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Chemical Remediation of Pharmaceutical Pollutants in Contaminated Soils: A Review of Oxidation-Based Approaches

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ABSTRACT: The objective of this study is to develop effective chemical treatment methods to break down stubborn pharmaceutical pollutants in contaminated soil, enhancing its quality and reducing environmental risks. Numerous pharmaceuticals, which are substances used to cure or prevent illnesses in both humans and animals, are classified as pollutants of increasing concern because of their extensive environmental dispersion and their negative effects on populations. This is due to the constant discharge of sludge and effluent from wastewater treatment plants, which happens far more quickly than the removal of pharmaceuticals; they are frequently discovered in soils at considerable concentrations. Conventional wastewater treatment is unable to effectively remove pharmaceuticals from influent streams or biosolids, despite the fact that they are often present at low ambient quantities. Furthermore, through surface runoff and leaching, the application of animal manure to the soil can cause pharmaceuticals to contaminate the soil. Adsorption to soil colloids and degradation through the soil profile are some of the mechanisms that influence the behaviour and fate of pharmaceuticals in soils. The primary factor influencing how much organic matter is absorbed by plant roots is the sorption of pharmaceuticals in soils. This pharmaceutical pollutant in contaminated soil can lead to a negative impact on human and soil health. Therefore, remediation techniques such as chemical oxidation, soil washing, bioremediation, and phytoremediation should be used to reduce the pharmaceutical pollutants in the contaminated soil.

KEYWORDS: Pharmaceutical pollutants; chemical oxidation; contaminated soil; adsorption; degradation

1. Introduction

Pharmaceuticals are physiologically active compounds that have been used as growth stimulants in animal husbandry and food production, as well as for therapeutic and preventive purposes in human and veterinary medicine. Antibiotic growth promoters, which are now banned, along with other veterinary drugs, were commonly used in the past to enhance breeding. This was primarily driven by the goal of increasing live weight gain, often at the expense of concerns regarding food quality, raw material safety, and animal-derived food products. The issue has since become global in scope, and Member States have been tasked with regulating food quality in accordance with European Commission regulations (Council Directive 96/23/EC and Commission Decision 93/256/EEC). Furthermore, as of January 1, 2006, all Member States were required to discontinue the use of antibiotic growth enhancers as feed additives, allowing only those compounds that were officially approved, and to carry out the necessary control measures [1].

In the realm of protecting human and animal health, the pharmaceutical industry has made major advances in science and research technologies. Nonetheless, numerous unresolved concerns remain regarding the presence of pharmaceutical active ingredient residues in food and the environment, which must be considered alongside progress in pharmacotherapy [1]. According to international organizations, the introduction of advanced technological solutions and improved access to more affordable medicines—especially generics—is expected to increase pharmaceutical consumption in the coming years. For example, the use of certain drug classes, such as antidiabetics, rose by an average of 75% between 2000 and 2009, a trend projected to continue. The global pharmaceutical market's compound annual growth rate (CAGR) between 2016 and 2020 was estimated at 4–7%, according to research by the QuintilesIMS Institute [2].

Two main sources of pharmaceutical and metabolite emissions into the environment have been identified: "point" sources and dispersed "non-point" sources. The pharmaceutical industry represents a key point source, contributing active ingredients during the manufacturing process. Meanwhile, improperly managed pharmaceutical waste from households, healthcare facilities, and commercial sources often ends up in the environment untreated. Non-point sources include wastewater and sewage sludge from municipal treatment plants, which commonly release pharmaceutical pollutants [3]. Human excretion from households, hospitals, and other care settings leads to pharmaceutical residues entering wastewater. The widespread use of biosolids and effluents for fertilization further contributes significant quantities of pharmaceutical contaminants to the soil. Compounds such as fluoroquinolones, ciprofloxacin, and norfloxacin are known to persist through wastewater treatment, accumulating in sewage sludge. It is estimated that veterinary pharmaceutical applications release several times more active ingredients into the environment than human use. Antibiotics are among the most frequently detected pharmaceutical contaminants in soil, sometimes found at concentrations exceeding 400 mg/kg [4].

According to Carter et al. [5], sewage sludge and fertilizer are key pathways for pharmaceutical pollutants to enter soils. Population growth, increasing wealth, and easier access to medicine have all contributed to a rise in pharmaceutical loads in sewage systems. In areas where biosolids or treated, partially treated, or untreated effluents are used for irrigation, pharmaceutical residues may accumulate in the soil. Yet, environmental risk assessments and chemical regulations do not currently apply to wastewater used for irrigation purposes. Pharmaceuticals can degrade through abiotic processes, water bodies, soil interactions, and biological treatment in wastewater systems. While these processes can reduce pharmaceutical toxicity, some degradation by-products remain just as harmful as the parent compounds [5].

The behavior and fate of pharmaceuticals in soil depend on their biological, chemical, and physical properties. These compounds may persist in the soil or leach into groundwater, depending on both the pharmaceutical's and the soil's physicochemical characteristics. Therefore, remediation of pharmaceutical-contaminated soils can involve chemical oxidation, soil washing, bioremediation, or phytoremediation [6]. This study reviewed the types and sources of pharmaceutical pollutants in contaminated soils, their fate and occurrence, their impacts on soil and human health, and remediation strategies with a focus on chemical oxidation.

2. Types of Pharmaceutical Pollutants in Contaminated Soil.

Pharmaceutical usage and consumption trends within a country can differ significantly from those of other nations or even between regions within the same country, due to factors such as population demographics, disease prevalence, healthcare practices, and economic conditions. These usage patterns directly influence the levels of pharmaceutical residues found in the aquatic environment, particularly in sewage systems. In Malaysia, the Ministry of Health (MOH) has been publishing data on pharmaceutical consumption since 2006 through the Malaysian Statistics on Medicines (MSOM). This report provides insights into national medication usage trends across both public and private healthcare sectors. The data are categorized according to the Anatomical Therapeutic Chemical (ATC) classification system developed by the World Health Organization (WHO), which enables standardized international comparisons. Pharmaceutical consumption is measured in defined daily doses (DDDs) per 1,000 population per day [7]. Figure 1 illustrates the therapeutic groups and specific pharmaceuticals commonly used in Malaysia.

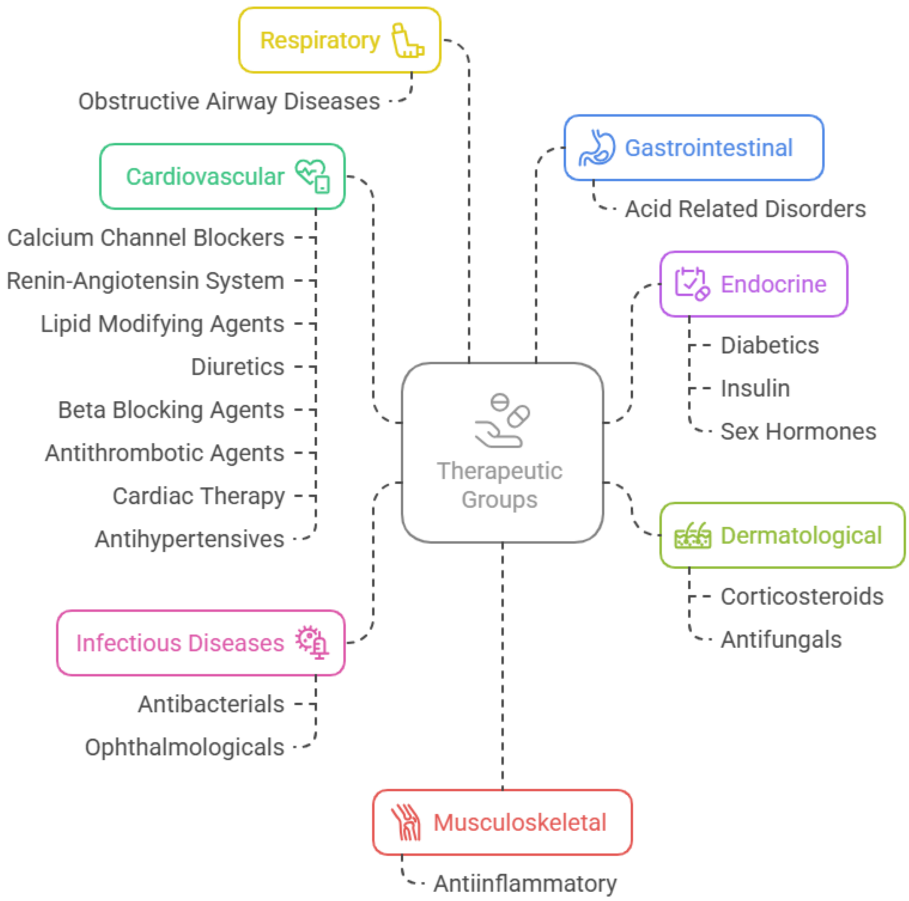

Figure 1. Pharmaceutical pollutants based on usage.

3. Sources of Pharmaceutical Pollutants in Contaminated Soil.

There Pharmaceuticals released into the environment fall into two main categories: veterinary and human pharmaceuticals. Veterinary pharmaceuticals are widely used around the world to treat diseases and maintain the health of animals. The types of compounds used often depend on the specific animal industry and regional practices. In Europe, common veterinary pharmaceuticals found in animal products include antimicrobials, anti-inflammatory agents, growth promoters, antiparasitics, insecticides, and tranquilizers. These compounds can enter the environment through animal manure, which contributes to the contamination of soil, surface water, and groundwater via leaching and surface runoff. On the other hand, human pharmaceuticals are prescribed and consumed globally for a wide range of therapeutic purposes. They represent numerous therapeutic classes and are frequently detected in the environment due to excretion and improper disposal. Table 1 presents various therapeutic classes of pharmaceuticals along with representative compounds.

Table 1. Therapeutic classes of pharmaceuticals and representative compounds.

Therapeutic Class	Description	Example Compounds
Analgesics and Anti-inflammatories	Relieve pain, reduce inflammation	Acetylsalicylic acid, Diclofenac, Ibuprofen, Naproxen, Ketoprofen, Indomethacin, Paracetamol
Antibiotics	Treat bacterial infections	Amoxicillin, Azithromycin, Clarithromycin, Erythromycin, Sulfamethoxazole, Ciprofloxacin, Norfloxacin, Tetracycline
Antiepileptics	Control or prevent seizures and epileptic activity	Carbamazepine, Phenytoin, Valproic acid, Lamotrigine, Levetiracetam, Gabapentin
Antimicrobials	Broad-spectrum agents against microbes (non-antibiotic)	Triclosan, Hexachlorophene, Chlorhexidine, Benzalkonium chloride, Iodopovidone
Antineoplastic Agents	Treat various forms of cancer	Cyclophosphamide, Methotrexate, 5-Fluorouracil, Doxorubicin, Tamoxifen, Cisplatin
β-blockers	Manage cardiovascular conditions such as hypertension	Atenolol, Propranolol, Metoprolol, Bisoprolol, Nadolol, Carvedilol
Hormones	Regulate biological processes, often reproductive or metabolic	17α-ethinylestradiol, Progesterone, Testosterone, Estradiol, Levonorgestrel, Dexamethasone
Illicit Drugs	Commonly abused substances or their metabolites	Benzoylecgonine, THC-COOH, Methamphetamine, Morphine, Heroin, MDMA (ecstasy)
Lipid Regulators	Manage cholesterol and triglyceride levels	Lovastatin, Simvastatin, Atorvastatin, Clofibrate, Gemfibrozil, Fenofibrate
SSRIs (Antidepressants)	Treat depression and anxiety by modulating serotonin	Fluoxetine, Paroxetine, Sertraline, Citalopram, Escitalopram, Fluvoxamine

Figure 2 illustrates the sources and transport pathways of pharmaceutical pollutants into the soil environment. One of the primary routes for veterinary pharmaceuticals to enter the environment is through the urine and feces of treated animals. Residues from these pharmaceuticals can persist in soils, accumulate in soil organisms and plants, and eventually enter the food chain [3]. Numerous studies, at both national and global levels, have examined the fate and environmental impact of veterinary pharmaceuticals. These findings show that variations in pharmaceutical usage, excretion rates, and manure management practices across different livestock sectors significantly affect the quantities of veterinary pharmaceuticals released into the environment. A key insight from this research is that existing data on veterinary drug usage can help identify environmental risks. However, there remains a lack of comprehensive and quantitative data on the actual amounts of veterinary pharmaceuticals applied, which warrants urgent attention.

For human pharmaceuticals, the major sources of soil contamination include improper disposal of expired drugs, discharge of treated wastewater, and the application of pharmaceutical-laden fertilizers in agriculture. Soil contamination can also occur through landfilling of incinerated pharmaceutical waste. Nevertheless, regulations such as the EU Landfill Directive and subsequent policies have been instrumental in reducing this impact. The EU's waste policy aims to minimize landfill usage. Between 2010 and 2020, the EU-27's average landfill rate decreased from 23% to 16%, despite rising overall waste production. In 2020, the volume of waste sent to landfills dropped by 27% compared to previous years. On average, each EU citizen generated 106 kg of waste per year. While some waste streams like household waste have seen improved landfill diversion, the amount of sorted residual waste ending up in landfills has doubled since 2010 [9].

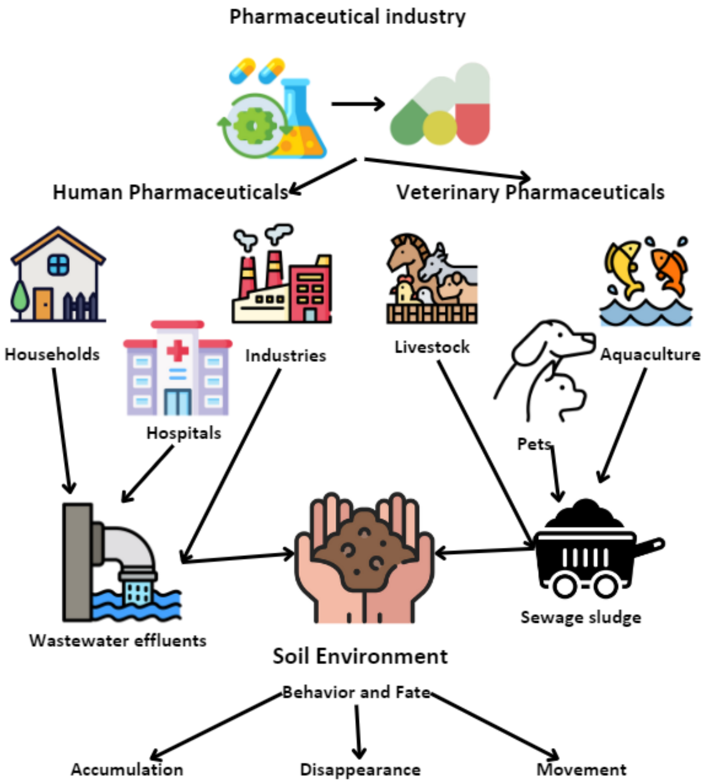

Figure 2. Sources and transport of pharmaceutical pollutants to the soil environment.

According to Abdallat et al. [1], carbamazepine concentrations were found to be higher in the upper soil layer (0–25 cm) compared to the root zone (25–45 cm) across all farms using drip irrigation systems with treated wastewater effluents. Notably, carbamazepine was detected exclusively in olives, indicating a high uptake rate by these plants. Since livestock commonly consume such crops, this poses a potential route for pharmaceuticals to enter the human food chain.

In contrast, paracetamol, nicotine, ibuprofen, and carbamazepine were detected at low concentrations in maize grains, suggesting limited uptake by maize. This disparity may be due to differences between pharmaceutical levels in soil and those in irrigation water. Treated wastewater effluents used for irrigation are another major source of pharmaceutical contamination.

The transfer of pharmaceuticals from water and soil to plants is influenced by several factors, including soil characteristics such as pH and clay content, and pollutant properties such as water solubility. According to Nguyen et al. [10], concentrations of diclofenac, sulfamethoxazole, and trimethoprim in soil vary depending on the quality of the treated wastewater applied. Biel-Maeso et al. [11] reported that pharmaceutical concentrations in surface soils ranged from 2 to 15 ng/g due to irrigation, with the highest levels (up to 14 ng/g) observed during winter months, indicating greater persistence at lower temperatures.

Other studies have found that antibiotics, psychiatric drugs, and anti-inflammatory medications pose the highest environmental risks, while the highest pharmaceutical concentrations in secondary effluent were linked to antihypertensives, beta-blockers, and anti-inflammatories. These insights can support scientists and decision-makers in developing strategies to reduce the impact of treated municipal wastewater discharge on soils and surface waters.

4. Fate of Pharmaceutical Pollutants

4.1.Adsorption and desorption.

One of the main mechanisms influencing the fate, migration, and bioavailability of pharmaceuticals in soil is sorption. It is dependent on a number of variables, including soil response, surface activity, temperature, moisture, and the physicochemical characteristics of the soil and pharmaceuticals. Adsorption is the concentration of atoms, molecules, or ions in the vicinity of a surface. This principle applies to pharmaceuticals, which act as adsorbates that are able to be retained in soil colloids, which are adsorbents. Soil colloids have two types, which are clays and humus, that are essential to this process because of the many negative charges they have at the soil's pH [11, 12]. This process involves two types of forces. One of the forces is chemical adsorption, which involves chemical bonds between adsorbed molecules. Another kind of force is physical adsorption, which involves van der Waals interactions.

often directly measured using batch studies. To minimise disruption of the soil mineral balance, aqueous 0.2 M $CaCl_2$, for example, are mixed together. A quantity of pharmaceutical is added to the slurry before mixing to achieve the concentration of the chemical in the liquid phase. The slurry is then carefully blended to limit disruption to the soil structure. Typically, this process takes 24 hours, but it can range from 2 to 48 hours. This can examine the aqueous equilibrium concentration. High Kd values, which are more than 200, do not indicate strong reversibility of this sorption, which proves that the pharmaceuticals can be adsorbed by the soil quickly. This method was first created for substances that are hydrophobic. The suitability of this normalization for ionizable pharmaceuticals is unclear. Given the possible impacts of a pharmaceutical's pKa on its possible ionization and subsequent sorption, the pH of the soil can be more pertinent for such normalization. The partition coefficient and soil organic carbon concentration are linearly correlated, as demonstrated by Karickhoff et al. The octanol–water partition coefficient (K_{ow}), a measure of pharmaceuticals' affinity for either soil which is high value or water which is low value, has a linear relationship with K_{oc}. If there is a lot of adsorption (chemisorption), the molecule won't be bioavailable. It will have less biological activity as a result. Furthermore, it is not biodegradable, which makes it more persistent in soil, and because of its significantly decreased mobility, there is less chance that groundwater will become contaminated. When soil conditions such as moisture, temperature, change, the chemical desorb to the soil with the accompanying biocidal danger. K_d values are frequently calculated at a constant temperature across a variety of concentrations. The resultant diagram, known as the adsorption isotherm, shows the connection between the adsorbed concentration (C_a) and the compound's equilibrium concentration (C_e) at a constant temperature [10–13].

The degradation of pharmaceuticals in soil is influenced by factors such as the presence of microorganisms, and the chemical properties of the pharmaceuticals. Some compounds, like naproxen and trimethoprim, exhibit strong sorption, while others, such as ibuprofen, diclofenac, and sulfamethoxazole, show minimal sorption, potentially increasing their mobility in soil and posing a risk of groundwater pollution. The presence of organic matter in soil can reduce the availability of ketoprofen, leading to its prolonged persistence [14].

A comprehensive study by Li et al collected data on the sorption of 21 pharmaceuticals in different kind of soil. The findings led to the assessment of existing models and the development of new and improved ones. The study revealed Kd values ranging from 1249 ml/g (perphenazine) to 0.2 (antipyrine) [8]. According to the principal component analysis (PCA), hydrophobic forces and electrostatic interactions had an impact on the sorption of the pharmaceuticals [15].

4.2.Degradation.

According According to research, the breakdown of pharmaceuticals in soil can take years, indicating a long degradation period. The fate of pharmaceuticals in soil is significantly influenced by their sorption to soil particles [13]. A study by Bolesta et al. examined how chemical mixtures affect the degradation of three pharmaceuticals: fluoxetine, naproxen, and carbamazepine. When tested individually, fluoxetine and carbamazepine were found to be more persistent, while naproxen degraded more rapidly, with half-lives of up to one week depending on the soil type. However, in combined treatments including the antibiotic sulfamethazine, fluoxetine and carbamazepine showed similar degradation rates as in the single-compound experiments, whereas naproxen degraded more slowly in the mixture [16].

Another studies assessed that the degradation of 23 pharmaceuticals in two soil types: silty clay loam and sandy loam. Most of the compounds degraded relatively quickly ($t½ < 20$ days), except for carbamazepine ($t½ = 170–330$ days) and roxithromycin ($t½ = 57–88$ days) [12, 13]. Most degradation models use the pharmaceutical concentration as the primary dependent variable. However, degradation in soil is influenced by various environmental and chemical factors, making it essential to understand degradation kinetics when assessing persistence. The most widely used model is single-first-order (SFO) kinetics. For compounds that show a fast initial decline followed by a slower rate, biphasic models such as first-order sorption-based, double first-order in parallel, first-order multi-compartment, and H models are applied. The primary mechanisms for pharmaceutical removal from soil are degradation and mobility, which may involve photochemical or biochemical processes [11, 13].

4.2.1. Photochemical degradation.

Pharmaceuticals are among the many micropollutants that are broken down by ultraviolet (UV) radiation. When the pollutant is exposed to energy, electrons are excited, which can cause bonds to break or become less stable. This happens as long as the absorbed photons' energy is at least as high as the bond energy. Indirect photolysis involves the compound absorbing UV light within the sun spectrum, which is less than 400 nm, whereas direct photolysis involves the compound absorbing the energy and transferring it to the pharmaceutical molecule or producing other reactive species. Pharmaceuticals can transition to triplet states after being promoted to their excited singlet levels by direct irradiation such as homolysis, heterolysis and photoionization. On soil surfaces, pharmaceuticals that are water soluble, non-volatile, and photodegradable are susceptible to photodegradation. Most antibiotics have these three characteristics in common. It has long been believed that, unlike what happens in aqueous solutions, light has no impact on the breakdown of pharmaceuticals in soils. Soil samples containing 0.6 mg/kg of two common veterinary fluoroquinolones which are enrofloxacin and marbofloxacin were exposed to sunlight, both compounds degraded extensively (80%) in 60–150 hours. All antibiotics underwent direct photodegradation in water in a different study where soil samples containing oxytetracycline, chlorotetracycline, sulfanilamide, sulfadimidine, sulfadiazine, sulfadimethoxine, sulfapyridine, fenbendazole, and p-aminobenzoic acid were either exposed to arc light. First-order rate coefficients (k) varied between 0.007 and 0.13/day. The average k for fenbendazole and sulfonamides in soil, however, was 0.02/day, which was 2.5 times lower than that in water. Therefore, photochemistry is the process of removing pharmaceuticals from the soil with the main influencing irradiation intensity, duration and pH of the soil, adsorption on the colloids and chemical structure of the pharmaceuticals [11–13].

4.2.2. Biochemical degradation.

Degradation can be classified as either chemical or biological in concept. Nonetheless, they are frequently intimately connected. As a function of moisture and chemical degradation includes oxidation and hydrolysis that take place in soil, whereas biodegradation is the process in which soil microorganisms transform or modify pharmaceuticals in the soil. In order to investigate chemical and biological degradation independently, soil microorganisms must be eliminated using suitable sterilization or irradiation methods. Other catalytic systems that significantly affect degradation must also be modified for this. Thie is due to two forms of degradation are sometimes merged and referred to as biochemical degradation [8–10].

Pharmaceutical’s biodegradability in an aerobic environment declines with increasing molecular weight, carbon atom count, and aromatic nuclei. The absence of vital nutrients for microorganisms, such as phosphorus and nitrogen, inadequate electron acceptors often oxygen and the existence of harmful substances in the contaminant mixture slows down the process of biological decomposition. Recalcitrant pharmaceuticals endure for years and decades, whereas biodegradable pharmaceuticals are broken down by soil microorganisms in a matter of days and weeks [9, 10].

Soil microorganisms such as bacteria can break down pharmaceuticals either anaerobically, using nitrates and other substances as electron acceptors, or aerobically, using oxygen as an electron acceptor. Certain anti-inflammatory medications such as clofibric acid and indomethacin have been shown to biodegrade poorly in anaerobic environments, with the exception of naproxen. The potential for increased oxygenation-induced breakdown of pharmaceuticals is suggested by the greater degradation rates seen in aerobic environments. Atenolol and similar pharmaceuticals degraded more slowly in soils with better structures and nutrient contents, whereas soils irrigated with effluents from wastewater treatment plants containing these pharmaceuticals degraded rapidly. This is most likely due to their chemical structure, while non-ionic compounds, including carbamazepine, lamotrigine were recalcitrant and accumulated. Grossberger et al. demonstrated that pharmaceutical properties affect biodegradation kinetics [8, 9].

Hydrolysis and oxidation all yield a good number of metabolites and transformation products. This is because there are so many pharmaceuticals with various characteristics now in use. Mineralization can totally break down these new structures into CO_2, H_2O, and mineral salts. As an alternative, they can be polymerized and added to the humic materials of soil. Other extremely stable compounds are created as a result. Soil-bound residues are those non-extractable and chemically unidentified fractions that are left in the soil's humic fractions following extraction using solvents with varying polarity. Figure 3 shows that the fate, transportation and the negative effects of pharmaceutical pollutants in the contaminated soil [8–10].

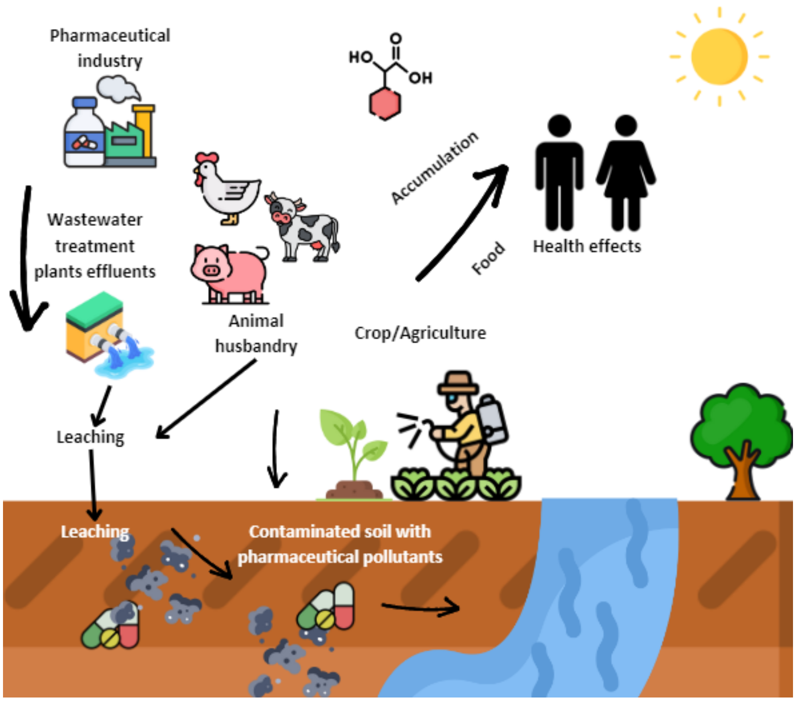

Figure 3. Fate, transportation and effects of pharmaceutical pollutants in contaminated soil.

5. Occurrence of Pharmaceutical Pollutants in Contaminated Soil.

Pollutants migrate into the soil profile based on how strongly they bind to the solid phase particles in the soil. The bioavailability of pharmaceuticals active ingredients and their durability in the soil environment are influenced by the sorption intensity. Thus, a key factor in the exposure of living things to pollution is the soil's sorption capacity. Kodešová et al. investigated the dispersion of specific active ingredients of pharmaceuticals from groups like beta-blockers such as atenolol and metprolol, psychotropic pharmaceutical such as carbamazepine, and antibiotics such as trimethoprim, sulfamethoxazole, clindamycin, and clarithromycin in 13 distinct soil types. The characteristics of the soil had an impact on the pharmaceuticals' half-life. Carbamazepine was shown to be the most persistent of the aforementioned compounds in soil, followed by atenolol, sulfamethoxazole, clarithromycin, trimethoprim, metroprolol, and clindamycin [17]. Thus, the half-life for these pharmaceuticals increased [18].

Previous study conducted a study to explain how pharmaceuticals leach into the environment and irrigation affects the movement of pharmaceuticals in soils. Biosolids improved the fate of weakly acidic pharmaceuticals in soil compared to wastewater treated effluents. The findings of the study imply that the regular usage of biosolids can drive pharmaceuticals to migrate in arable soils. Besides that, the mobility of weakly acidic medicines is increased by treated effluents mostly because the pH of the soil solution rises, not because of the complexation interaction between the pharmaceuticals and dissolved organic matter [19]. Relying on actual values found in the environment rather than data from model trials conducted at high concentrations is crucial for accurately assessing the mobility of pharmaceuticals in the environment.

6. Challenges and Impact of Soil Contamination.

Pharmaceuticals usage has more detrimental effects than beneficial ones. The biodiversity of plants and animals, terrestrial and aquatic food chains, ecological systems, and non-target species are all seriously harmed by the pollutants. This is because around 85% of the pharmaceutical pollutants are more volatile, meaning they evaporate within a few days after application, spreading the contaminated area and moving the pharmaceutical pollutants far from their original location. It is crucial to use pharmaceutical appropriately in all sectors to prevent their toxicity from endangering biodiversity, including terrestrial and aquatic ecosystems [20]. By maintaining its surroundings, a healthy soil mechanism may promote ecological integrity. It can also maintain and enhance plantations' and living things' habitats. The three components that determine the integrity of soil are biological (the behaviour of microorganisms), chemical (the alkalinity or acidity of the soil and the amount of organic carbon), and physical (the structure of the soil and its capacity to retain water). These components are interconnected and influence one another. It is commonly recognized that pharmaceutical pollutants can linger in soil for extended periods of time and change into compounds with harmful and toxic properties. Additionally, the pollutants will decrease the pH of the soil, which hastened the breakdown of mineral-rich soil particles. This led to very compacted soil with inadequate sewage and air circulation. This is because microorganisms help to sustain the soil's nutritional element cycle, their presence is also essential to the formation of healthy soil. They are more susceptible to changes in the environment, the beneficial microorganisms can become less prevalent in acidic soil [21].

6.1.Human health.

Human health benefits greatly from soil, which supports crops providing about 78% of global calorie intake and terrestrial food sources that contribute another 20% through indirect dependence. In addition to being a significant source of nutrients, soil serves as a natural filter to rid water of impurities. About 94% of the food humans comes from the soil, which is the basis for almost all food-producing crops. Two cubic meter of soil can retain up to 500 l of water, making it the greatest active carbon storage after the oceans. This enables crops to flourish even during dry spells [22]. Numerous sources, such as untreated water used for drinking, irrigation, and domestic tasks, allow pharmaceutical pollutants to reach into the soil. This causes the soil to be contaminated and antimicrobial-resistant bacteria to grow. The main purpose of pharmaceuticals is to help people and animals, however when they enter the terrestrial environment, they might have the same pharmaco-dynamic effects on creatures with comparable biological traits. All types of pharmaceuticals pollutants in contaminated soil lead to negative impact to human health. These pharmaceuticals pollutants have demonstrated detrimental health effects that are mediated by the induction of inflammation. These factors can raise the risk of neurodegenerative diseases, cancer, obesity, and other cardiometabolic complications. It is estimated that 26 million agricultural workers are impacted by the pharmaceutical pollutants in contaminated soil each year [23].

6.2.Soil health.

Soil health refers to the ability of soil to sustain humans, animals, and plants as a crucial ecosystem. Healthy soils are crucial for preventing desertification and land degradation, ensuring a clean and circular economy, and achieving climate neutrality. In addition, they are necessary to maintain human health, provide nutritious food, and reverse the loss of biodiversity. A framework and specific actions for preserving, repairing, and guaranteeing the sustainable use of soils are provided by the EU Soil Strategy for 2030. A new soil monitoring directive has been developed to ensure a high level of environmental and health protection. The primary hazards to EU soils that are addressed in this plan are mostly to soil biodiversity [24].

Contaminated soil with pharmaceutical pollutants leads to toxic effects on living organisms and disrupt ecological balance. Study shows that these soil nutrients such as nitrogen (N), phosphorus (P), carbon (C), and sulfur (S) are good for soil quality [25]. Zuzana Frková et al. studied six types of pharmaceuticals which are clindamycin, sulfamethoxazole, carbamazepine, citalopram, fexofenadine, and irbesartan. These pharmaceuticals last for 12 to 60 days on microbial activity. Cambisol Dystric mostly showed the inhibitory impact of citalopram, irbesartan, and a pharmaceutical combination, with a slight of alterations on the structure of the microbial as compared to an unsupplemented reference. All pharmaceuticals in Arenosol and Cambisol Haplic showed a stress effect, but the majority of pharmaceuticals in Chernozem Siltic mostly showed a dormant effect [26]. A number of factors, including time, soil type, and particular pharmaceuticals, significantly influenced the microbial responses. This emphasizes how crucial it is to take into account these factors, such as how resistant soil microbial populations are to micropollutants, while managing agricultural soils over the long run. Understanding the effects of pharmaceutical on soil microbial activity in soils while accounting for pharmaceutical resistance in long term agricultural soil management can be aided by determining microbial responses to varied exposure situations [27].

7. Remediation Technologies

7.1.Chemical oxidation.

Chemical oxidation is one of the remediation to restore and treat the contaminated soil with pharmaceutical pollutants by changing them into less toxic or non-hazardous chemicals that are inert, stable, and less mobile, oxidation eliminates dangerous pollutants (Figure 4). Common oxidizing agents include hypochlorites, chlorine, hydrogen peroxide, ozone, and chlorine dioxide. The oxidizing agents and chemical pollutants affect chemical oxidation. The treatment of cyanide-bearing metals including arsenic, iron, and manganese also includes chemical oxidation. The oxidation process causes metal oxides to precipitate out of the solution more easily. A combination of oxidizing agents or the use of UV radiation in conjunction with an oxidizing agent is necessary for some substances. Chemical oxidation causes a contaminant's oxidation state to grow while the reactant's oxidation state decreases. The pros of this remediation are that it is a fast process where quick chemical reactions occur and minimizes the need for waste materials to be handled after treatment. However, the cons of this remediation are that fast process always requires high cost in the remediation and certain pharmaceuticals could not completely break down which can produce hazardous metabolites. In addition, chemical oxidation can be conducted with other techniques using soil washing, bioremediation and phytoremediation [28].

7.2.Soil washing.

Physical separation and chemical leaching by aqueous solutions are the two methods used in soil washing, an ex situ technique, to remove pharmaceutical pollutants from the soil. The coarse particles are separated by different density whereas organic and inorganic pollutants bind to clay and silt. Washing concentrates pollutants into sludge, which can be treated using techniques like bioremediation. This involves separating the coarser sand and gravel soil particles from the finer clay and silt particles. Backfill can be made from the coarse soil particles. The pollutants undergo selective dissolution, followed by chemical transformation or recovery in the second step. The type of pollution to be treated determines which reagents and additives are added to the water. The method's implementation often necessitates a step-by-step procedure employing several washing solutions in soils polluted by many compounds with disparate properties. Using technologies appropriate for the impurities, the tainted water is cleaned which is the cons of the remediation. The pro of this remediation is its cost-effectiveness, since it minimizes the quantity of material that would need additional treatment using a different technology [29].

7.3. Bioremediation.

Utilizing naturally existing microbes, bioremediation techniques cleanse the contaminated soil with pharmaceutical pollutants, converting them into harmless byproducts that fertilize soil. Because of its environmentally beneficial qualities, bioremediation is using the microorganisms to clean up contaminated sites has shown itself to be dependable and successful. The effective restoration of damaged habitats in an economical and environmentally responsible manner has been the driving force behind recent advancements in bioremediation techniques during the last 20 years. To clean up contaminated areas, scientists have created a variety of bioremediation methods. Both native and non-native microorganisms can be introduced to the polluted site as part of the bioremediation process. The majority of the problems pertaining to the biodegradation and bioremediation of pollutants may be resolved by using the native microorganisms found in contaminated areas. Among the main benefits of bioremediation over chemical and physical remediation techniques are its cost-effectiveness and environmental-friendly [30]. Reducing or changing more harmful contaminants into less harmful ones is one of the mechanisms of bioremediation. The type of the pollutants which include pharmaceutical determines the pollutant removal method. Cleaning methods are used to rid contaminated environments of harmful waste. Through the comprehensive activity of microorganisms, bioremediation plays a significant role in the degradation of various chemical and physical harmful elements from the environment. However, the cons of this remediation are that it takes a longer time to achieve the process compared to chemical oxidation treatment and the efficiency of the microorganisms which is dependent on factors like pH, temperature and nutrition is what the performance feasible [31].

7.4.Phytoremediation.

The process by which plants break down or accumulate contaminant soil with pharmaceutical pollutants into less hazardous materials is known as phytoremediation. Through extraction, sequestration, and degradation, it makes advantage of plants' innate capacity to clean up dioxin and furan-contaminated soils. This process is based on plants' physiological and biochemical capacities to mineralize dangerous pollutants into non-toxic molecules. Rhizodegradation, phytodegradation, phytoextraction, rhizofiltration, phytovolatilization, and phytohydraulics are some of the several kinds of phytoremediation techniques that carry out distinct processes such accumulation, dissipation, immobilization, and degradation. In this technique, plants are grown in polluted soil, and their roots produce exudates that use metal translocation and cell membrane transporters like Zn^{2+} and Fe^{2+} to solubilize or chelate any pollutants for absorption. In order to remove pharmaceutical pollutants, plants often release enzymes that serve as surfactants. The pros of phytoremediation are the plants can prevent the soil erosion. However, the cons of phytoremediation include the need for more accessible polluted region and a longer time for the plants to absorb the metals from the pharmaceutical pollutants [32]. According to Jeevanantham et al., the amount of pharmaceutical pollutants in soil has decreased by 30% using this this remediation [33].

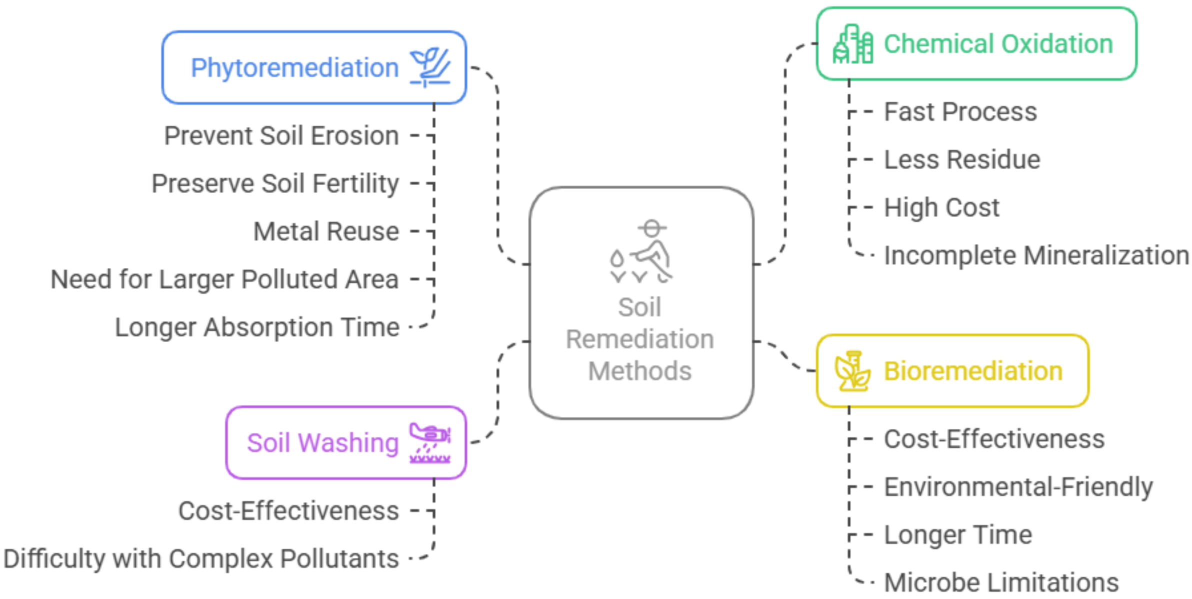

Figure 4. Advantages and disadvantages of remediation technology.

8. Case Study of Pharmaceutical Pollutants in Contaminated Soil

In United States of America (USA), the contaminated soil with pharmaceutical pollutants are treated with chemical oxidation which is known as In Situ Chemical Oxidation (ISCO). ISCO is an easy and fast process. ISCO entails injecting chemical oxidants straight into the source of contamination which is the pharmaceutical pollutants The common oxidant they use is hydrogen peroxide. Based on the research, three different target depth intervals, three injector wells of varying sizes were erected. Single intermediate injectors were placed where contamination was detected between 15 and 20 feet, single shallow injectors screened from 8 to 14 feet were placed where contamination was found between 15 and 20 feet, and paired shallow and deep injectors screened from 20 to 26 feet were placed where contamination was discovered at both shallow and deep depths. A vent flow balancing system was also constructed to help ensure an efficient radial dispersion of catalyst and H_2O_2, and 25 deep ground-water injector wells were employed for monitoring. The polluted soil was treated with H_2O_2 and trace amounts of ferrous sulfate and acid to regulate pH using the Geo-Cleanse proprietary injection technique. Over the course of 120 days, 109,000 gallons of 50% H_2O_2 were delivered through 255 injectors to cause the soil to chemically oxidize. While the full-scale treatment was still underway, post-treatment sampling got underway. When pollutant concentrations were still higher than Soil Screening Levels (SSLs), the area was retreated for polishing [34]. Results show that sampling and polishing were successful in bringing pollutant concentrations in clays down below SSLs in the locations where they were carried out. Trichloroethylene concentrations in the soil that were as high as 1,760 mg/kg have been lowered to levels below detection. Depending on the outcomes of the final sample in the remaining blocks, more polishing treatment could still be necessary. As previously said, further cash has been asked for in order to finish this procedure. There is no detrimental organic movement to nearby soils, according to operating data [35].

Researching pharmaceutical pollutants still faces several obstacles. It requires sophisticated analytical tools to identify minuscule amounts and a thorough grasp of the long-term effects on the environment and human health. One of the major challenges in environmental management is the lack of comprehensive data on pharmaceutical contaminants. Many countries do not have regular monitoring systems for these contaminants in water bodies, leading to significant gaps in our knowledge of their occurrence and effects. This lack of information is often due to insufficient funding, inadequate regulations, and a lack of analytical tools to detect contaminants at low concentrations. Moreover, pharmaceutical contamination is complex, involving a variety of substances with varying levels of toxicity and persistence. This complexity makes it difficult to assess exposure risks, establish effective regulations, or implement targeted wastewater treatment upgrades without reliable data. Additionally, the lack of information hinders research on the cumulative effects of pharmaceutical pollutants on ecosystems and human health, as well as limits public awareness of the issue [36].

Therefore, in order to effectively address pharmaceutical pollutants, it is crucial for academics and companies to collaborate and share knowledge. Universities have diverse research skills and advanced techniques to study the environmental and chemical impacts of drugs. Understanding the complexities of pharmaceutical pollutants and their effects on ecosystems and human health requires familiarity with this academic knowledge. On the other hand, industries can provide valuable insights based on their practical experiences, highlighting the limitations of current solutions and real-world challenges. For instance, regulatory barriers or financial constraints may hinder the adoption of advanced wastewater treatment technologies by industries. By exchanging this knowledge, both sides can develop more feasible and efficient pollution control strategies [37].

9. Conclusion

The presence of pharmaceutical pollutants in contaminated soil has raised significant concerns due to its adverse effects on agriculture crops, soil quality and human health. The constant release of effluent from wastewater treatment plants, which occurs far more quickly than the rates at which they are removed causes pharmaceuticals pollutants to be present in soils in large amounts. In dry and semiarid regions, the use of recovered water to augment available water supplies is growing. Nevertheless, when this water is used for irrigation, it introduces pharmaceuticals residues and other emerging pollutants into the soil due to its intricate matrix. Furthermore, adding sewage sludge to soils as an organic amendment can contaminate the soil with additional contaminants. The utilization of treated wastewater for crop irrigation and repurposing sewage sludge in agriculture need to be increased to enhance soil fertility. Even though pharmaceuticals are typically found at low environmental quantities, it is yet unknown whether or not their presence in aquatic and terrestrial ecosystems can have a negative impact on wildlife or humans. Adsorption controls the breakdown and movement of pharmaceuticals in soils, but other mechanisms also influence their behaviour and fate. Both the organic (humus) and inorganic (clays) colloidal components of the soil are important in this regard. Pharmaceuticals absorption by plants is often inhibited by the sorption of these compounds, particularly when the compounds have a positive charge or are highly hydrophobic. Nevertheless, studies have shown that a wide range of crops cultivated in regions where pharmaceuticals are known to be prevalent can absorb some of these harmful pollutants from the soil. The fact that these pharmaceuticals' residues can enter the food chain and endanger the health of humans and animals when consumed is a significant effect of pharmaceutical-polluted soil. In order to improve the soil's later reuse and safeguard both human and animal health, steps must also be taken to clean up and remediate soil contamination.

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Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Aimie Peace Siganul conceived the study, and led the writing of the manuscript. Upeksha Gayangani Jayasekara, Kadupitige Shashikala Dilrukshi Premarathna was responsible for review and editing. All authors reviewed and approved the final manuscript.

References

[1] Abdallat, G.A.; Salameh, E.; Shteiwi, M.; Bardaweel, S. (2022). Pharmaceuticals as emerging pollutants in the reclaimed wastewater used in irrigation and their effects on plants, soils, and groundwater. *Water 14*(10), 1560. https://doi.org/10.3390/w14101560.

[2] Mosharaf, M.K.; Gomes, R.L.; Cook, S.; Alam, M.S.; Rasmusssen, A. (2024). Wastewater reuse and pharmaceutical pollution in agriculture: Uptake, transport, accumulation and metabolism of

pharmaceutical pollutants within plants. *Chemosphere*, *364*, 143055–143055. https://doi.org/10.1016/j.chemosphere.2024.143055.

[3] Pérez-Lucas, G.; Navarro, S. (2024). How pharmaceutical residues occur, behave, and affect the soil environment. *Journal of Xenobiotics*, *14*(4), 1343–1377. https://doi.org/10.3390/jox14040076.

[4] Gworek, B.; Kijeńska, M.; Wrzosek, J.; Graniewska, M. (2021). Pharmaceuticals in the Soil and Plant Environment: a Review. *Water, Air, & Soil Pollution*, *232*(4). https://doi.org/10.1007/s11270-020-04954-8.

[5] Carter, L.J.; Ryan, J.J.; Boxall, A.B.A. (2016). Effects of soil properties on the uptake of pharmaceuticals into earthworms. *Environmental Pollution 213*, 922–931. https://doi.org/10.1016/j.envpol.2016.03.044.

[6] Gautham, D.; Liu, X.; Balu, R.; Ayyamperumal, R.; Arasu, M.V.; Lavanya, M.; Vasudeva; Kim, W.K.; Karthika, P.C. (2024). Innovative remediation strategies for persistent organic pollutants in soil and water: A comprehensive review. *Environmental Research 118404*, 1–20. https://doi.org/10.1016/j.envres.2024.118404.

[7] Ghazal, H. (2023). Pharmaceuticals contamination in the environment. *Environmental Toxicology and Pharmacology*, *103*, 104251. https://doi.org/10.1016/j.etap.2023.104251.

[8] Li, W.C. (2014). Occurrence, sources, and fate of pharmaceuticals in aquatic environment and soil. *Environmental Pollution*, *187*, 193–201. https://doi.org/10.1016/j.envpol.2014.01.015.

[9] Vatovec, C.; Kolodinsky, J.; Callas, P.; Hart, C.; Gallagher, K. (2021). Pharmaceutical pollution sources and solutions: Survey of human and veterinary medication purchasing, use, and disposal. *Journal of Environmental Management*, *285*, 112106. https://doi.org/10.1016/j.jenvman.2021.112106.

[10] Nguyen, M.-K.; Lin, C.; Nguyen, H.-L.; Hung, N.T.Q.; Duong La, D.; Nguyen, X.H.; Woong Chang, S.; Chung, W.J.; Duc Nguyen, D. (2023). Occurrence, fate, and potential risk of pharmaceutical pollutants in agriculture: Challenges and environmentally friendly solutions. *Science of the Total Environment*, *899*, 165323–165323. https://doi.org/10.1016/j.scitotenv.2023.165323.

[11] Biel-Maeso M.; Corada-Fernández, C.; Lara-Martín, P.A. (2018). Monitoring the occurrence of pharmaceuticals in soils irrigated with reclaimed wastewater. *Environmental Pollution 235*, 312–321. https://doi.org/10.1016/j.envpol.2017.12.085.

[12] Zhang, C.; Barron, L.; Sturzenbaum, S. (2021). The transportation, transformation and (bio)accumulation of pharmaceuticals in the terrestrial ecosystem. *Science of the Total Environment*, *781*, 146684. https://doi.org/10.1016/j.scitotenv.2021.146684.

[13] Salvia, M.-V.; Experton, J.; Geandel, C.; Cren-Olivé, C.; Vulliet, E. (2014). Fate of pharmaceutical compounds and steroid hormones in soil: study of transfer and degradation in soil columns. *Environmental Science and Pollution Research*, *21*(17), 10525–10535. https://doi.org/10.1007/s11356-014-3038-x.

[14] Chacón, L.; Reyes, L.; Rivera-Montero, L.; Barrantes, K. (2022). Transport, fate, and bioavailability of emerging pollutants in soil, sediment, and wastewater treatment plants: potential environmental impacts. *Elsevier EBooks*, 111–136. https://doi.org/10.1016/b978-0-323-85160-2.00020-2

[15] Aryal, N.; Wood, J.; Rijal, I.; Deng, D.; Jha, M.K.; Ofori-Boadu, A. (2020). Fate of environmental pollutants: A review. *Water Environment Research 92*(10), 1587–1594. https://doi.org/10.1002/wer.1404.

[16] Bolesta, W.; Głodniok, M.; Styszko, K. (2022). From sewage sludge to the soil—transfer of pharmaceuticals: A review. *International Journal of Environmental Research and Public Health 19*(16), 10246. https://doi.org/10.3390/ijerph191610246.

[17] Verlicchi, P.; Zambello, E. (2015). Pharmaceuticals and personal care products in untreated and treated sewage sludge: Occurrence and environmental risk in the case of application on soil — A

critical review. *Science of the Total Environment*, *538*, 750–767. https://doi.org/10.1016/j.scitotenv.2015.08.108.

[18] Aydın, S.; Ulvi, A.; Bedük, F.; Aydın, M.E. (2022). Pharmaceutical residues in digested sewage sludge: Occurrence, seasonal variation and risk assessment for soil. *Science of the Total Environment 817*, 152864. https://doi.org/10.1016/j.scitotenv.2021.152864.

[19] Borgman, O.; Chefetz, B. (2013). Combined effects of biosolids application and irrigation with reclaimed wastewater on transport of pharmaceutical compounds in arable soils. *Water Research 47*(10), 3431–3443. https://doi.org/10.1016/j.watres.2013.03.045

[20] Shahsavari, E.; Rouch, D.; Khudur, L.S.; Thomas, D.; Aburto-Medina, A.; Ball, A.S. (2021). Challenges and current status of the biological treatment of PFAS-contaminated soils. *Frontiers in Bioengineering and Biotechnology*, *8*. https://doi.org/10.3389/fbioe.2020.602040.

[21] Mahar, A.; Wang, P.; Ali, A.; Awasthi, M.K.; Lahori, A.H.; Wang, Q.; Li, R.; Zhang, Z. (2016). Challenges and opportunities in the phytoremediation of heavy metals contaminated soils: A review. *Ecotoxicology and Environmental Safety*, *126*, 111–121. https://doi.org/10.1016/j.ecoenv.2015.12.023

[22] Che Lat. D.; Mat Yusof, D.A.; Yasin, M.H.; Mohd Noor, S.N.A.; A Rahman, N.S.; Razali, R. (2023). Effect of soil contamination on human health and environment with preventive measures: A review. *Construction 3*(1), 142–151. https://doi.org/10.15282/construction.v3i1.9404.

[23] Münzel, T. (2022). Soil and water pollution and human health: what should cardiologists worry about? *Cardiovascular Research*, *119*(2). https://doi.org/10.1093/cvr/cvac082.

[24] Cabana, L.A.; Santiago-Martín, A.de; Meffe, R.; López-Heras, I.; Bustamante, I.de. (2024). Pharmaceutical and trace metal interaction within the water–soil–plant continuum: Implications for human and soil health. *Toxics 12*(7), 457. https://doi.org/10.3390/toxics12070457.

[25] Gutiérrez, C.; Fernández, C.; Escuer, M.; Campos-Herrera, R.; BeltránRodríguez, M.E.; Carbonell, G.; RodríguezMartín, J.A. (2016). Effect of soil properties, heavy metals and emerging contaminants in the soil nematodes diversity. *Environmental Pollution*, *213*, 184–194. https://doi.org/10.1016/j.envpol.2016.02.012.

[26] Frkova, Z.; Vystavna, Y.; Koubová, A.; Kotas, P.; Grabicová, K.; Grabic, R.; Kodešová, R.; Chroňáková, A. (2020). Microbial responses to selected pharmaceuticals in agricultural soils: Microcosm study on the roles of soil, treatment and time. *Soil Biology & Biochemistry*, *149*, 107924–107924. https://doi.org/10.1016/j.soilbio.2020.107924

[27] Carter, L.J.; Harris, E.; Williams, M.; Ryan, J.J.; Kookana, R.S.; Boxall, A.B.A. (2014). Fate and uptake of pharmaceuticals in soil–plant systems. *Journal of Agricultural and Food Chemistry 62*(4), 816–825. https://doi.org/10.1021/jf404282y.

[28] Rao, M.N.; Sultana, R.; Kota, S.H. (2017). Hazardous waste. *Solid and Hazardous Waste Management*, 159–207. https://doi.org/10.1016/b978-0-12-809734-2.00005-5.

[29] Bolan, N.; Makino, T.; Kunhikrishnan, A.; Kim, P.J.; Ishikawa, S.; Murakami, M.; Naidu, R.; Kirkham,M.B. (2013). Cadmium contamination and its risk management in rice ecosystems. *Advances in Agronomy*, 183–273. https://doi.org/10.1016/b978-0-12-407247-3.00004-4.

[30] Bala, S.; Garg, D.; Thirumalesh, B.V.; Sharma, M.; Sridhar, K.; Inbaraj, B.S.; Tripathi, M. (2022). Recent Strategies for Bioremediation of Emerging Pollutants: A Review for a Green and Sustainable Environment. *Toxics*, *10*, 484. https://doi.org/10.3390/toxics10080484.

[31] Chibwe, L.; Geier, M.C.; Nakamura, J.; Tanguay, R.L.; Aitken, M.D.; Simonich, S.L.M. (2015). Aerobic bioremediation of PAH contaminated soil results in increased genotoxicity and developmental toxicity. *Environmental Science & Technology 49*(23), 13889–13898. https://doi.org/10.1021/acs.est.5b00499.

[32] Chakraborty, S.C.; Qamruzzaman, M.; Zaman, M.W.U.; Alam, M.M.; Hossain, D.; Pramanik, B.K.; Nguyen, L.N.; Nghiem, L.D.; Ahmed, M.F.; Zhou, J.L.; Mondal, Md.I.H.; Hossain, M.A.; Johir, M.A.H.; Ahmed, M.B.; Sithi, J.A.; Zargar, M.; Moni, M.A. (2022). Metals in e-waste:

Occurrence, fate, impacts and remediation technologies. *Process Safety and Environmental Protection 162*, 82–97. https://doi.org/10.1016/j.psep.2022.04.011.

[33] Jeevanantham, S.; Saravanan, A.; Hemavathy, R.V.; Kumar, P.S.; Yaashikaa, P.R.; Yuvaraj, D. (2019). Removal of toxic pollutants from water environment by phytoremediation: A survey on application and future prospects. *Environmental Technology & Innovation*, *13*, 264–276. https://doi.org/10.1016/j.eti.2018.12.007.

[34] Samborska-Goik, K.; Ulańczyk, R.; Krupanek, J.; Pogrzeba, M. (2024). A PHREEQC-Based Tool for Planning and Control of In Situ Chemical Oxidation Treatment. *Applied Sciences*, *14*, 3600. https://doi.org/10.3390/app14093600.

[35] Besha, A.T.; Bekele, D.N.; Naidu, R.; Chadalavada, S. (2018). Recent advances in surfactant-enhanced in-situ chemical oxidation for the remediation of non-aqueous phase liquid contaminated soils and aquifers. *Environmental Technology & Innovation 9*, 303–322. https://doi.org/10.1016/j.eti.2017.08.004.

[36] Gavrilescu, M.; Demnerová, K.; Aamand, J.; Agathos, S.; Fava, F. (2015). Emerging pollutants in the environment: present and future challenges in biomonitoring, ecological risks and bioremediation. *New Biotechnology*, *32*(1), 147–156. https://doi.org/10.1016/j.nbt.2014.01.001.

[37] Fatta-Kassinos, D.; Meric, S.; Nikolaou, A. 2010. Pharmaceutical residues in environmental waters and wastewater: current state of knowledge and future research. *Analytical and Bioanalytical Chemistry 399*(1), 251–275. https://doi.org/10.1007/s00216-010-4300-9.