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Silent Contaminants: The Environmental Toll of Pharmaceutical Waste in Waterways

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Abstract:

Pharmaceutical substances are progressively recognized as developing natural toxins due to their determined nearness in different biological systems, especially sea-going situations. The worldwide rise in pharmaceutical utilize, combined with the wastefulness of ordinary wastewater treatment plants in completely debasing these compounds, has driven to their nonstop discharge into characteristic water bodies. This developing collection postures noteworthy biological dangers and potential dangers to human wellbeing. Over the final a few a long time, extended get to to pharmaceuticals and their visit utilize have contributed to a sharp increment in their concentrations over streams, lakes, and other freshwater frameworks. Conventional water treatment strategies were not initially outlined to handle the complex chemical nature of pharmaceutical buildups, permitting numerous of these compounds to endure and circulate within the environment. Classified as developing contaminants, pharmaceutical poisons show special challenges for natural administration and remediation. As a result, there's an critical got to actualize supplementary treatment arrangements that can be coordinates with existing frameworks to improve expulsion proficiency. Among the inventive methodologies beneath examination, bioremediation advances have appeared impressive guarantee. Eminently, mycoremediation, a frame of bioremediation that utilizes the common enzymatic properties of organisms, has developed as an eco-friendly and compelling strategy for breaking down pharmaceutical toxins in water. Organisms have the metabolic capacity to debase a wide assortment of complex natural particles, making them perfect specialists for treating pharmaceutical squander. This survey highlights the progressing concerns related with pharmaceutical contaminants in water environments and investigates the advance being made in bioremediation, with a specific accentuation on fungal-based strategies as a feasible and imaginative arrangement for pharmaceutical contamination.

Keywords: *pharmaceutical dynamic compounds, bioremediation, wastewater, mycoremediation, rising contaminants, pharmaceutical contamination.*

Introduction:

In recent years, the advancement of modern medicine has led to a significant rise in both the production and use of pharmaceutical substances. It is estimated that over 3,000 different pharmaceutical compounds are currently in use, with annual production volumes reaching into the hundreds of tons (Carvalho and Santos, 2016; Grenni et al., 2018). Among the most frequently consumed drugs globally are antibiotics, analgesics, and anti-inflammatory medications. As a result, there has been growing concern over the presence of water-soluble, biologically active micropollutants—also known as pharmaceutical active compounds (PhACs)—in various aquatic environmentsWhile these substances are essential for human health, they are also widely utilized in veterinary practices, particularly in intensive livestock farming, where they are used to prevent and treat diseases in animals and to enhance productivity (Blancoet al., 2017; Ekpeghere et al., 2017; Gros et al., 2019; Ramírez-Morales et al., 2021).

Once administered, these pharmaceutical substances are typically excreted through human and animal waste in either their original form or as metabolites (Sui et al., 2015; aus der Beek et al., 2016). Traces of these compounds have been detected not only in raw and treated wastewater but also in various water bodies, including rivers, lakes, and marine ecosystems. Additionally, groundwater contamination hasbeen observeddue to theinfiltration of effluentthrough soil during recharge processes (Deo, 2014; Furlong et al., 2017; Ojemaye and Petrik, 2018; Reis-Santos et al., 2018; Fekadu et al., 2019; Letsinger et al., 2019; Zainab et al., 2020). A major challenge lies in the inefficiency of conventional wastewater treatment plants tocompletely remove these emerging contaminants (ECs).

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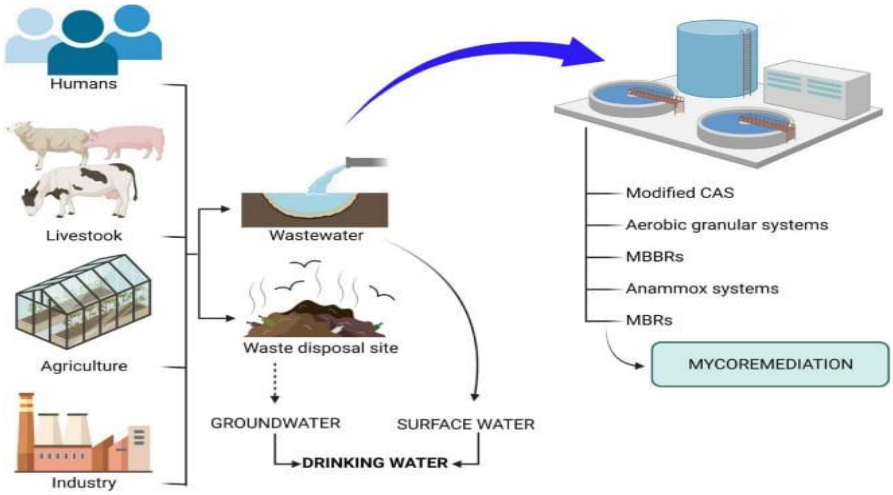
Consequently, innovative treatment methods—especially those involving mycoremediation—are being explored toenhance removal efficiency (Danner et al., 2019). The significance of researching pharmaceutical pollutants stems from the dramatic growth in their global use and their potential to persist in both aquatic and terrestrial ecosystems. In the context of wastewater treatment and environmental safety, pharmaceutical substances are categorized as ECs due to insufficient disposal regulations and limited understanding of their long-term ecological impacts (Dhangarand Kumar, 2020; Valdez-Carrillo et al., 2020; Chaturvedi et al., 2021b; Rathi et al., 2021; Barber et al., 2015; Ahmed et al., 2017). Furthermore, the widespread availability of certain medications without prescription or proper regulatory oversight contributes to their pervasive distribution in the environment (Gil et al., 2017). Given the classification of pharmaceuticals as ECs and the ongoing development of new PhACs, this review seeks to provide a comprehensive summary of commonly detected pharmaceutical pollutants in surface and groundwater. It also highlights their environmental implications and evaluates recent progress in bioremediation techniques, with a particular focus on mycoremediation, as a supplementary approach for improving the performance of wastewater treatment plants.

Methodology

This review was conducted through a comprehensive analysis of peer-reviewed literature related to the presence, sources, and impacts of pharmaceutical compounds in aquatic environments. Scientific databases including ScienceDirect, SpringerLink, PubMed, and Google Scholar were used to retrieve relevant research articles published between 2004 and 2021. Keywords such as "pharmaceutical pollution," "emerging contaminants," "surface water," "groundwater," "wastewater treatment," and "bioremediation of pharmaceuticals" were used during the search process.

Articles were selected based on their relevance to the following themes: (i) detection of pharmaceutical active compounds (PhACs) in water bodies, (ii) sources of pharmaceutical pollutants such as municipal wastewater, livestock waste, and industrial discharge (Kim et al., 2008; Barrios-Estrada et al., 2018), and (iii) limitations of conventional wastewater treatment plants in removing these contaminants (Danner et al., 2019). Special attention was given to studies discussing bioremediation and mycoremediation as sustainable treatment strategies (Dhangar and Kumar, 2020; Chaturvedi et al., 2021b).



Search Strategy:

To gather relevant data and studies for this review, a systematic search was conducted across multiple academic databases including ScienceDirect, SpringerLink, PubMed, and Google Scholar. The search focused on peer-reviewed articles published between 2004 and 2021 to ensure inclusion of both foundational and recent research.

Key search terms and Boolean operators used included

"pharmaceutical pollution" AND "aquatic environment"

"emerging contaminants" AND "surface water" OR "groundwater"

"wastewater treatment" AND "pharmaceutical residues"

"bioremediation" OR "mycoremediation" AND "pharmaceuticals"

"antibiotic resistance genes" AND "treated wastewater"

The inclusion criteria were:

Studies written in English

Focus on the detection, sources, or impact of pharmaceuticals in aquatic system

Research on biotic/abiotic degradation and resistance gene transmission

Case studies, experimental research, and review papers

Exclusion criteria involved:

Non-peer-reviewed articles

Studies not related to environmental pharmaceuticals

Papers lacking clear methodology or relevant data

Priority was given to studies that provided quantitative data, detailed environmental impact assessments, or discussed sustainable remediation strategies such as bioremediation (Dhangar and Kumar, 2020; Chaturvedi et al., 2021b).

Criteria for Inclusion and Exclusion:

This review included peer-reviewed articles published in English, focusing on bioremediation techniques used to remove pharmaceutical pollutants from aquatic environments. It prioritized recent studies (mainly from the past decade) that explored microbial, algal, and enzymatic approaches. Research unrelated to pharmaceutical contaminants, not involving aquatic systems, or lacking a bioremediation focus was excluded. Conventional treatment studies without biological components were also left out (Ram et al., 2021).

Search Results:

According to the comprehensive review by Ram et al. (2021), there has been a significant rise in scientific investigations centered around biological methods for the removal of pharmaceutical pollutants from various aquatic environments. Among the different strategies explored, microbial bioremediation emerged as the most widely studied and efficient approach. This method primarily employs bacteria and fungi, which are known for their robust metabolic versatility and ability to break down a wide range of complex pharmaceutical compounds. These microorganisms can survive in stressful conditions, making them suitable candidates for large-scale environmental applications. In addition, the study discussed the role of algal bioremediation, which harnesses algae to absorb and transform pharmaceutical residues, and enzymatic degradation, which involves the use of isolated enzymes to catalyze the breakdown of pollutants. Although these alternatives show promise, they are still under development and require more research to optimize their efficiency and cost-effectiveness. Furthermore, the review highlighted innovative technologies such as the use of genetically modified microbes and biofilm-based systems, which offer enhanced degradation capabilities and greater stability during treatment processes. The growing attention towards these methods reflects a global trend of adopting greener, more sustainable solutions to tackle the persistent issue of pharmaceutical contamination in water bodies (Ram et al., 2021).

Ram, S., Kumar, R., Singh, V. P., & Tripathi, R. D. (2021). Bioremediation of pharmaceutical pollutants: Recent advances and future perspectives. Journal of Environmental Management, 277, 111402. https://doi.org/10.1016/j.jenvman .2020.111402

Antibiotics:

Continuous discharge of antibiotics into the environment has led to prolonged exposure for both aquatic and soil organisms (Gothwal and Shashidhar, 2015; Bengtsson-Palme and Larsson, 2016). These substances, even at very low concentrations, exhibit toxicity and can produce synergistic effects when combined with other pharmaceuticals or xenobiotic compounds (González-Pleiter et al., 2013). Algae and aquatic plants are particularly vulnerable, with several antibiotics identified as photosynthesis inhibitors that disrupt the photosystem II electron transport chain and elevate oxidative stress levels (Brain et al., 2008; Brausch et al., 2012; Nie et al., 2013). Meanwhile, microorganisms such as bacteria and fungi are developing resistance to these agents due to repeated exposure to sub-lethal concentrations across generations (Kollef et al., 2017; Willyard, 2017; García et al., 2020; Wang et al., 2020). Invertebrates like Hydra attenuata and crustaceans such as Artemiasalina, Daphnia magna, and Ceriodaphniadubia tend to show low acute toxicity in response to antibiotics (Wollenberger et al., 2000; Kołodziejska et al., 2013; Minguez et al., 2016). In contrast, fish generally display toxic effects only at elevated antibiotic concentrations, and in some cases, no toxicity is observed at all (Santos et al., 2010; Brausch et al., 2012; Minguez et al., 2016; Table 2).

A significant environmental concern is the proliferation of antibiotic resistance genes (ARGs), which provide bacteria with resistance mechanisms and can spread either through the growth of resistant strains or via horizontal gene transfer. These ARGs are now recognized as emerging pollutants in the environment (Nadimpalli et al., 2020; Hu et al., 2021). Although wastewater treatment significantly reduces ARG levels compared to untreated water, downstream aquatic environments can still experience an increase in ARG prevalence due to mobile genetic elements like conjugative plasmids, integrative and conjugative elements, transposons, and integrons (Amos et al., 2018; Freeman et al., 2018; Jäger et al., 2018; Karkman et al., 2018; Liu et al., 2018). These vectors are highly efficient at spreading ARGs, often leading to multi-drug resistance. Among the most commonly identified genetic markers in both effluents and aquatic systems is the Class 1 integron-integrase gene (intI1), which is closely linked with ARGs and plays a key role in horizontal gene transfer (Gillings et al., 2015; Cacace et al., 2019).

Endocrine disruptors pose significant risks to the health of both humans and animals by interfering with the endocrine system. They can imitate or block the action of natural hormones, thereby disrupting the normal functioning of various organs (Vieira et al., 2020). While these compounds have been widely researched in humans, their impact on the environment remains comparatively underexplored. In humans, exposure to endocrine disruptors has been linked to reproductive issues, thyroid dysfunction, Alzheimer's disease, obesity, and certain types of cancers, including prostate, breast, and endometrial cancer (Heindel et al., 2015; Forte et al., 2016, 2019; Braun, 2017; Nadal et al., 2017; Marotta et al., 2019). Similarly, in natural ecosystems, these substances can impair reproductive health, reduce hatchability, alter vitellogenin levels, and promote feminization in wildlife, ultimately posing a threat to biodiversity (Vieira et al., 2020; Akhbarizadeh et al., 2021)

Antiretrovirals:

Unlike many other pharmaceuticals, antiretrovirals—despite being commonly found in wastewater—are insufficiently monitored, though a few studies haveaddressed their presence (Ngumba et al., 2016; Abafe et al., 2018; Rimayi et al., 2018; Mosekiemang et al., 2019; Mtolo et al., 2019). These compounds can persist through wastewater treatment processes and potentially contaminate drinking water sources, posing serious ecotoxicological risks to human health (Hawkins, 2010; Ncube et al., 2018; Mlunguza et al., 2020). A major concern today is the potential development of drug-resistant HIV strains in individuals exposed to water contaminated with antiretroviral residues (Daouk et al., 2015; Ncube et al., 2018; Table 2).

Anticancer Drugs

Although anticancer medications are intended to target rapidly dividing tumor cells, many of them lack specificity and also damage healthy cells (Chari, 2008). As a result, they may cause a wide range of harmful effects—including cytotoxicity, genotoxicity, mutagenicity, and teratogenicity—in virtually any eukaryotic organism (Kümmerer et al., 2000; Johnson et al., 2008). Due to these risks, anticancer drugs are recognized as significant environmental contaminants, particularly threatening vulnerable groups like children, pregnant women, andthe elderly (Rowney et al., 2009). Long-term exposure over two generationsof Danio rerio (zebrafish) has been shown to induce liver and kidney tissue damage, compromise DNA integrity, and trigger widespread alterations across the organism's transcriptome (Kovács et al., 2015; Gajski et al., 2016; Table 2).

Pharmaceutical residues are commonly present in the environment as complex mixtures. Even when individual substances occur at low concentrations, their combined or "cocktail" effect can have substantial ecotoxicological impacts (Heath et al., 2016). Although many studies have focused on individual species and tested single drugs or small sets of them, there remains a lack of research addressing the collective impact of pharmaceuticals on entire communities or multiple populations. Such studies would be vital for understanding broader ecological risks, including the "domino effect" across trophic chains—where the death of a key group due to a toxic drug may disrupt the entire ecosystem through bioaccumulation or food web collapse.

Development of Bioremediation Technologies:

Enhancing technologies for removing pharmaceuticals from wastewater has become a crucial objective, as traces of these substances have been detected globally in the effluent from wastewater treatment plants (WWTPs), as well as in surface water, groundwater, and even drinking water (Bartolo et al., 2021). Although present at very low concentrations—ranging from nanograms to micrograms per liter—these compounds can still pose risks due to their biological activity, which may lead to chronic toxicity, bioaccumulation, and biomagnification (Ruan et al., 2020). Furthermore, microplastics have been identified as carriers for pharmaceutical contaminants, thereby increasing exposure potential (Santos et al., 2021). Since conventional wastewater treatment methods often fail to fully remove these substances (Reyes et al., 2021), there is growing interest in the development of alternative treatment solutions, particularly biological transformation approaches considered as environmentally friendly technologies (Domaradzka et al., 2015). Incorporating bioremediation into standard WWTP processes is a promising step, offering a less environmentally invasive and more cost-effective solution than chemical treatments, while also helping detoxify harmful substances. Continued research and optimization efforts may eventually enable the complete removal of these pollutants, preventing their release into ecosystems.

Wastewater containing pharmaceutical active compounds (PhACs) and their byproducts is typically processed using various purification systems. The effectiveness of biological treatments—particularly those using microbial agents—for drug remediation has been demonstrated (Kebede et al., 2018). Due to inherent limitations, biological systems are often integrated with advanced methods alongside conventional activated sludge (CAS) systems (Crini and Lichtfouse, 2019). Some of the advanced biological approaches include modified CAS, aerobic granular sludge systems, moving bed bioreactors (MBBRs), anammox processes, and membrane bioreactors (MBRs) (Grassi et al., 2012). However, certain methods like MBRs may produce byproducts such as biosolids or sewage sludge, which require additional handling. After stabilization steps like thermophilic anaerobic digestion, this sludge may undergo processes like composting—potentially introducing PhACs and their derivatives into various trophic levels when the compost is used to amend soil (Marcoux et al., 2013).

Bioremediation, which employs native microbial monocultures, microbial consortia, or bioaugmentation techniques, has long served as a sustainable solution for addressing pollution caused by human activity (Ahumada-Rudolph et al., 2021). This method is advantageous due to its reduced demand for hazardous chemicals, energy, and time, and its relatively low cost compared to alternative technologies (Azubuike et al., 2016). A key benefit of bioremediation is that it chemically transforms pollutants, rather than merely relocating them to a different environment (Mashi, 2013). One major challenge, however, is the slow pace of the remediation process, which often falls short of treatment capacity demands. Despite this, ongoing efforts to improve efficiency and reduce retention times are being made and will be discussed below in relation to mycoremediation. Research progress in plant- and algae-based pharmaceutical remediation (phyto- and phycoremediation) has also been significant, as reviewed in other studies (Vilvert et al., 2017; Rao et al., 2019; Kaloudas et al., 2021; Kurade et al., 2021), and thus is not covered here.

Beta-Blockers and Psychoactive Drugs:

Carbamazepine, a pharmaceutical compound that is poorly removed by conventional wastewater treatment processes, is frequently found in environmental waters (Ekpeghere et al., 2018). Research has shown that the white-rot fungus Trametesversicolor can effectively degrade this compound. In experiments using flasks, Jelic et al. (2012) reported 94% degradation of carbamazepine at a concentration of 9 mg/L within six days. When the concentration was reduced to 50 µg/L, the degradation efficiency dropped to 61% after seven days. The same researchers tested the fungal degradation in an air-pulsed fluidized bed bioreactor under both batch and continuous operations. In batch mode, carbamazepine removal reached 96% in just two days, a result attributed to better process control, including glucose supply, pH regulation, and aeration. In continuous mode, the removal rate declined to 54% when treating an inflow concentration of 200 µg/L (Jelic et al., 2012). Pleurotusostreatus, another species of white-rot fungus, was able to remove 68% of carbamazepine over seven days in liquid culture, although degradation halted after that point (Buchicchio et al., 2016).

Trichodermaharzianum, a filamentous fungus, demonstrated a higher efficiency than P. ostreatus, degrading 72% of carbamazepine at environmentally relevant levels (4 µg/L) (Buchicchio et al., 2016). Phanerochaetechrysosporium, tested in a non-sterile bioreactor setup, degraded up to 80% of carbamazepine (5 mg/L) when fed with a diluted synthetic medium (Zhang and Geißen, 2012). In a fed-batch stirred bioreactor, the same fungus removed up to 60% of carbamazepine at 0.5 mg/L but showed no degradation capacity for diazepam at concentrations of 0.25–0.5 mg/L (Rodarte-Morales et al., 2012a). However, when

immobilized in polyurethane foam within a fixed bed reactor, P. chrysosporium significantly enhanced the breakdown of both carbamazepine and diazepam (Rodarte-Morales et al., 2012b).

Although lab-scale studies using flasks and bioreactors have shown high potential for fungal degradation of beta-blockers and psychoactive drugs, the next critical step is conducting pilot- or full-scale trials. These will help determine whether fungal bioremediation remains effective and economically viable when scaled up for real-world application in wastewater treatment plants.

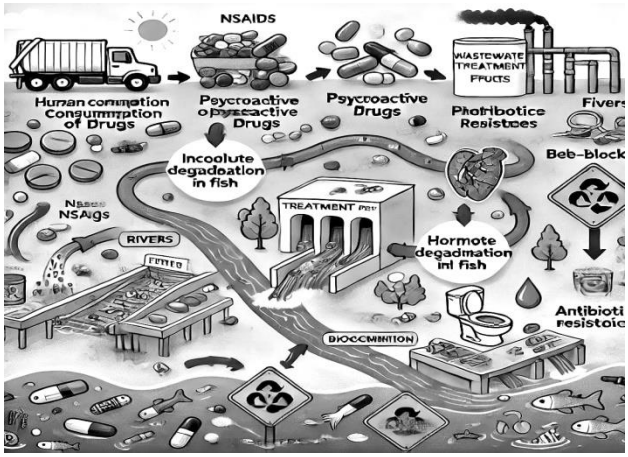
Non-steroidal Anti-inflammatory Drugs and Analgesics:

Efforts to remove NSAIDs using single-strain bacterial cultures have been largely unsuccessful so far (Wojcieszyńska et al., 2014). However, some success has been reported when using bacterial consortia within wastewater treatment plants. For instance, the removal of acetaminophen in a membrane bioreactor (MBR) was attributed primarily to heterotrophic bacteria, suggesting that microbial consortia within MBRs may serve as effective post-treatment systems for pharmaceutical-laden effluents (De Gusseme et al., 2011). Nevertheless, as observed in conventional activated sludge (CAS) systems, these microbial communities are often undefined and subject to change depending on wastewater characteristics, potentially leading to reduced treatment efficiency. To fully understand the role of bacterial consortia in bioreactors, extended on-site studies are necessary to examine their composition and stability, along with predictive modeling to assess how microbial shifts could impact remediation outcomes.In contrast, fungi have shown strong promise for the bioremediation of NSAIDs. Trametesversicolor has proven particularly effective, achieving 55% removal of diclofenac (0.3–1.5 mg/L) in a continuous MBR with a hydraulic retention time of 24 hours (Yang et al., 2013) (Asif et al., 2017; Tínma et al., 2021). The edible mushroom Lentinula edodes (shiitake) has also shown the ability to degrade anti-inflammatory drugs like piroxicam, although exact remediation rates were not specified (Muszyńska et al., 2019).

Penicilliumoxalicum completely eliminated diclofenac (29.6 mg/L) within 24 hours (Olicón-Hernández et al., 2019). Similarly, Mucorhiemalis f. irnsingii, isolated from German groundwater, achieved 90–97% removal of diclofenac (10–50 µg/L) over six days (Esterhuizen-Londt et al., 2017). This fungus was also effective in degrading acetaminophen at up to 50% after just one day of exposure to concentrations as high as 20 µg/L (Esterhuizen-Londt et al., 2016b,a). Although diclofenac removal plateaued after 24 hours, maintaining optimal pH levels helped sustain the process (Esterhuizen et al., 2021).

Phanerochaetechrysosporium demonstrated even greater efficacy in removing acetaminophen, achieving 97% and 99% elimination of 250 µg/L after 3 and 7 days, respectively. Interestingly, co-culturing with M. hiemalis reduced the overall remediation efficiency compared to using P. chrysosporium alone (Esterhuizen et al., 2021).

Olicón-Hernández et al. (2020) also evaluated P. oxalicum for its ability to degrade a mixture of common analgesics (acetaminophen, diclofenac, ibuprofen, ketoprofen, and naproxen) at 50 µM each. Higher removal rates were achieved in bench-scale fluidized bioreactors compared to flasks, and with the addition of glucose, complete degradation of all five drugs was observed within eight days. In another study, P. chrysosporium effectively removed up to 99% of diclofenac, ibuprofen, and naproxen (0.8 mg/L each) in a fed-batch stirred bioreactor (Rodarte-Morales et al., 2012a).In continuously stirred setups, it still achieved up to 95% degradation of the same drugs at concentrations of 1 mg/L. These lab-scale findings underscore the significant potential of fungal bioremediation for NSAIDs and analgesics, though further scale-up studies are essential to confirm feasibility and efficiency in real-world wastewater treatment systems.



Endocrine Disruptors

Hamid and Eskicioglu (2012) reviewed how well full-scale wastewater treatment plants (WWTPs) using activated sludge systems remove estrogenic hormones. They found that systems designed with nutrient removal capabilities were able to break down more than 90% of these hormones in most cases. Fungi have also shown strong potential in hormone degradation. For instance, Lentinula edodes was reported by Muszyńska et al. (2018) to completely eliminate testosterone and 17α-ethinylestradiol (EE2) within 21 days. Another fungus, Pleurotusostreatus HK 35, achieved up to 90% degradation of 17β-estradiol (E2) within 12 days when used alongside natural microbial communities from WWTPs under various bioreactor setups (Křesinová et al., 2018). Moreover, Trichodermacitrinoviride AJAC3 removed 99.6% of E2 (initial concentration 200 mg/L) in just four days due to the production of lignin-degrading enzymes (Chatterjee and Abraham, 2019). In another study, the polypore fungus Pycnoporus sp. SYBC-L3 reduced E2 levels by 78.4% in poultry litter through solid-state fermentation, enhanced by the addition of citric acid and

lignocellulosic material to stimulate laccase activity (Liu et al., 2016). This technique could be adapted for improving hormone removal from wastewater.

Although fungal methods sometimes yield higher removal efficiencies than conventional activated sludge (CAS) processes, direct comparison is difficult. The fungal studies were conducted in lab settings, whereas the CAS studies took place in real-world WWTPs. Laboratory conditions eliminate many factors that can influence effectiveness, and they also typically focus on single contaminants. In contrast, wastewater contains a mixture ofpharmaceuticals and other chemicals, which can interact and impact removal efficiency (Chatterjee and Abraham, 2019). Fungi also offer hormone removal via bioabsorption. L. edodes and Agaricusbisporus stalks were able to absorb 100% of EE2 in 20 and 30 minutes respectively, while Shiitake growing substrate absorbed 80% (de Jesus Menk et al., 2019). Despite the promising outcomes from these fungal applications, limited research has been published in recent years. Further studies are needed to advance this approach and address the environmental risks posed by untreated hormone residues from WWTPs.

Isolated Fungal Enzymes:

Isolating fungal enzymes offers a way to address some of the challenges associated with mycoremediation. Ligninolytic enzymes, in particular, are well known for their ability to break down a wide variety of persistent pharmaceutical compounds (PhACs). However, large-scale fungal cultivation is hindered by lengthy incubation periods, extended growth phases, and spore formation. As a result, researchers have increasingly focused on using crude extracts or purified enzymes instead (Stadlmair et al., 2018). Despite this, the high cost of enzyme purification remains a major limitation.Commercial laccases derived from Trametesversicolor have shown effectiveness in degrading individual drugs like diclofenac, trimethoprim, carbamazepine, and sulfamethoxazole, but their efficiency drops significantly when treating combinations of these drugs (Alharbi et al., 2019). Laccases isolated from Bjerkandera species have been found effective in degrading acetaminophen across a wide pH range (Kang et al., 2021). Similarly, when laccases from Trameteshirsuta were immobilized and used, higher removal rates were observed for carbamazepine and acetaminophen in individual settings (40% and 70%) compared to mixtures (5% and 25%) (Hachi et al., 2017).

In another example, laccases (2,000 U/L) extracted from Myceliophthorathermophila were able to degrade 94.1% of estrone (E1) and 95.5% of 17β-estradiol (E2) within 8 hours in a fed-batch bioreactor, aided by a natural mediator. When applied in an enzymatic membrane reactor (EMR) with a stirred-tank design, the removal efficiency increased further—up to 95% for E1 and nearly complete degradation of E2 (Lloret et al., 2010). This highlights the influence of bioreactor design on enzyme-based remediation efficiency. Becker et al. (2017) also reported successful degradation of estrogenic compounds (E1, E2, and EE2) within mixtures usingimmobilized laccases from T. versicolor and M. thermophila, achieving removal rates of 83% and 87% within 6 hours. Likewise, Pycnoporussanguineus laccase (1,642 U/mL) achieved a 96.5% reduction of 10 mg/L EE2 in 8 hours, supported by the addition of 1% (v/w) to the fungal culture to boost enzyme production prior to extraction (Golveia et al., 2018).Isolated enzymes offer several advantages: they eliminate the lag phase of fungal growth, reduce sludge formation, and allow for greater process control (Jebapriya and Gnanadoss, 2013). However, in addition to their high production cost, they may be less effective in some cases. Nguyen et al. (2014) showed that whole fungal cells outperformed isolated enzymes in degrading trace organic pollutants, likely due to biosorption and the combined activity of intracellular and surface-associated enzymes.

Conclusion:

Growing concern has emerged in recent years regarding the environmental impact of pharmaceuticals and the urgent need for their effective removal from wastewater. Although these compounds are designed to support human and animal health, their widespread and uncontrolled use can result in lasting harm to ecosystems and public health. It is therefore essential to develop updated regulations that align with sustainable practices and responsible consumption. Environmentally friendly solutions such as mycoremediation are being explored for their potential to degrade pharmaceutical pollutants efficiently, yet most of these methods remain at the laboratory scale, with limited application in real-world wastewater treatment plants. Despite advancements in the development and optimization of new remediation techniques, their implementation continues to lag behind the rapid pace of pharmaceutical innovation. Promising technologies like genetic engineering, including CRISPR-Cas9, offer potential by enabling the introduction of specific metabolic genes targeting persistent compounds, but these tools are still in the early stages. Continued research is crucial to advance these innovative strategies and effectively combat the growing issue of pharmaceutical contamination in the environment.

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Conflicts of interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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