prescriptions of antibiotics, well-developed waste management practices, and improved practices on disposal of antimicrobial drugs strategies are some of the methods. This field helps the world to conserve the efficacy of antibiotics by increasing the resistance reservoirs within the environment.[108]

Informing Clinical and Public Health Practices

Pharmacoenvironmentology, on its part, promotes evidence-based healthcare policies since it aims at identifying high-risk pharmaceuticals and how they can be used safely. As an illustration, non-steroidal anti-inflammatory (NSAIDs) medicines such as diclofenac have been associated with disastrous outcomes on wildlife.[109] Pharmacoenvironmental research informs regulatory alerts, like the use of safer substitution strategies, like promoting safer substitutes. The field is also engaged in promoting people's education; patients are encouraged to discard the unused drugs by sending them back when these drug companies design take-back programs to prevent dumping of the drugs into drains. This type of intervention reduces the pollution of the environment and is a new trend in pharmacy practice and in community health outreach.[110]

Shaping Sustainable Healthcare Policies

The concept of sustainability is being pursued in healthcare systems across the world according to global guidelines such as the UN Sustainable Development Goals (SDGs). The basis of these efforts lies with pharmacoenvironmentology, which promotes policies to incorporate environmental concerns into pharmacologic prescriptions, hospital practices, and pharmaceutical use. The principles of this discipline form the basis of the national and regional plans, including the Strategic Approach to Pharmaceuticals in the Environment of the EU. Additionally, pharmacoenvironmentology enables life-cycle thinking, assessing the environmental risks of the synthesis and packaging of drugs, to consumer use and disposal. Such a wholesome approach will make environmental stewardship a fundamental duty for contemporary healthcare systems.[111]

Supporting Research and Innovation

Being a developing science, pharmacoenvironmentology triggers the innovation of treatment technologies, biodegradation, and green chemistry. The joint effort among healthcare organizations, environmental programs, and pharmaceutical companies to develop new technology like bio-remediation with the help of microorganisms, hybrid wastewater treatment technology, and predictive computer programs that fashion the interaction of the drug in the environment is currently forming an agile solution. Pharmacoenvironmentology improves the scientific

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informational support in regulatory decision-making and clinical heuristics by promoting interdisciplinary cooperation, meaning that the protection of the environment is an unavoidable part and parcel of therapeutic progress.[112]

Recent Advances and Use of Technology

The nature of the contamination of pharmaceuticals and their prevalence of occurrence in diverse ecosystems demand innovative explanations in detection, monitoring, and risk control. The techniques developed recently in technology, such as artificial intelligence (AI), machine learning (ML), nanotechnology, and big data analytics, have transformed the capability of predicting, detecting, and treating pharmaceutical remains in the environment. These tools complement the conventional pharmacoenvironmentology paradigm and offer a more proactive and data-driven paradigm approach to environmental and population health safety.[113]

AI and Machine Learning for Environmental Risk Prediction

The new trends that have been unveiled are artificial intelligence and machine learning which can be useful in forecasting the risks of pharmaceutical products in the environment. Conventional environmental risk assessment (ERA) uses experimental toxicity information and estimates of exposure and which are seldom fast or cheap. Models are now AI-driven so researchers are able to determine the persistence, mobility, and ecotoxicity of drug compounds based on chemical structure and physicochemical traits.[114]

Applications include:

Predictive modelling of fate and transport: The performance of APIs in various environmental compartments: water, soil, and sediments, can be estimated with the help of the ML algorithms: random forests and neural networks.

QSAR (Quantitative Structure-Activity Relationship) models: Such AI-based models make predictions of ecotoxicological endpoints without requiring a large-scale laboratory test.

Early identification of high-risk compounds: Recent applications incorporate AI into screening large libraries of drug candidates in preclinical stages, like drug design companies to generate molecules with a reduced environmental risk, as is possible with the attitude to the green pharmacy principle. Recent studies combine AI with geospatial data to detect hotspots of contamination and predict seasonal changes in the pharmaceutical load at surface waters. This predictive ability allows making regulatory decisions and providing particular mitigation actions.[115]

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Biosensors and Nanotechnology for Residue Detection

Pharmaceutical trace concentrations in the environment are seldom detected, making it a challenge since all water matrices are complicated and contain low concentrations of traces. Recent applications in biosensors and nanotechnology have facilitated ultra-sensitive and real-time pharmaceutical detection, superior to conventional solutions such as HPLC or GC-MS because of their speed and portability.[116]

Key innovations include:

Electrochemical biosensors: These are enzyme or antibody-based detectors that selectively detect antibiotics, NSAIDs, and hormones in sewage water and surface water samples.[117]

Nanomaterial-enhanced sensors: Adding nanoparticles in the form of gold, graphene oxide, and carbon nanotubes enhances amplification of signals, which are detected in levels as small as picograms.[118]

Paper-based microfluidic devices: These inexpensive and easy-to-carry devices are able to conduct quick screening of pharmaceuticals in distant locations without having any elaborate laboratory facilities.[119]

Fluorescent and colorimetric nano sensors: They are also used in visual detection without needing the costly instrumentation to simplify nanotechnology research; perhaps better remediation approaches have been pursued by photocatalytic nanoparticles (e.g., TiO2-based systems) attributed the capability to degrade pharmaceutical pollutants found in water during treatment.[120]

Big Data Analytics for Monitoring Pharmaceutical Pollution

The transformative role of big data analytics in pharmacoenvironmentology is that it allows the incorporation of various datasets of the environmental monitoring programs, hospital discharge, prescription patterns, and wastewater treatment plants. These data sets can be huge and heterogeneous, and they have to be analysed using sophisticated analytics to derive valuable information.[121]

Applications include:

Trend analysis: Big data tools help identify long-term trends in pharmaceutical contamination across regions, linking pollution levels to demographic and prescribing behaviours.

Wastewater-based epidemiology (WBE): Coupling chemical analysis with big data approaches would enable community pharmaceutical usage to be monitored in real-time, of which can be used

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to track both licit and illicit drugs.

Early warning systems: Big data hubs can anticipate particular pharmaceutical pollution spikes by combining prescribing data with environmental sensor data, patterns in the weather (e.g., flu season, heat waves) so on.

Policy development: To decide on interventions like specific wastewater treatment upgrades or awareness and education campaigns, governments and health agencies rely on insights provided by big data, where sensors installed in rivers or WWTP effluents send the data through the centralized analysis. Emerging platforms embrace cloud computing and IoT (Internet of Things) that would continuously monitor the environment where a sensor installed in rivers or WWTP effluents transmits the data. The real-time alert on the contamination levels is then provided by AI-driven dashboards, enabling a dynamic approach to risk management.[122]

Integration with Pharmacoenvironmentology

The combination of these technologies, unlike AI-based prediction, nanotechnology-based detection, and decision-making based on big data, is the area of paradigm shift in pharmacoenvironmentology. Instead of relying solely on reactive measures, healthcare and environmental systems can now adopt proactive, predictive, and precision-based strategies for managing pharmaceutical residues. These innovations complement traditional monitoring programs and regulatory frameworks, ensuring that pharmaceutical pollution is addressed with greater efficiency and sustainability.[123]

Challenges and Future Perspectives

Pharmacoenvironmentology sits at the intersection of pharmacology, ecology, and public health, but advancing it from an academic concern to effective policy and practice faces several persistent challenges. Drawing solely on the papers you provided, the following subsections summarize the main research gaps and limitations, the need for coordinated global policy and collaboration, and likely future trends that the field should pursue.[124]

Research Gaps and Limitations

Despite growing detection of pharmaceuticals across environmental compartments, large evidence gaps remain. Current regulatory risk assessments are largely predictive and performed pre-market; post-market environmental monitoring is sparse or non-existent, so real-world concentrations and chronic effects are often unknown.[92] The Pharma Times review highlights that agencies such as the FDA typically rely on modelled Predicted Environmental Concentrations (PEC) and have rarely rejected drugs on environmental grounds, yet do not systematically verify PECs after marketing. Empirical toxicology is also limited. Most ecotoxicological studies are acute assays or use sentinel species;

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chronic, low-dose, mixture, and multi-generational effects remain poorly characterized. The reviewed literature notes that studies linking environmental exposure to human outcomes are few and largely experimental (cell or sentinel-species work), leaving uncertainty about long-term human health consequences of low-level, mixed exposures. Methodological obstacles compound these gaps: many pharmaceuticals are present at nanogram–microgram per litre levels, requiring sensitive, standardized analytics; metabolites and transformation products complicate exposure assessment; and illicit, herbal or non-regulated products (e.g., aristolochic acid) are often omitted from routine monitoring despite demonstrated toxicity. Finally, practical monitoring and stewardship frameworks (Eco pharmacovigilance) are underdeveloped. While the EU and some nations have advanced ERA guidance, systematic life-cycle tracking, environmental risk management plans (ERMPs), and transparent, accessible environmental data for marketed medicines are not yet routine, limiting timely detection and response to environmental harms. [125]

Table 2. Key Challenges and Future Perspectives in Pharmacoenvironmentology

Challenge	**Description**	**Future Perspectives**
Research Gaps	Limited data on chronic low-dose and mixture toxicity; few human epidemiological studies	Expand long-term, multi-generational studies; standardized monitoring
Regulatory Limitations	ERA often pre-market only; weak enforcement of post-marketing monitoring	Global harmonization of ERA, mandatory post-marketing studies
Wastewater Treatment	Conventional plants poorly remove pharmaceuticals	Adopt advanced processes (AOPs, ozonation, membranes, bioremediation)
AMR Risk	Antibiotics driving resistance in environmental microbiota	Integrated "One Health" approaches linking the environment, human, and animal sectors
Public Awareness	Improper drug disposal remains widespread	Strengthen take-back programs, public campaigns

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Global Collaboration	Fragmented national actions	Establish international pharmacoenvironmentology networks

Need for Global Collaboration and Policies

Pharmaceutical contamination is transboundary by nature: water systems, trade in medicines, and waste shipments extend exposure beyond national borders. The papers stress that isolated national measures will be insufficient; global coordination is required across regulators, manufacturers, health systems, and environmental agencies[18]. The "producer-pays" principle is advocated: manufacturers should be accountable for the end-of-life management of products (take-back, safe destruction), reducing leakage and incentivizing greener design. Several practical policy elements emerge from the literature: harmonized, mandatory environmental risk assessment requirements that include post-marketing surveillance; standardized monitoring networks for water, soil and sludge with shared data platforms; financing mechanisms (public or producer-funded) to upgrade wastewater treatment where needed; and international guidance on safe disposal and emergency handling (WHO guidance cited as a template for health-sector waste management). Collaboration should also link clinical stewardship (prudent prescribing, reducing stockpiling) with environmental action. The Swedish model of environmental classification of medicines providing prescribers with hazard information illustrates how cross-sector coordination (industry, academia, health services) can inform greener clinical choices.[126]

Conclusion

Pharmacoenvironmentology has emerged as an essential discipline for understanding and mitigating the environmental and health implications of pharmaceutical residues. This review highlights that the presence of active pharmaceutical ingredients in water, soil, and living organisms poses significant ecological and public health challenges, including endocrine disruption, bioaccumulation, and the alarming rise of antimicrobial resistance. The manufacturing discharges and hospital effluents compound the contamination points through improper disposal and agricultural activities, leading to increased complexity of the risk issues by rendering the problem widespread and enduring. Nevertheless, in spite of legislative attempts and technological breakthroughs, modern policy usually takes a disjointed and reactive form. High-level wastewater treatment, drug take-back programs, and green pharmacy programs are potentially effective, but have a high level of regional variability. Also, there remain knowledge deficits around chronic levels of low-dose exposures, mixture toxicity, and the long-term effects of chronic exposure on humans, and integration of the research and monitoring mechanisms is therefore essential. In the

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future, pharmacoenvironmentology in contemporary healthcare needs to transform a niche scholarly discipline into a widespread element of health policy worldwide. This involves the harmonization of global laws, designing drugs in an environmentally friendly manner, large-scale installation of more modern removal methods, and proper community participation in avoiding disposal. Predicting, monitoring, and mitigating risks will become further easier through the application of emerging instruments and technologies, including AI-based risk prediction, detection using nanotechnology, and analytics of big data. After all, ecosystems and human health cannot be taken separately as points of interest. The scientific background and strategic direction of the pharmaceutical ecology can help deliver sustainable healthcare systems that reduce the pharmaceutical pollution without compromising the therapeutic effects of modern-day medicine.

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