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Pharmaceutical Pollutants in the Ecosystem: Impact on Microbial Community Functioning and Its Ecological Implications

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Abstract - Due to the extensive use of pharmaceuticals, their presence in the environment is ubiquitous. Such compounds are classified as emerging contaminants and pose a risk to the microbial flora, which contributes to the balanced functioning of ecosystems and biogeochemical cycles. This paper aims to provide an overview of the characteristics, persistence, and impacts of pharmaceutical pollution, particularly its influence on the microbial world. To conduct research on the topic under consideration, a literature review approach was applied through data collected from analysis, molecular, and environmental methods. The method can be useful for studying the characteristics of pharmaceuticals and their impact on soil and aquatic ecosystems. Besides, it is useful for determining how microbes counteract the adverse effects of pharmaceutical contamination. Pharmaceutical pollution has a significant effect on the microbial world. An increased amount of these compounds promotes horizontal gene transfer, which is responsible for the development of antimicrobial resistance in microorganisms. Furthermore, due to persistence, pharmaceutical pollutants accumulate and biomagnify in ecosystems, becoming part of food chains and posing risks to ecosystems and people. Importantly, some bacteria and fungi degrade pharmaceutical products enzymatically, which opens perspectives for bioremediation approaches. Pharmaceutical pollution can significantly impact ecosystems, as its effects extend beyond microorganisms. Rather, the effect extends to higher trophic levels, thus negatively impacting ecosystems and human beings. As noted above, conventional approaches to reducing pharmaceutical pollutants in wastewater are often ineffective. Therefore, the use of microbial remediation, improved wastewater treatment techniques, and more environmentally friendly pharmaceuticals needs to be explored.

Keywords: Pharmaceutical Pollutants, Microbial Communities, Ecosystem Stability, Antibiotic Resistance, Bioaccumulation, Bioremediation.

Nomenclature:
NSAIDs: Non-Steroidal Anti-Inflammatory Drugs
ARG: Antibiotic Resistant Gene
ARB: Antibiotic-Resistant Bacteria
WWTP: Waste Water Treatment Plant
MOF: Metal Organic Framework

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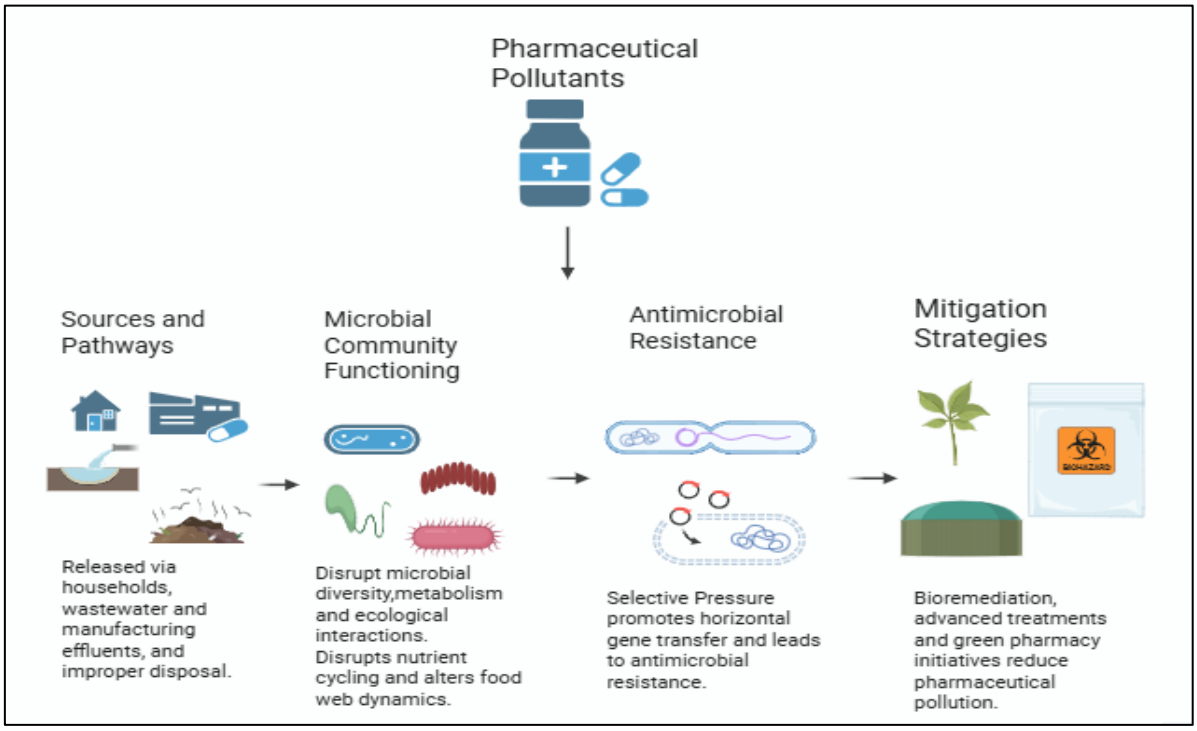
I. INTRODUCTION

Pharmaceuticals are biologically active compounds that are widely and increasingly used in both human and veterinary medicine to treat various health conditions. The extensive use of different pharmaceutical classes results in their continuous release into the environment, making them emerging pollutants of significant concern. The rapid growth in the production and use of synthetic chemicals, including pharmaceuticals, far outpaces other global change factors—such as biodiversity loss, rising carbon dioxide levels, nutrient pollution, and land-use changes. Pharmaceuticals mainly enter the environment through wastewater treatment plants (WWTPs), but they also come from agricultural practices, landfills, hospitals, and residential waste [1].

Research has confirmed the presence of pharmaceutical substances in various environmental media, including surface water, settling dust, and groundwater [2]. Several studies have confirmed the presence of pharmaceuticals in aquatic species in both freshwater and marine environments. Drugs such as psychoactive medicines, synthetic hormones, and NSAIDs have been found within those organisms [3].

Microbial communities are essential energy sources in food webs and are fundamental components of global energy and matter cycles. By breaking down organic material, microorganisms release inorganic substances that primary producers utilise [4]. If the microorganisms fail to do so, the ecosystem's energy and nutrient cycles would be disrupted. From another perspective, the microbial community is an ideal indicator of an ecosystem's health status. The community is important for aquatic ecosystems' self-purification, thereby removing certain organic and inorganic substances and pharmaceutical impurities [5]. Pharmaceutical pollutants in aquatic environments can have significant, long-lasting effects, inducing substantial reductions in energy and oxygen levels and thereby affecting the overall well-being of ecosystems [6].

This review examines the effects of several pharmaceutical classes frequently found in ecosystems—either individually or collectively—on soil and aquatic microbial communities.



[Fig.1: The Lifecycle and Ecological Impact of Pharmaceutical Pollutants]

II. SOURCES AND PATHWAYS OF PHARMACEUTICAL POLLUTANTS

A. Route of Entry of Human and Veterinary Pharmaceuticals

Pharmaceutical contaminants enter the environment through multiple pathways, mainly via effluents from wastewater treatment plants resulting from typical patient use and excretion. Moreover, drug pollutants originating from either humans or animals are increasingly being detected in diverse environmental compartments globally, including surface water, groundwater, soils, and biota [7], [8].

The discharge of pharmaceuticals into wastewater via excretion or skin rinse, together with incomplete removal at wastewater treatment plants, leads to their distribution in the hydrosphere, including drinking water, sediments, soils, food chains, and plants [9].

High quantities of unused drugs and their metabolites, as well as breakdown products, are discharged to the aquatic environment through untreated wastewater, treated wastewater effluents, and effluents from livestock and aquaculture operations. Such pollutants ultimately reach marine and coastal environments, where they serve as sinks [10].

Pharmaceutical factory effluents have been identified as an important source of pollution owing to their high content of active pharmaceutical compounds in the receiving ecosystem. The global occurrence of such pollutants is evident by the discovery of 631 different compounds in 71 countries [11].

More significantly, up to 30% to 90% of the drug intake through oral administration is excreted in urine in the form of the drug itself in human beings and other animals. The excreted drug is subsequently flushed out into the sewage system, which is not equipped to filter drugs and thus acts as the major route of entry for pharmaceutical contamination [12].

B. Manufacturing and Disposal Practices

Pharmaceutical production and manufacture are major sources of environmental pollution through various pathways. Pharmaceutical production involves processes that generate effluents, including fermentation broth, process liquor, solvents, cleaning water from equipment, and undesirable products containing APIs and their metabolites. Effluents are usually contaminated with pharmaceuticals, sometimes more than the environmental safety limits, inadequately treated, or incorrectly disposed of before they enter aquatic environments. Research indicates that pharmaceutical production is the main contributor to increased concentrations of drugs in the environmental surroundings around drug usage zones. The inappropriate disposal of pharmaceuticals significantly contributes to pollution through various modes of transport. Practices such as flushing medicines down toilet bowls and sinks, disposing of them in garbage bins, or dumping them in landfills without any treatment make it easier for pollutants to enter aquatic ecosystems directly or indirectly. Household disposal methods, for example, enable APIs to seep from landfills into groundwater or flow into water bodies through rainfall [13].

At times, healthcare institutions and industries may engage in the illegal dumping of excess or outdated medications that contain API. In addition, poor disposal techniques, such as burning, release hazardous airborne substances, leading to environmental pollution and contamination of soil and water bodies [14].

It is important to note that the outcome of such actions is the presence of medications in the environment since most drugs are formulated to

withstand chemical processes and decompose slowly. Traditional wastewater treatment facilities are ineffective at breaking down such components. As a consequence, pharmaceutical drugs are disposed of in aquatic habitats, sedimentary basins, and organisms. The deposits cause environmental contamination and the bioaccumulation of pharmaceuticals in marine organisms, leading to antimicrobial resistance [15].

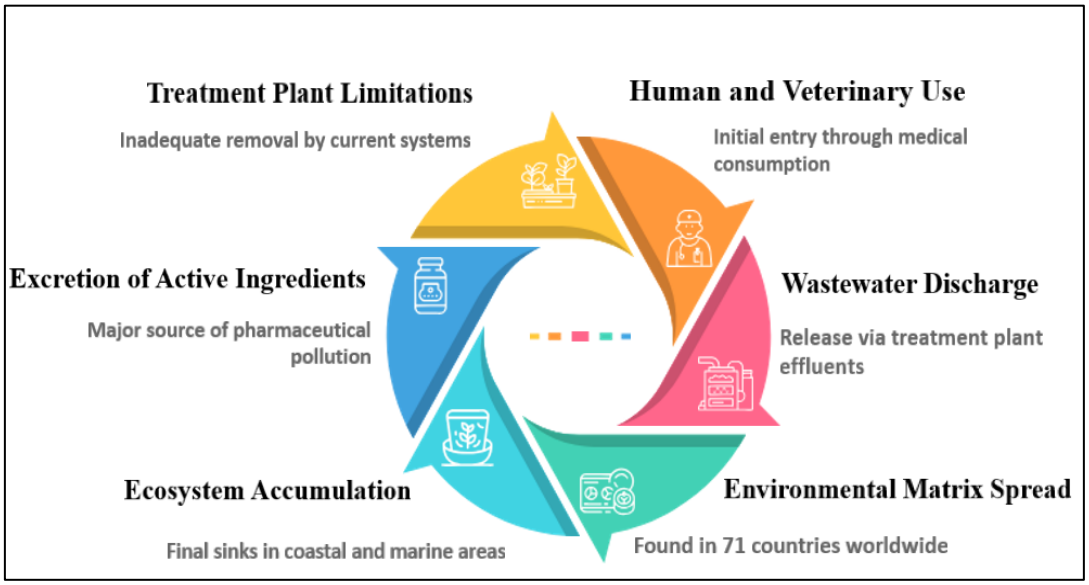
C. Environmental Fate and Transport

Processes that control the fate of pharmaceutical pollutants in environmental matrices include sorption, photodegradation, biodegradation, and oxidation. It is important to note that pharma pollutants are relatively stable, meaning they will accumulate at higher rates than they degrade. This means that such attributes as toxicity, mobility, bioaccumulation, and persistence will determine the influence of drug pollutants in the environment. Moreover, conventional water purification methods typically do not eliminate these pollutants, leaving them detectable in purified water [16].

Pharmaceutical drugs may enter the soil matrix through leaching and runoff. Their behaviour in the soil matrix will largely depend on components such as pH, organic matter, clay, and humus. Certain drugs persist in the soil and are known to bioaccumulate or migrate into groundwater. In contrast, others are controlled by abiotic factors such as oxidation or biological reactions that produce transformation products. If these processes are not efficient enough, pharmaceuticals will stay in their environmental matrix or be eliminated from it; either way, soil organisms may become involved [17].

Table I: Environmental Sources of Major Pharma Pollutants

Source	Route of Entry	Environmental Compartments Affected	Key Pollutants
Wastewater Treatment Plants (WWTPs)	Effluent discharge	Rivers, lakes, sediments	Antibiotics, NSAIDs
Pharmaceutical Manufacturing Plants	Industrial effluent	Surface water, soil	Active Pharmaceutical Ingredients (APIs)
Hospitals	Direct sewer discharge	Urban waterways	Antibiotics, cytotoxic drugs
Agriculture & Livestock	Runoff, manure application	Soil, groundwater	Veterinary antibiotics
Household Disposal	Flushing, landfill leachate	Groundwater, surface water	Mixed pharmaceuticals



[Fig.2: Dynamics of Pharmaceutical Pollution and its Global Environmental Footprint]

III. FORMS OF PHARMACEUTICAL POLLUTANTS AND THEIR ECOLOGICAL EFFECTS

A. Antibiotics

Antibiotics enter the environment through various means, such as emissions during the manufacture of medicines, poor storage of excess or out-of-date medicines, effluent from hospitals, runoff from farms, and utilisation of the chemicals as crop disinfectants and disease-control agents in aquaculture operations. The presence of these chemicals in water bodies and soil exerts selective pressure on resistant bacteria. It facilitates the transfer of resistance genes, thereby contributing to environmental pollution from medicines and increasing antibiotic resistance in the environment [18].

B. Analgesics and Anti-Inflammatory Drugs

Non-steroidal anti-inflammatory drugs (NSAIDs) get into the environment through human excretion. Once consumed by people, these drugs, including ibuprofen, naproxen, and diclofenac, pass through the human body partially unchanged or as active metabolites and later get discharged into municipal wastewater systems. Conventional wastewater treatment techniques are inefficient at removing chemicals because of the drugs' persistence.

Inevitably, the NSAIDs find their way into surface water systems such as rivers and coastal marine environments [19].

As per [20], the estimated concentrations of a few forms of pharmaceutical pollutants in their sources are listed below:

Table II: Concentrations of Some Pharmaceutical Pollutants and their Sources [20].

Pharmaceutical Class	Typical Concentration Range	Sources
Ciprofloxacin	0.32 – 299.88	Groundwater (high) and surface waters
Acetaminophen	73.48 – 346.3	Rivers and water bodies
Diclofenac	12.01 – 4.84 (surface); 0.14 – 0.0495 (water)	Rivers and drinking water
Sulfamethoxazole	0.16 – 100.56	Water bodies and surface water
Amoxicillin	0.001 – 7.45	Surface water and drinking water

IV. IMPACT OF PHARMACEUTICAL POLLUTANTS ON MICROBIAL COMMUNITIES

A. Effects on Microbial Diversity and Abundance

Pharmaceutical pollution, primarily comprising antibiotics and non-antibiotics, might have a considerable effect on population dynamics and the diversity of microorganisms present in aquatic environments. Biofilm structure and function might be altered by pharmaceutical pollution, leading to changes in community structure, a decline in the number of taxa, and shifts in dominant microbial taxa. Empirical data show that exposure to specific drugs reduces the abundance of Rhodobacteraceae and increases Gammaproteobacteria. Moreover, pharmaceutical pollution might help the dissemination of antibiotic-resistant genes within microbial communities. Drugs such as diclofenac and ciprofloxacin are characterised by lower bacterial richness, reduced Cyanobacteria and diatoms, and increased resistant strains. Thus, pharmaceutical pollutants are known to reduce microbial diversity and abundance, as well as to disrupt biogeochemical cycles and ecological processes in polluted ecosystems [21].

In addition, because of the increased number of cases of substance abuse, the levels of chemical substances have risen, which might negatively affect the survival rate, reproduction capabilities, metabolism, and other population dynamics features [22].

The use of medicinal products can influence microbial-trophic interactions and detritivore activities, and disrupt the ecosystem's energy balance. Heavy stream pollution leads to higher rates of leaf degradation by microorganisms while reducing detritivore activity, altering basic energy flow pathways. As for chemical pollutants, such as drugs, their characteristic feature is not only their influence on bacteria but also their effects on archaea, fungi, and protozoa. The metagenomic analysis of the polluted river system has shown that, in addition to reductions in microbial abundance and biodiversity, chemical pollution increases the abundance of certain bacterial and archaeal taxa in several cases [23].

The effect of non-steroidal anti-inflammatory drugs (NSAIDs) on wastewater treatment could include changes in microbial community structure and activity, especially in nitrogen removal and in increasing bacterial diversity. It is worth mentioning that among the tested NSAIDs, naproxen and ibuprofen were removed better while diclofenac remained in water for a longer time. Moreover, NSAIDs stimulate the development of some bacteria, namely Bacteroidetes and Actinobacteria, which could degrade these chemicals [24].

B. Alterations in Microbial Metabolic Functions

Exposure to pharmaceutical pollutants affects the functions of microbial populations in the ecosystem. They affect the metabolism of soil microflora with respect to carbon source utilisation, leading to decreased metabolic activity and diversity. Pharmaceuticals, especially antibiotics, are among the most dangerous contaminants. In particular, pharmaceuticals could affect the activities and functioning of microbial processes in ecosystems [25].

In general, contamination with pharmaceuticals, such as antibiotics, affects the community structure and metabolism of marine microorganisms in coastal sediments. Whole-genome metagenomic profiling analysis demonstrated shifts in gene composition associated with metabolic processes (purine and pyrimidine metabolism, ABC transporters, carbon fixation) and an increased abundance of antibiotic resistance genes [26].

Dibutyl phthalate contamination induces genes related to nitrogen, carbon, and sulphur metabolism [27].

The influence of pharmaceuticals on fungal assemblages is complex, and, in addition to affecting their biodiversity, it can alter their functions and roles in ecosystems. Being present in water sources and their surroundings, the substances can exert selective pressures that lead to structural changes within fungal communities. In other words, some fungi might develop resistance to such substances or become adapted to the presence of toxins of these pollutants. Studies have shown that fungi used in pharmaceutical bioremediation, such as Trametes versicolor, can degrade certain compounds in these pollutants. Yet excessive concentrations and prolonged exposure may negatively affect fungal and enzyme development, reducing their effectiveness. Besides, negative metabolites formed during the decomposition of such pollutants can harm fungi and enzymes involved in biodegradation processes [28].

The drug ibuprofen present in streams can negatively affect the metabolism of streambed biofilms (consortia of microbes living on substrates). The process is crucial for the performance of metabolic functions in microbes, which are essential for numerous ecosystem processes. What is important to note is that the combined effects of pharmaceutical pollutants, along with other substances such as 17α-estradiol, can reduce the aforementioned inhibition [29].

C. Changes in Microbial Interactions and Ecosystem Dynamics

Selective pressure may be exerted upon microbial

communities by certain pharmaceutical compounds, such that bacteria resistant to those drugs and able to degrade and transform them will emerge and flourish in the ecosystem. At the same time, the survival of the rest will be suppressed. This increases the growth and survival rate of those microbial taxa that are usually subdominant members of the microbial community. This leads to a profound alteration in the overall diversity of microbes and their functioning in the ecosystem [30].

Interactions between the active moieties of drugs have been reported to alter biofilm groups in aquatic systems and shift the equilibrium between disparate bacterial populations [31].

Under contaminated conditions, relationships among microbes (e.g., syntrophy in pollutant dechlorination) could be compromised. At several contaminated sites, populations of dechlorinating bacteria had been disturbed, and relationships among other pollutant-cracking taxa had been disrupted. Disturbance can compromise the inbuilt capacity for bioremediation and may catalyse intervention to complement the microorganisms' action [32].

Hormone pollutants such as 17-estradiol alter the structure of biological communities and gene expression. This change shifts the ratio of methanotropy to methanogenesis in an oxygen-rich water body, thereby facilitating greater methane release [33].

Experiments on contaminated river ecosystems have shown that pharmaceutical pollutants alter co-occurrence and modularity-based patterns in microbial networks. These alterations may diminish resilience and create conditions in which key species are vulnerable to extinction, ultimately destabilising the ecological system [34].

Pharmaceuticals and pollutants might play a role in transforming host–pathogen interactions, thereby altering parasite and disease transmission and population dynamics. Pharmaceuticals, for instance, have an often-underestimated effect on the parasite's life cycle and even on the mollusc host's life cycle, altering ecosystem health and the risk of disease transmission [35].

Table III: Impact of Pharmaceuticals on Microbial Taxa and Ecosystem Functions

Pollutant	Observed Microbial Changes	Affected Taxa	Ecological Implications
Ciprofloxacin	Reduced bacterial richness	Cyanobacteria, diatoms	Disruption of primary productivity
Diclofenac	Shift in biofilm structure	Rhodobacteraceae ↓	Reduced nutrient cycling
NSAIDs	Increased resistant strains	Bacteroidetes, Actinobacteria	Functional shifts
Antibiotics (general)	ARG proliferation	Multiple taxa	Antibiotic resistance spread

V. ECOLOGICAL CONSEQUENCES

A. Disruption of Nutrient Cycling

Pharmaceuticals are increasingly recognised as strong ecosystem disruptors, mainly because they can affect microorganisms and microbial assemblages, and they are a key part of the turnover cycle of essential elements such as nitrogen, phosphorus, and carbon. Microorganisms in freshwater and soils, particularly bacteria and fungi, are highly diverse and functionally diverse. Exposure to an array of well-characterised wastewater- and biosolid-linked pharmaceuticals has been shown to reduce microbial diversity and alter community architecture, thereby hindering important processes such as decomposition and nutrient mineralisation. It has been found to deliver phosphorus from the soil into the plants through their mycorrhizal fungi. However, antifungal azoles reduce plant nutrient uptake to a degree [36].

Pharmaceutical pollutants in sewage sludge, animal manure, or irrigation effluents could negatively affect soil microorganisms and certain enzymes involved in nutrient transformation. Although the negative effects of residues from anticancer drugs on human well-being are well documented, relatively few studies have examined their persistence, breakdown, and interactions with soil quality and biological health. Assessments of potential ecotoxicological effects of anticancer drug residues are much less common compared to those of other xenobiotics. Nonetheless, there is increasing interest in understanding the environmental fate of these pharmaceutical residues, especially in situations involving higher environmental risks. Sewage sludge and hospital wastewaters are the primary sources of anticancer drug residues entering the soil. Their environmental impact and transformation depend on the chemical nature and persistence of these residues. Based on their chemical properties, residues from anticancer drugs could be biodegraded and undergo biochemical changes, producing highly mobile molecules that migrate through the soil into surface and groundwater, leading to soil changes that affect microbial populations as well as their functional roles in energy flows, nutrient cycles, and overall ecosystem functions [37].

Pharmaceuticals such as albendazole, a veterinary anthelmintic, can prevent the colonisation and functioning of arbuscular mycorrhizal fungi, thereby hindering plant nutrient uptake, particularly phosphorus. These actions are brought about by the application of fertilisers laced with pharmaceuticals to crops, and they interfere with the symbiotic relationship between microbes and plants that is required for plants to uptake nutrients [38].

B. Alteration in the Decomposition Process

Pharmaceutical pollutants significantly affect ecosystem decomposition by impeding the normal functioning of microbial populations responsible for degrading organic matter. The pollutants are adept at decreasing microbial diversity and activity, thereby decreasing the levels of microbial enzymes required for efficient degradation. Specifically, pharmaceutical chemicals, in addition to adjunct pollutants such as heavy metals, nanoparticles, and pesticides, can have deleterious effects on the indigenous microbiota of aquatic and terrestrial ecosystems, thereby impeding the degradation of organic matter. The interference could lead to a slowed degradation of organic matter, an

accumulation of residual matter that is not degraded, and, in the long run, impaired nutrient turnover. Furthermore, environmental events and pharmaceutical residues may alter environmental parameters such as pH and oxygen levels, which are crucial in environmental microbiology and degradation. These effects may lead to an imbalanced microbial population composition, with a few robust strains favoured at the expense of others, thereby compromising overall ecosystem health [39].

Biodegradation entails the breakdown of drug pollutants by minute organisms, such as fungi, bacteria, and algae, through specific chemical reactions. The microorganisms release enzymes, chemicals that catalyse chemical reactions, to reduce large pollutant molecules into smaller, less harmful ones, such as carbon dioxide, water, and inorganic ions [40].

It will typically involve several steps:

Identification and internalisation of pollutants: microorganisms identify drug molecules emanating from outside and internalise them.

Transformation by Enzymes-It is the phenomenon by which favoured enzymes catalyse a variety of reactions, such as oxidation and reduction, hydrolysis, and conjugation, due to changes in the chemical character of the pollutants.

Metabolic pathways: The reactions occur along several metabolic pathways. These pathways gradually produce intermediate metabolites that are broken down until they become less toxic or inactive compounds.

End-products: The metabolism must produce non-toxic end-products, such as carbon dioxide and water, which complete the detoxification process.

This biodegradation allows natural degradation mechanisms to be disrupted by the application of biological action and enzymatic selectivity to break down intricate, refractory pollutants that would otherwise accumulate in the environment. The natural degradation mechanisms are driven by the active metabolism of these refractory substances and their subsequent accumulation, thereby accelerating overall decay while reducing pollution levels. Additionally, an understanding of the metabolic products and pathways developed during biodegradation is required to optimise processes and prevent the production of harmful metabolites, which may otherwise hinder environmental recovery [41].

C. Effects on Primary Productivity

Pharmaceutical pollutants have been identified as the principal perturbers of ecosystem functioning, foremost in terms of primary productivity, indicating how quickly primary producers, such as photosynthetic microorganisms, algae, and higher plants, transform inorganic carbon into organic matter, primarily through photosynthesis. Primary productivity is a foundation of food webs and is an essential component in ecological stability in aquatic and terrestrial ecosystems. Even at sub-lethal levels relevant to environmental conditions, pharmaceuticals have been shown to reduce photosynthetic efficacy and inhibit the growth of aquatic primary producers such as microalgae and cyanobacteria. For example, experiments have shown that the antidepressant fluoxetine can suppress diatom growth by amplifying oxidative stress and disrupting energy metabolism, thereby reducing photosynthetic performance and primary productivity [42].

NSAIDs and other substances reduce pigment content and maximum quantum efficiency in photosensitive algal or plant organisms, thereby restricting photosynthetic capacity. Directly, these pharmaceutical waste products inhibit the growth and development of chlorophyll in cyanobacteria, which are the primary producers in any aquatic habitat; hence, they become lethal to their continued existence in addition to changing the entire productivity of the ecosystems [43].

Phytoplanktons, which constitute the diatoms and planktonic algae contributing about 40% of Earth's oxygen, are highly affected when pharmaceuticals are discharged into streams. Low productivity leads to low carbon capture, low oxygen output, and low contributions in sustaining the higher levels. In addition, drugs affect some biological functions. For example, if the rate of respiration goes higher while that of photosynthesis drops, then there would be low amounts of carbon available. Thus, oxygen levels might be affected, resulting in an environment with low oxygen content [44].

Impacts can extend beyond this extent depending on the type of drugs, interactions with other pollutants such as microplastics and heavy metals, and chemical-related factors such as temperature and nutrients. Global measurements reveal that pharmaceutical contamination at nanogram-to-microgram per litre levels is sufficient to disrupt main production in rivers, lakes, estuaries, and inshore waters [45].

D. Impact on food web dynamics

Pharmaceutical pollutants can enter aquatic food webs through direct uptake by primary producers, including algae and phytoplankton. The organisms absorb pollutants from substrates or water through their cell membranes or other intracellular uptake mechanisms. At the feeding level just above the primary producers in the food web, contaminated algae are consumed by herbivorous zooplankton or pharmaceuticals are taken directly from solution, enabling bioaccumulation in zooplankton tissue. Filter-feeding organisms that are important in the food webs of aquatic ecosystems may accumulate pharmaceuticals at levels above those of the immediate environment, thereby enabling their movement through the food web. Pharmaceutical pollutants and other harmful organic pollutants can enter the food web through polluted inland waters, soil, and sediments. They can build up in plants and aquatic animals and then end up in the food chain, affecting fish and crops. These chemicals can harm wildlife and humans by disrupting hormone function, causing cancer, and other health problems [46].

Table IV: Effects of Pharmaceutical Pollutants on Ecological Functions

Ecosystem Process Affected	Mechanism of Disruption	Observed Ecological Impact
Nutrient Cycling	Enzyme inhibition, microbial suppression	Reduced mineralisation
Decomposition	Lower microbial activity	Organic matter accumulation
Primary Productivity	Photosynthetic inhibition	Reduced oxygen production
Food Web Dynamics	Bioaccumulation & biomagnification	Trophic transfer risk

VI. ANTIMICROBIAL RESISTANCE

A. Development and Spread of Resistant Genes

Pharmaceuticals enter the environment through various pathways, including human excretion, improper waste disposal, factory effluents, and runoff from animal husbandry. Wastewater treatment plants (WWTPs) are usually significant sites where the above-mentioned pollutants accumulate and from which antibiotics are inadequately removed from the environment, thereby emitting high concentrations of active moieties into natural water bodies. The repeated presence of the moieties, albeit in smaller amounts, exerts selective pressure on bacterial communities in both aquatic and terrestrial systems. Recurrent or episodic environmental exposure to sub-therapeutic antibiotic doses imposes selective pressure on microbial communities. Surviving bacteria that possess the resistance genes resist the drugs, spread, and overgrow non-resistant bacteria. The selective environment enhances the proliferation of antibiotic-resistant bacteria (ARB) within wastewater, soil, and aquatic systems. Areas affected by pharmaceutical pollutants have witnessed a growing clinically significant population size of ARB. Antibiotics, along with other drug-based pollutants, may facilitate the horizontal transfer of ARGs between bacteria. This is achieved through processes such as conjugation (plasmid exchange), transduction (bacteriophage-mediated gene transfer), and transformation (absorption of extracellular DNA), which enable the dissemination of resistance across various genera and species. Certain pharmaceutical compounds have the mechanism to increase the membrane permeability of the bacterial cells. They can induce stress responses (e.g., SOS response), and upregulate plasmid mobilising genes, all of which favourably alter the frequency of gene transfer [47].

The majority of contaminated sites, mostly those in proximity to hospitals or downstream farms, including rivers, have high levels of ARGs with broad antimicrobial spectra. The selective pressure is exacerbated by co-pollutants, such as heavy metals and antiseptics, which co-select ARGs in the presence or absence of antibiotics at subinhibitory concentrations. These environmental compartments, in turn, become reservoirs of multidrug resistance, as observed in natural, agri-food, and aquatic environments. Research in various countries demonstrates a strong association between the abundance of ARGs and the occurrence of pharmaceutical residues. Metagenomic and molecular characterisation have confirmed the presence of ARGs in pollution hotspots, with ARGs co-occurring with mobile genetic elements, enabling horizontal transfer between microbial communities. Research spotlights hotspots of pharmaceutical pollution—in the form of hospital waste-impacted zones, animal manure, aquaculture, and drug manufacturing—as the main areas where environmental pools of ARGs could be significantly reduced through intervention. Effective mitigation measures include enhanced wastewater treatment technologies, natural adsorption, bioremediation products (e.g., microalgae, natural coagulants such as Moringa oleifera seeds), and environmental discharge policies to reduce pharmaceuticals [48].

B. Implications on the Environment and Human Health

ARGs and ARB developed as a result of pharmaceutical pollution can propagate through water networks, be consumed by wildlife, and reintroduce themselves in human communities through polluted water, food, and direct contact with contaminated environments. Water sources raise major concerns because, in addition to harbouring resistant genes, they also transfer and distribute them through a chain of interlinked ecosystems, thereby harming human health and ecosystem stability. In relation to the threat of human infections, the development of resistant microorganisms and thus increased opportunities for resistance will result in the transmission of resistant agents to humans through water, food products, and even contact. The spread of antibiotic-resistant bacteria from livestock to humans may occur via direct contact with livestock, consumption of contaminated meat, and environmental routes mediated by manure and agricultural runoff. Research has confirmed that antibiotic-resistant bacteria, such as Campylobacter and Escherichia coli, are transmitted from livestock to humans through the food chain. This results in serious infections whose treatment becomes very difficult [49].

VII. BIOACCUMULATION AND BIOMAGNIFICATION

A. Accumulation in Microbial Biomass

Bioaccumulation is the process by which chemicals, such as medicinal compounds, accumulate in the tissues of various organisms, including microbes, at levels greater than those in the surrounding environment. This accumulation is acquired either directly from the environment or through the food chain. Biomagnification is the process by which chemicals become increasingly concentrated as they move through a food web. This leads to greater exposure to organisms higher up in the food chain.

Microorganisms are significant in the environment because their populations can accumulate a wide range of drugs due to their diversity and sheer numbers. The pollutants adhere to or are assimilated by microbial cells; hence, they become constituents of the microbial mass. This accumulation is significant because microbes form the foundation of numerous food chains. Hence, harmful pollutants accumulated in microbial mass may be magnified by

biomagnification and affect larger ecological systems.

The microbial cells are likely to gather substances through several ways, such as:

- **Adsorption and Uptake:** Extracellular polymeric substances and microbial cells provide sites for drug attachment, particularly charged or hydrophobic drugs. Adsorption through such a process could lead to high drug concentrations in biofilms and clumps of microbial cells.
- **Intracellular Uptake and Metabolism:** Certain fungal and bacterial organisms can internalise drugs into cellular structures, resulting in metabolic conversion or drug breakdown. However, a proportion of such drugs is not subject to microbial catabolism and accumulates in cells, leading to their net accumulation in a biological system.
- **Enzymatic Biotransformation:** Microbial enzymes, such as cytochrome P450 monooxygenases and ligninolytic enzymes (notably from fungi), can metabolise and, in certain instances, detoxify pharmaceuticals. Non-complete metabolism, though, generates stable transformation products themselves that also accumulate.

Extracellular polymeric substances produced by aquatic microbial cells mature into sophisticated matrices as a constituent of biofilm material. EPS, comprising a range of biomolecules such as polysaccharides, proteins, lipids, and nucleic acids, exhibits physicochemical properties for the sorption of drug molecules. Due to their three-dimensional networks, they enable the sequestration and concentration of pollutants in microdomains surrounding microbial aggregates, thereby facilitating bioaccumulation. EPS regulates pollutant availability. Bacterial organisms are protected from harmful chemicals by diffusion barriers. EPS present in water bodies is an important contributor to drug sequestration, ensuring prolonged residence times and enhanced biological effects. Furthermore, EPS's participation in the formation of marine snow and transparent exopolymer particles indicates its contribution to biogeochemical cycles and pollutant transport in aquatic environments [50].

The presence of drug pollutants in the microbial ecosystem poses a serious risk to biotic communities and biodiversity. The resultant negative effects are as follows:

- **Modified Microbial Diversity:** When drugs are released into the environment, microbial diversity is modified. Research has found higher levels of Pseudomonas, Gemmobacter, and some members of the Comamonadaceae family when drugs are emitted. This unveils how these pollutants affect some microbes [51].
- **Disruption of Biodegradative Function:** This occurs when drugs damage certain groups of microbes, reducing their capacity to degrade organic matter or nutrients. This decline then impairs ecosystem services such as purifying wastewater and cycling nutrients.
- **Selection of Resistance to Antibiotics:** Non-antibiotic substances sometimes induce stress in microorganisms. This will stimulate the shuffling of genes to produce microorganisms resistant to antibiotics and to propagate organisms that pose a risk to public health.

B. Transfer through Trophic Levels

Pharmaceutical chemicals embedded in microbial biomass are likely to be transferred to these organisms through biomagnification. This has been observed in aquatic food webs, where pharmaceutical chemicals, through their metabolites, accumulate to higher concentrations in predators than in organisms at lower trophic levels. This is compounded by the lipophilic character and tendency to accumulate of certain pharmaceutical molecules, which support their incorporation into food chains and transfer within the trophic web. The manner in which drugs interact with microbial populations influences how pollutants are transformed and degraded. It also influences how compounds accumulate in microbial cells. Accumulating pharmaceutical compounds are transferred along ecosystem food chains by microbial grazers, protozoa, and higher consumers, leading to potential biomagnification in successive higher trophic levels. Such transfer increases exposure risk from invertebrates to fish and ultimately to human consumption, hence the relevance of evaluating microbial functions and vectors in pollutant transfer. Pharmaceutical compounds and metabolites have been detected in several biological compartments of microbial food webs, including microbial grazers such as protozoa and small invertebrates feeding on microbial biofilms. Gradient concentrations of pharmaceutical compounds have been documented in several studies, with higher concentrations in grazers than in microbial producers, indicating high trophic transfer and potential biomagnification. Biofilms, densely clustered aggregations of microorganisms embedded in EPS, act as pools for pharmaceutical accumulation and hold them, thereby serving as both sites of storage and exchange in aquatic ecosystems. Such an accumulation in the biofilm makes the effective transfer of pharmaceutical compounds via grazing efficient. For example, stream ecosystem studies documented the presence of various pharmaceutical compounds in invertebrates and in riparian spiders, providing evidence of the transfer of pharmaceutical compounds from aquatic insects in aquatic larval stages by terrestrial predators, describing cross-ecosystem channels of biomagnification [52].

In aquatic ecosystems, biomagnification is the transfer of pollutants through feeding links, such that chemical accumulation in predator species occurs at rates higher than their removal. It has been well-documented for traditional pollutants, such as heavy metals and recalcitrant organic chemicals, but is now emerging for pharmaceuticals as well. Pharmaceutical chemicals with physicochemical traits favouring persistence and bioaccumulation, especially lipophilicity and resistance to metabolic breakdown, are particularly vulnerable to biomagnification. An increase in concentration with higher trophic levels can have toxic effects on wildlife and pose a risk of human exposure through the consumption of aquatic organisms. Aquatic microbial assemblages are responsible for pharmaceutical

accumulation at the base of the food web and are involved in the early stages of biomagnification. Experiments carried out in aquatic food webs demonstrate that biomagnification of certain pharmaceutical substances is possible; however, biomagnification is specific to particular compounds and is complicated by metabolism and depuration. The persistence and accumulation of pharmaceutical compounds by aquatic organisms underscore the importance of understanding their trophic transfer kinetics [53].

Biofilm structures consist of highly organised communities of microorganisms entrapped within EPS matrices bound to surfaces of aquatic ecosystems. These structures provide sites for pollutant accumulation and sequestration, making them important contact points for pharmaceuticals and microbial communities that inhabit them. Such biofilms serve as sources of pollutant interactions with a variety of microbial species and as nutrient sources for microbial grazers. Protozoans and small invertebrates feeding on organic matter in biofilms are important links in the accumulation and transfer of pollutants up the food chain. According to past research, the importance of biofilms in the retention of pharmaceuticals and as transition points affecting pollutant dynamics is evident. The detection of pharmaceuticals in grazers, as reported in existing studies, clearly suggests biomagnification via biofilms [54].

Table V: Pharmaceutical Pollution Accumulation in Living Organisms

Trophic Level	Uptake Mechanism	Transfer Pathway	Ecological Risk
Microbial Biomass	Adsorption, intracellular uptake	Base of the food web	Pollutant reservoir
Zooplankton	Grazing on biofilms	Aquatic food web	Tissue accumulation
Fish	Dietary uptake	Higher trophic transfer	Toxicity risk
Humans	Consumption of aquatic organisms	Food chain	Health risk

VIII. MITIGATION STRATEGIES

A. Microbial Degradation of Pharmaceutical Pollutants

The use of microbial mechanism-based bioremediation represents an excellent approach for eliminating pharmaceutical contaminants from water sheds. Advances such as microbial fuel cells, biofilters, and engineered microbial consortia for enhanced degradation, Adsorption, and Catalytic action represent possibilities for efficient pollutant removal. Integration of green nanobiotechnology, leveraging microbial properties combined with nanomaterials, can increase pollutant removal efficiency [55]. Innovations in synthetic biology, metagenomics, and microbial ecology enhance microbial consortia with improved metabolic pathways for the removal of pharmaceutical contaminants.

There are various microbial mechanisms for degrading pharmaceutical contaminants. These include:

8.1.1 Adsorption and Catalytic Action: Microbes produced nanomaterials (NPs) such as iron oxide NP and Palladium NPs having high surface area and dense active sites, allowing for drug adsorption like ibuprofen, 17β-estradiol, and sulfamethoxazole. These NPs also promote chemical reactions that break down complex drug molecules into less toxic compounds.

- **Biogenic Nanocatalysts:** Microbial production of metal nanoparticles supports the development of biocatalysts for dehalogenating and detoxifying drug molecules like diclofenac and steroids. For example, producing palladium nanoparticles with *Shewanella oneidensis* demonstrates their capacity to dehalogenate aromatic drug molecules and reduce their toxicity.
- **Enzymatic Activity:** Microbial organisms produce enzymes capable of degrading the pharmaceutical pollutants. The enzymes can degrade or convert drug molecules, thereby detoxifying them and facilitating their eventual removal from an aquatic environment.
- **Higher Removal Efficiency:** Biogenic NPs synthesised from bacteria like *Pseudomonas putida* were capable of effectively eliminating endocrine-disrupting compounds (e.g., estrone) and medicines under in situ conditions [56].

B. Improved Wastewater Treatment Technologies

WWTPs now have to be designed to operate in tandem to remove pharmaceutical pollutants, given their staying power in the environment. Conventional strategies such as sedimentation, filtration, and biological treatment are ineffective at stopping such chemicals. As such, recourse is required and is often implemented in recent and hybrid technologies for WWTPs.

- **Membrane and Advanced Oxidation Technologies**: Membranes are effective in removing harmful substances and are applied to industries where high-grade drinking water is required. Membrane bioreactors (MBRs) in conjunction with advanced oxidation technologies (AOPs), such as ozonation, UV/H_2O_2, and the Fenton reaction, are highly effective in degrading hard pharmaceuticals and organo-pollutants and do so without forming harmful by-products. The combination utilises the physical screening effectiveness of membranes and chemical oxidation to degrade hard molecules [57].
- **Adsorption Processes**: High-order adsorption by virtue of activated carbon, carbonaceous nanomaterials, biochar, and functionalized nanocomposites in the form of MOFs and chitosan derivatives has been effective in realising the removal of several drug molecules. As an example, carbon-based and biochar adsorbents are an economical and high-capacity method for removal. In contrast, nanocomposite adsorbents, such as chitosan-based adsorbents, are highly promising in terms of sustainability and

performance-specific effectiveness [58]. Scalability issues and material regeneration are still roadblocks.

- **Constructed Wetland Treatments**: Biological processes, such as activated sludge, upflow anaerobic sludge blankets (UASB), and constructed wetlands, may enhance elimination of certain drugs, particularly when combined. Hybrid processes that use fungi or bacteria to degrade chemicals are ideal from an environmental and economic standpoint. Certain types of fungi, such as *Ganoderma lucidum*, are true eliminators of certain drugs, and specifically chosen bacteria can tackle recalcitrant substances [59].

C. Green Pharmacy Initiative and Pharmaceutical Take-Back Programmes

The Green Pharmacy Project seeks to promote sustainability in drug development and production to minimise environmental impact. Such a strategy employs techniques such as green chemistry, including energy-saving measures, renewable sources for drug production, and safer solvents, which considerably reduce the amount of hazardous waste. Besides, the strategy utilises new techniques that minimise the generation of harmful byproducts during the conventional drug manufacturing process, such as biotransformation, enzymatic catalysis, and nanotechnology. On the other hand, the drug collection program can be considered an effective means of eliminating unused drugs. Research shows that failure to establish proper procedures for the disposal of pharmaceutical waste, such as flushing medications down toilets and disposing of them in garbage cans, results in the discharge of active pharmaceutical ingredients into sewage treatment facilities and landfill sites. Consequently, these toxins pollute surface water and groundwater sources and pose significant harm to aquatic life [60].

IX. CONCLUSION

Owing to their persistence and the potential indirect effects on microbial communities, pharmaceutical pollution is becoming a significant environmental problem. Pharmaceutical pollutants disrupt essential biogeochemical cycles and ecosystem stability by altering microbial community function. The development of antibiotic resistance among microbes that naturally occur in the environment poses yet another threat to human health. Despite the progress that has been made, many unknowns remain regarding the effects of pharmaceutical drug combinations, the recovery ability of ecosystems, and what constitutes irreparable functional disruption. It would thus be beneficial for future research in this field to adopt a more multidisciplinary approach that encompasses aspects of molecular biology and modelling. Finally, legislative intervention, improved sewage treatment facilities, and recognition of the role of microorganisms in supporting ecosystems should all be part of future efforts to alleviate ecological risks posed by pharmaceutical substances.

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REFERENCES

1. Bernhardt ES, Rosi EJ, Gessner MO. Synthetic chemicals as agents of global change. Front Ecol Environ. 2017;15(2):84–90. DOI: https://doi.org/10.1002/fee.1450
2. Sibeko AP, Naicker D, Mdluli PS, Madikizela LM. Naproxen, ibuprofen and diclofenac residues in river water and sediments. Environ Forensics. 2019;20(2):129–138. DOI: https://doi.org/10.1080/15275922.2019.1597780
3. Wada OZ, Olawade DB. Occurrence of pharmaceuticals in freshwater and emerging treatment technologies: a review. Chemosphere. 2025; 374:144153. DOI: https://doi.org/10.1016/j.chemosphere.2025.144153
4. Cavicchioli R, Ripple WJ, Timmis KN, et al. Scientists' warning to humanity: microorganisms and climate change. Nat Rev Microbiol. 2019; 17:569–586. DOI: https://doi.org/10.1038/s41579-019-0222-5
5. Demaria, F., Suleiman, M., Corvini, P. and Junier, P. (2025), Microbes as Resources to Remove PPCPs and Improve Water Quality. Microb. Biotechnol., 18: e70084. DOI: https://doi.org/10.1111/1751-7915.70084
6. Battin TJ, Besemer K, Bengtsson MM, et al. Ecology and biogeochemistry of stream biofilms. Nat Rev Microbiol. 2016;14:251–263. DOI: https://doi.org/10.1038/nrmicro.2016.15
7. Świacka K, Maculewicz J, Kowalska D, Grace MR. Do pharmaceuticals affect microbial communities in aquatic environments? Front Environ Sci. 2023;10:1093920. DOI: https://doi.org/10.3389/fenvs.2022.1093920
8. aus der Beek T, Weber FA, Bergmann A, et al. Pharmaceuticals in the environment: global occurrences and perspectives. Environ Toxicol Chem. 2016;35(4):823–835. DOI: https://doi.org/10.1002/etc.3339
9. Vaudin P, Augé C, Just N, et al. pharmaceutical drugs as environmental pollutants: neural effects and mechanisms. Environ Res. 2022; 205:112495. DOI: https://doi.org/10.1016/j.envres.2021.112495
10. Vieno N, Hallgren P, Wallberg P, et al. Pharmaceuticals in the aquatic environment of the Baltic Sea region: a status report. 2017. https://www.researchgate.net/publication/330258356_Pharmaceuticals_in_the_Aquatic_Environment_of_the_Baltic_Sea_Region_-_A_status_Report
11. Osuoha JO, Anyanwu BO, Ejileugha C. Pharmaceuticals and personal care products as emerging contaminants. J Hazard Mater Adv. 2023; 9:100206. DOI: https://doi.org/10.1016/j.hazadv.2022.100206
12. Gubae K, Moges TA, Wondm SA, et al. Ecopharmacology knowledge and disposal practices among pharmacy students. Integr Pharm Res

Pract. 2023; 12:185–193. DOI: https://doi.org/10.2147/IPRP.S428457
13. Nipa NY, Ahmed S, Shahariar MD, et al. Improper management of pharmaceutical waste in South and Southeast Asia. J Environ Stud. 2017;3(1):1–7. https://www.researchgate.net/publication/315823710_Improper_Management_of_Pharmaceutical_Waste_in_South_and_South-East_Asian_Regions
14. Nyaga MN, Nyagah DM, Njagi A. Pharmaceutical waste: overview, management and disposal impacts. 2020. https://www.researchgate.net/publication/345766304_Pharmaceutical_waste_overview_management_and_impact_of_improper_disposal
15. Sadiq FK, Sadiq AA, Matsika TA, Momoh BA. Sustainable remediation of persistent organic pollutants. Curr Res Biotechnol. 2025; 9:100293. DOI: https://doi.org/10.1016/j.crbiot.2025.100293
16. Jayasekara U, Siganul A, Premarathna K. Chemical remediation of pharmaceutical pollutants in soils. Ind Dom Waste Manag. 2025; 5:50–67. DOI: https://doi.org/10.53623/idwm.v5i1.710
17. Ajekiigbe VO, Agbo CE, Ogieuhi IJ, et al. Antibiotic pollution from pharmaceutical waste and the rise in resistance. Discov Public Health. 2025; 22:120. DOI: https://doi.org/10.1186/s12982-025-00506-9
18. DLS, B VG, Murali V. Ecological consequences of NSAIDs in aquatic ecosystems. Toxicol Rep. 2024; 13:101775. DOI: https://doi.org/10.1016/j.toxrep.2024.101775
19. Iancu VI, Chiriac LF, Paun I, et al. Pharmaceutical contaminants along the Romanian Black Sea coast. Toxics. 2025; 13:498. DOI: https://doi.org/10.3390/toxics13060498
20. Pino-Otín MR, Muñiz S, Val J, Navarro E. Environmental risk of pharmaceutical residues. 2017. DOI: https://doi.org/10.1016/j.scitotenv.2017.04.002
21. Martinez N, Cuautle M. Impact of pharmaceutical waste on biodiversity. 2017. https://www.researchgate.net/publication/322127132_Impact_of_Pharmaceutical_Waste_on_Biodiversity
22. Burdon FJ, et al. Environmental context determines the impacts of pollution on ecosystem functioning. Oikos. 2022. DOI: https://doi.org/10.1111/oik.09131
23. Muhie S, et al. Environmental pollutants and microbiome diversity insights. Toxics. 2025. DOI: https://doi.org/10.3390/toxics13020142
24. Mussa, Z. H., Al-Qaim, F. F., Jawad, A. H., Scholz, M., & Yaseen, Z. M. (2022). A Comprehensive Review for Removal of Non-Steroidal Anti-Inflammatory Drugs Attained from Wastewater Observations Using Carbon-Based Anodic Oxidation Process. Toxics, 10(10), 598. DOI: https://doi.org/10.3390/toxics10100598
25. Cycoń, M., Mrozik, A., & Piotrowska-Seget, Z. (2019). Antibiotics in the Soil Environment: Degradation and Their Impact on Microbial Activity and Diversity. Frontiers in microbiology, 10, 338. DOI: https://doi.org/10.3389/fmicb.2019.00338.
26. Habibi N, et al. Metagenomes from coastal sediments: microbiome and resistome. Microorganisms. 2023. DOI: https://doi.org/10.3390/microorganisms11020531
27. Xu W, et al. Dibutyl phthalate alters microbial metabolic pathways. Sci Rep. 2018. DOI: https://doi.org/10.1038/s41598-018-21030-8
28. Nancy N, Kumari U. Biodegradation of pharmaceutical pollutants using fungal enzymes. Int. J. Res. Appl. Sci. Eng. Technol. 2024;12(5):827–833. DOI: https://doi.org/10.22214/ijraset.2024.61672
29. McClean P, Hunter W. Estradiol limits ibuprofen impact on stream biofilms. bioRxiv. 2019. DOI: https://doi.org/10.1101/718924
30. Pinto IC, et al. Impact of pharmaceuticals on aquatic microbial communities. Antibiotics. 2022. DOI: https://doi.org/10.3390/antibiotics11121700
31. Suleiman M, et al. Removal efficiency of pharmaceutical micropollutants in membrane bioreactors. bioRxiv. 2023. DOI: https://doi.org/10.1101/2023.04.11.536351
32. Gan X, Liu Q, Liang X, et al. Microbial shifts in pharmaceutical-contaminated soils. Soil Syst. 2025. DOI: https://doi.org/10.3390/soilsystems9030065
33. Gao Z, Zheng Y, Li Z, Ruan A. Estradiol pollution effects on microbial communities. Toxics. 2024. DOI: https://doi.org/10.3390/toxics12050373
34. Hu A, et al. Anthropogenic contamination impacts riverine microbial communities. Environ Microbiol. 2017. DOI: https://doi.org/10.1111/1462-2920.13942
35. Costa A, et al. Contaminated freshwater and the risk of disease spread. Front Environ Sci. 2024. DOI: https://doi.org/10.3389/fenvs.2024.1410821
36. Durant E, Field K, Sallach J, et al. Azole antifungals disrupt mycorrhizal function. Plants People Planet. 2025. DOI: https://doi.org/10.1002/ppp3.70068
37. Adil M, Riaz M, Arif M, Akhtar K. Ecotoxicology of anticancer drug residues in soils. 2023. DOI: https://doi.org/10.56946/jspae.v2i2.215.
38. Gkimprixi E, Lagos S, Nikolaou CN, et al. Albendazole inhibits mycorrhizal symbiosis. FEMS Microbiol Ecol. 2023. DOI: https://doi.org/10.1093/femsec/fiad048
39. Alobaidi WA, et al. Pharmaceutical pollutants in aquatic systems. J Basrah Res Sci. 2024. DOI: https://doi.org/10.56714/bjrs.50 .2.8
40. Ortúzar M, Esterhuizen M, Olicón-Hernández DR, et al. pharmaceutical pollution and bioremediation systems. Front Microbiol. 2022; 13:869332. DOI: https://doi.org/10.3389/fmicb.2022.869332
41. Karkman A, Do TT, Walsh F, Virta MPJ. Antibiotic-resistance genes in wastewater. Trends Microbiol. 2018;26(3):220–228. DOI: https://doi.org/10.1016/j.biotechadv.2021.107731
42. Larsson DGJ, Andremont A, Bengtsson-Palme J, et al. Critical knowledge gaps and research needs related to the environmental dimensions of antibiotic resistance. Environ Int. 2018; 117:132–138. DOI: https://doi.org/10.3389/fmicb.2020.01803
43. Grenni P, Ancona V, Barra Caracciolo A. Ecological effects of antibiotics on natural ecosystems: a review. Microchem J. 2018; 136:25–39. DOI: https://doi.org/10.3390/ijms22168856
44. Bengtsson-Palme J, Larsson DGJ. Antibiotic concentrations are predicted to select for resistant bacteria. Environ Int. 2016; 86:140–149. DOI: https://doi.org/10.1525/ELEMENTA.252
45. Manaia CM, Macedo G, Fatta-Kassinos D, Nunes OC. Antibiotic resistance in urban aquatic environments. Front Microbiol. 22016; 7:1640. DOI: https://doi.org/10.1021/acs.est.2c05817
46. Zhengxin Xie, Guanghua Lu, Zhenhua Yan, Jianchao Liu, Peifang Wang, Yonghua Wang, Bioaccumulation and trophic transfer of pharmaceuticals in food webs from a large freshwater lake, Environmental Pollution, Volume 222,2017. DOI: https://doi.org/10.1016/j.envpol.2016.12.026
47. Sassi, A.; Basher, N.S.; Kirat, H.; Meradji, S.; Ibrahim, N.A.; Idres, T.;Touati, A. The Role of the Environment (Water, Air, Soil) in the Emergence and Dissemination of Antimicrobial Resistance: A One Health Perspective.Antibiotics 2025, 14, 764. DOI: https://doi.org/10.3390/antibiotics14080764
48. Wu, Z., Shao, X., & Wang, Q. (2025). Antibiotics and Antibiotic Resistance Genes in the Environment: Dissemination, Ecological Risks, and Remediation Approaches. Microorganisms, 13(8), 1763. DOI: https://doi.org/10.3390/microorganisms13081763
49. Daniel Martak, Charles P. Henriot, Didier Hocquet, Environment, animals, and food as reservoirs of antibiotic-resistant bacteria for humans: One health or more?,Infectious Diseases Now, Volume 54, Issue 4,2024,104895, ISSN 2666-9919, DOI: https://doi.org/10.1016/j.idnow.2024.104895
50. Flemming, HC., van Hullebusch, E.D., Little, B.J. et al. Microbial extracellular polymeric substances in the environment, technology and medicine. Nat Rev Microbiol 23, 87–105 (2025). DOI: https://doi.org/10.1038/s41579-024-01098-y
51. Muhie, S., Gautam, A., Mylroie, J., Sowe, B., Campbell, R., Perkins, E. J., Hammamieh, R., & Garcia-Reyero, N. (2025). Effects of Environmental Chemical Pollutants on Microbiome Diversity: Insights from Shotgun Metagenomics. Toxics, 13(2), 142. DOI: https://doi.org/10.3390/toxics13020142
52. Samantha J. Harriage, Nick L. Schultz, Philip S. Barton, Minna Saaristo, Benjamin M. Long, The trophic transfer of pharmaceuticals and personal care products: A global systematic review and meta-analysis, Journal of Hazardous Materials, Volume 498,2025,139806, ISSN 0304-3894, DOI: https://doi.org/10.1016/j.jhazmat.2025.139806
53. M. C. Gómez-Regalado, Julia Martín, J. Santos, I. Aparicio, E. Alonso, A. Zafra-Gómez Science of the Total Environment·2022 DOI: https://doi.org/10.1016/j.scitotenv.2022.160638
54. Bonnineau, C. et al. (2020). Role of Biofilms in Contaminant Bioaccumulation and Trophic Transfer in Aquatic Ecosystems: Current State of Knowledge and Future Challenges. In: de Voogt, P. (eds) Reviews of Environmental Contamination and Toxicology Volume 253. Reviews of Environmental Contamination and Toxicology, vol 253. Springer, Cham. DOI: https://doi.org/10.1007/398_2019_39
55. Fatmata Sesay, Richard Edmond Victor Sesay, Musa Kamara, Xuesong Li, Chengxin Niu, Biodegradation of pharmaceutical contaminants in wastewater using microbial consortia: Mechanisms, applications, and challenges, Journal of Environmental Management, Volume 384,2025,125564, ISSN 0301-4797, DOI: https://doi.org/10.1016/j.jenvman.2025.125564
56. Mónica Martins, Cláudia Mourato, Sandra Sanches, João Paulo Noronha, M.T. Barreto Crespo, Inês A.C. Pereira, Biogenic platinum and palladium nanoparticles as new catalysts for the removal of pharmaceutical compounds, Water Research, Volume 108,2017, Pages 160-168, ISSN 0043-1354,

DOI: https://doi.org/10.1016/j.watres.2016.10.071
57. J. Papac Zjačić, S. Morović, K. Košutić, and D. Ašpergerc. DOI: https://doi.org/10.15255/KUI.2022.008
58. H.Dinarvand, O.Moradi, Sustainable Approaches for Pharmaceutical Pollutant Removal: Advances in Chitosan-Based Nanocomposite Adsorbents. ChemistrySelect2025, 10, e202405962. DOI: https://doi.org/10.1002/slct.202405962
59. H. Vistanty and F. Crisnaningtyas, 2021, IOP Conf. Ser.: Earth Environ. Sci. 623 012082. https://iopscience.iop.org/article/10.1088/1755-1315/623/1/012082
60. Prema Rathinam; Senthilkumar Chelladurai; Khalidha Banu Sheik Abdulla; Chandrasekharan Padmanaban; Sabitha Rajamanickam; Balachandru Velmurugan. "Green Pharmacy Practices: Progress in Sustainable Drug Synthesis and Waste Mitigation." Volume. 10 Issue. 8, August 2025 International Journal of Innovative Science and Research Technology (IJISRT), 419-422. DOI: https://doi.org/10.38124/ijisrt/25aug305

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