Vol. 19 (Supplementary Issue 3A), September 2025, ISSN 0973-8916 (Print)., 2230-7303 (Online)
10.5530/ctbp.2025.3s.14

Sustainable Degradation of Plastic and Pharmaceutical Waste using Fungal Strains Based Strategies

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Abstract

The persistent accumulation of plastic and pharmaceutical waste in terrestrial and aquatic ecosystems presents a significant environmental challenge. Conventional treatment methods—such as landfilling, incineration, and chemical recycling—are often limited by inefficiency, high energy demands, and secondary pollution. In this context, fungal-based bioremediation has emerged as a sustainable, cost-effective, and eco-friendly alternative. This review comprehensively explores the role of filamentous and ligninolytic fungi in the degradation of synthetic polymers and pharmaceutically active compounds, with a focus on their enzymatic mechanisms, environmental adaptability, and metabolic versatility. Case studies involving strains such as *Fusarium solani*, *Penicillium brevicompactum*, *Bjerkanderaadusta*, and *Fomitopsismeliae* demonstrate high degradation efficiencies through enzymatic pathways involving laccases, peroxidases, and hydrolases. We also examine the environmental and economic implications of fungal bioremediation through the lens of life cycle assessment (LCA), industrial feasibility, and regulatory alignment. Despite challenges in scalability and environmental control, future prospects include genetic engineering, bioreactor development, and microbial consortia for enhanced biodegradation. This review positions fungi as pivotal agents in the global transition toward circular economy models and sustainable waste management.

Keywords: Fungal bioremediation, Plastic degradation, pharmaceutical waste, Laccases, Peroxidases, Mycoremediation, Environmental sustainability, Wastewater treatment, Microbial enzymes, Circular economy

Abbreviations:
LCA- Life Cycle Assessment
PE- Polyethylene
PP- Polypropylene
PS- Polystyrene
PU- Polyurethane
PET- Polyethylene terephthalate
PCL- Polycaprolactone
MnPsandLiPs- Manganese Peroxidases and Lignin Peroxidases
TCA- Tricarboxylic Acid
LDPE- Low-density polyethylene
ROS- Reactive oxygen species
Ru- Rubber
FTIR-Fourier Transform Infrared Spectroscopy
SEM- Scanning Electron Microscope
PhACs- Pharmaceutically active compounds
NSAIDs- Non-steroidal anti-inflammatory drugs
DCF- Diclofenac
WWTPs- Wastewater treatment facilities
DDT- (1,1,1-trichloro-2,2-bis (4-chlorophenyl) ethane)
DDE- (1,1-dichloro-2,2-bis (4-chlorophenyl) ethylene)
DDD- (1,1dichloro-2,2-bis (4-chlorophenyl) ethane)
DBP- (4,4-dichlorobenzophenone)
DBH- (4,4-dichlorobenzhydrol)
DDMU- (1-chloro-2,2-bis (4-chlorophenyl) ethylene)

1. Introduction

Plastics are synthetic polymers with a high molecular weight, consisting of long

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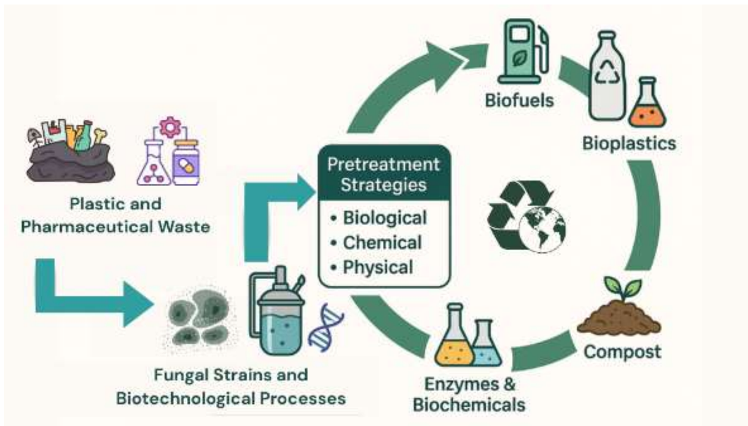

Graphical Abstract

carbonated chains typically derived from petroleum,natural gas, and coal. Over the last few decades, these materials have become so deeply embedded in our daily lives that it is hard to imagine living without them(1). Plastics are used across numerous sectors, such as food packaging, home appliances, construction, transportation, healthcare, and leisure. Their extensive use is largely due to their unique advantages over other materials, including high strength, light weight, long-lasting durability, ease of production, cost-effectiveness, and resistance to microbial decay(2).However, over-usage of plastic and improper disposal methods has created detrimental impacts on the environment. The waste generated by the usage of plastic has become omnipresent in natural and urbanenvironments(3). The most frequently used plastics, polyethylene (PE), polypropylene (PP), and polystyrene (PS), polyester, (Figure 1) are of great concern due to their durability, hydrophobicity, and resiliency to natural degradation mechanisms. Plastics can exist for decades or centuries in terrestrial and marine habitats, accumulating in landfills, water tributaries, and natural settings to contribute to microplastic pollution and disrupt ecological stability(4).

Traditional methods of managing plastic waste include landfill disposal, incineration, and mechanical recycling (Figure 2). Each of these practices has

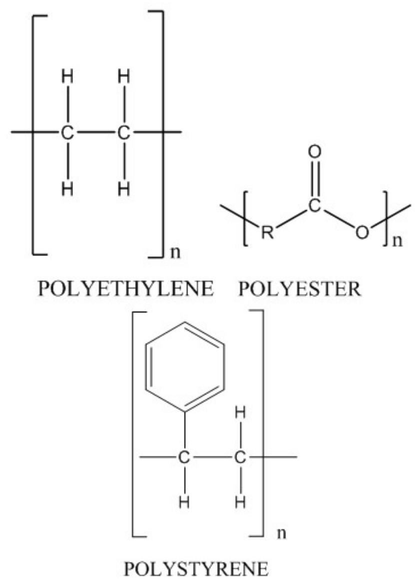

Fig. 1: Different types of plastics present in environment as pollutant

important limitations. Landfill sites can take up considerable land space and can leach toxins into soil and water. Incineration produces greenhouse gases and hazardous byproducts, compounding climate change(4,5). Although mechanical recycling is effective for repurposing plastic waste, it can still have issues with contamination, quality, or energy use. As a result of these difficulties, researchers have begun looking

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for and studying new, more sustainable waste management solutions to plastic waste(6).

In recent years, biological degradation using microorganisms has gained considerable momentum as a more environmentally positive alternative. Fungi are microorganisms that break down the bulk of organic chemicals in the environment. They have demonstrated remarkable capability in degrading diverse pharmaceuticaland personal care compounds, making them highly valuable for the bioremediation ofemerging contaminants in wastewater because they provide necessary extracellular enzymes for degrading the complex polymers

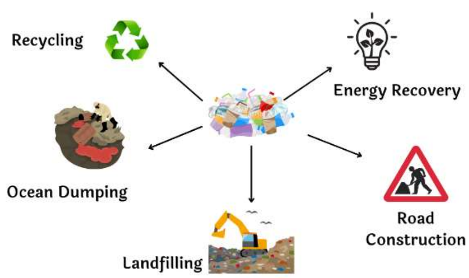

Fig. 2: Different uses of plastic waste to control the pollution

in plastic waste(7). Fungi have been utilized in water and soil bioremediation techniques since the1980s. Moreover, research has indicated that fungi can also employ biosorption to remove pharmaceutical and personal care substances. Several reports have shown the efficientremoval of pharmaceutical compounds via filamentous fungi, achieving removal rates ranging from 78% to 100% in synthetic wastewater media. Some fungi species, such as Aspergillus, Penicillium, Fusarium, and Pleurotus fungi, have shown this ability to degrade various synthetic plastics via hydrolytic and oxidative mechanisms. Fungi especially have some fascinating characteristics of adaptability, allowing them to colonize the different environments of soil, marine environments, and plastic waste. Fungi's practical ability to act in varying environment conditions is what scientists continue to study as a tool for degradation of plastic wastes from a bioremediation approach(8).

This review offers a comprehensive overview of the role fungi play in the biodegradation of plastics and pharmaceutical waste, aiming to consolidate current knowledge and present it in a structured and accessible manner (Figure 3). It delves into

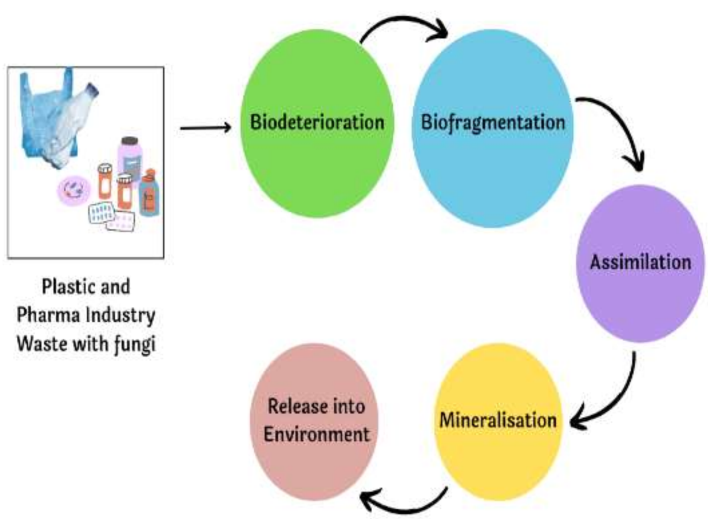

Fig. 3: General process of degradation of plastic and pharma waste by fungal strains

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the underlying mechanisms by which fungi break down synthetic polymers, emphasizing both hydrolytic and oxidative enzymatic pathways.Beyond the biological mechanisms, the review discusses the environmental and physicochemical factors that influence fungal degradation efficiency, such as pH, temperature, oxygen availability, and nutrient levels. It also examines practical applications of fungal biodegradation in real-world scenarios, such as soil and aquatic environments, wastewater treatment facilities, and industrial waste management systems. It highlights the current challenges in scaling up fungal bioremediation efforts, including limitations in degradation rates, potential risks of introducing foreign fungal species, and gaps in understanding enzyme-plastic interactions. It underscores the need for further research into genetic engineering, microbial consortia, and bioprocess optimization to enhance the efficacy and applicability of fungal bioremediation strategies.With continued research and innovation, fungi may become a cornerstone in the fight against plastic pollution, offering a sustainable and eco-friendly alternative to conventional disposal and recycling methods.

2. The Fungal Kingdom: A Biotechnological Asset

Fungi are a significant biotechnological asset due to their diverse metabolic capabilities and long history of use. For centuries, they have been integral to processes like baking and brewing using yeasts such as *Saccharomyces cerevisiae*. Modern biotechnology leverages fungi for the production of numerous industrial products, including enzymes like amylases and cellulases derived from *Aspergillus* and *Trichoderma*, and organic acids such as citric acid produced by *A. niger*.

Furthermore, fungi are crucial in the pharmaceutical industry, serving as the source for life-saving antibiotics like penicillin from *Penicillium chrysogenum* and other pharmaceutical products such as cyclosporin from *Tolypocladiuminflatum*. Advances in genomics and Recombinant DNA technology have further enhanced their industrial potential, allowing for genetic modification to improve yields and produce novel compounds. The term "mycotechnology" encompasses these various roles of fungi in biotechnology and their impact on the economy(8).

Fungi exhibit significant biodegradation capabilities, positioning them as crucial agents in environmental sustainability and making them a valuable focus for review. Their diverse enzymatic machinery allows them to break down a wide array of organic pollutants, contributing to the detoxification of contaminated environments.

Fungi use enzymatic action, mechanical penetration, and metabolic assimilation to break apart synthetic plastics, making them useful for bioremediation. It secretes extracellular enzymes that degrade the complex polymer into constituents that can then be used for energy and biomass. Degradation can occur in three general phases: surface colonization, enzymatic oxidation; the assimilation into fungal biomass.Furthermore, soil fungi have been shown to play a vital role in the disintegration of pesticides within the soil environment. Studies have investigated the ability of pure fungal isolates to degrade herbicides like atrazine.

3. Fungal Strains In Plastic Industry Waste Management

With the growing volumes of world plastic production and the subsequent plastic waste collection, there is a necessity to pursue quick and efficient measures to protect nature and, by extension, the whole world. This is also aggravated by the very slow natural processes of degradation of the different forms of plastic. It is therefore imperative to investigate ways by which the degradation of plastics can be accelerated. Some of the suggested alternatives are photo-degradation (light-induced degradation), chemical degradation, thermal degradation(10) (heat-induced degradation),

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irradiation by using gamma rays, and biodegradation (additives or microorganisms-induced degradation). Biodegradation has been the most preferred option as it is an environment-friendly process.

Fungi produce a variety of oxidative and hydrolytic enzymes that cause the depolymerization of a polymer chain into smaller oligomers and monomers(11). Fungal enzymes that have significance in the degradation of plastics include:

•Laccases: Copper-containing oxidases, laccases are essential in the degradation of polyethylene (PE) and polystyrene (PS), where they oxidize aromatic/phenolic structures that further facilitate degradation via oxidation by laccases or hydrolysis by other enzymes or microorganisms.

•Manganese Peroxidases (MnPs) and Lignin Peroxidases (LiPs): Originally described in the degradation of lignin, these peroxidases have been described to degrade a variety of plastic polymers, mainly the more complex aromatic polymer polyurethane (PU) and polyethylene terephthalate (PET).

•Lipases and Esterases: These enzymes hydrolyze ester bonds in PET and polycaprolactone (PCL), leading to depolymerization of the polymer chain and potentially uptake by microorganisms.

After enzymatic degradation, fungi take up smaller degradation products such as oligomers and monomers into their metabolic processes. These products are converted via the tricarboxylic acid (TCA) cycle to generate energy and biomass (Figure 4). Certain fungal species, such as *Aspergillus flavus* and *Penicillium simplicissimum*, have been shown to utilize plastic degradation byproducts as their only carbon source, indicating their potential use in strategies for plastic bioremediation(12).

Numerous environmental factors influence the efficacy of fungal plastic degradation including:

•Temperature: Enzymatic activity in fungi tend to occur optimally between 25°C and 40°C, and some thermophilic fungi can degrade plastics at high temperatures.

•pH Levels: Although some fungal enzymes function over a range of pH levels, enzymes exhibit optimal activity functions under slightly acidic to neutral conditions (pH 5.0–7.0).

•Oxygen Availability: Many oxidative enzymes, including laccases and peroxidases, require the presence of oxygen to breakdown polymer.

•Plastic Type and Additives: The presence of plasticizers, stabilizers, and fillers in commercial plastics may influence fungal colonization and enzyme efficiency.

Understanding these mechanisms provides a basis of use to optimize resulting strategies on plastic degradation via the use of fungi in lieu of current physical and

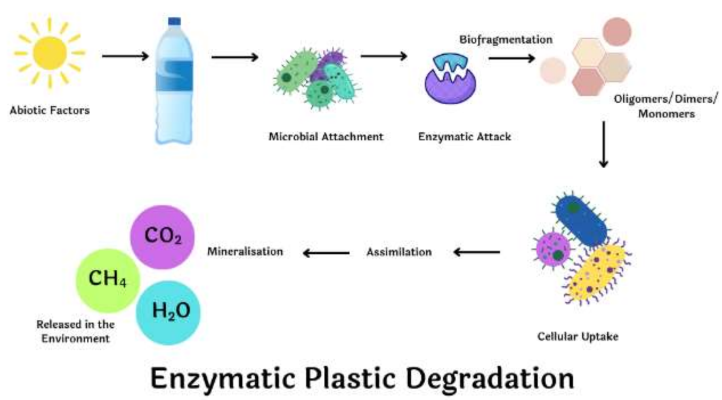

Fig. 4: Degradation of plastic waste through enzymatic process

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chemical plastic waste disposal methods. The knowledge obtained will offer insight on scaling up fungal based plastic degradation, and assist in bioremediation and waste management, if required for persistent market plastics.

3.1 Key Fungal Species Involved in Plastic Degradation

Fungi are important in plastic biodegradation because they secrete extracellular enzymes that degrade complex polymer structures. Several fungal species possess prominent plastic degradation abilities to target a diversity of synthetic polymers. These fungi degrade plastic into smaller compounds while using oxidative and hydrolytic enzymes to breakdown complex plastics (Figure 5). Once degraded, they assimilate the remaining smaller compounds as carbon and energy sources. Below is a summary of important fungal species and their plastic degradation abilities, along with the polymer of focus and enzymes involved in their breakdown (Table 1).

3.1.1 *Cladosporium sphaerospermum*

Cladosporium sphaerospermum is an extremotolerant fungus that can survive extreme environments, including extreme levels of plastic pollution. The fungus has shown to be able to degrade low-density polyethylene (LDPE) efficiently by secreting lignolytic enzymes outside of the cell, in particular laccases and manganese peroxidases. These oxidative enzymes are essential for the breakdown of the long-chain polymer structure of LDPE, as they catalyze oxidation reactions that incorporate functional groups such as carbonyls and hydroxyls in the polymer, followed by the cleavage and fragmentation of the polymer chain.

Table 1: Key fungal enzymes involved in plastic degradation and their target polymer substrates

Enzyme	Fungal Source	Target Plastic	Mechanism
Laccases	*Aspergillus spp., Trametes versicolor*	PE, PS	Oxidation of aromatic rings
Manganese Peroxidase (Mnp)	*Phanerochaete chrysosporium*	PU, PET	Breakdown of complex polymers
Lipases	*Candida rugosa, Fusarium spp.*	PET, PCL	Hydrolysis of ester bonds
Lignin Peroxidase (Lip)	*Phanerochaete chrysosporium*	PU, PET	Cleavage of aromatic structures

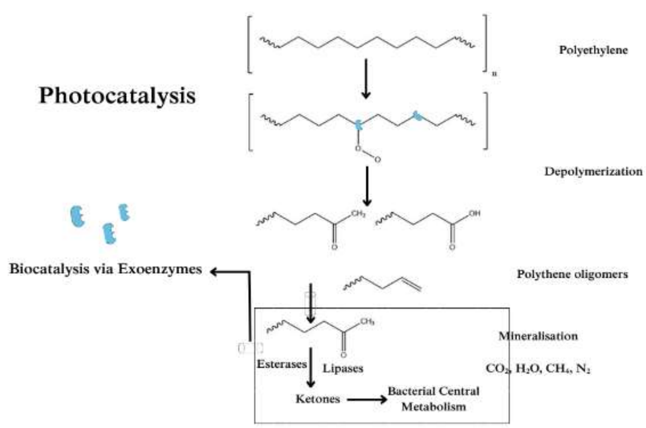

Fig. 5: Degradation of polyethylene via fungal strain *Ascotricha sinuosa*

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3.1.2 *Pleurotus ostreatus*

Pleurotus ostreatus, more commonly referred to as the oyster mushroom, is a ligninolytic fungus well-known for the decomposition of organic feeds, particularly recalcitrant synthetic polymers like plastics. P. ostreatus is a white-rot fungus that produces numerous lignin-modifying enzymes (LMEs), especially laccases, manganese peroxidases (MnPs), and lignin peroxidases (LiPs), that promote oxidative breakdown of complex polyphenolic structures. P. ostreatus can degrade difficult plastics like polyurethane (PU) and polyethylene terephthalate (PET), thus representing a good candidate for biotechnological applications in waste management and bioremediation. Plastic biodegradation by *P. ostreatus* can happen in a series of enzymatic and physicochemical processes. These processes can be categorized as follows:

3.1.3 Acremonium and Penicillium species

Fungal species belonging to the *Acremonium* and *Penicillium* genera have been demonstrated as efficient degraders of microplastics in contaminated habitats (Table 2). These fungi possess enzyme activity that degrades several synthetic polymers, such as polyethylene, polystyrene, and polyurethane. *Acremonium strictum* and *Penicillium chrysogenum* have been shown to degrade microplastics to smaller molecular pieces, enabling greater microbial community assimilation(13). Their ability to occupy varied ecological spaces (soil, water, and extreme habitat) enables their potential use in bioremediation strategies.

3.1.4 *Ascotricha sinuosa*

The fungus *Ascotrichasinuosa* SPF21 has demonstrated potential for degrading polypropylene (PP), particularly from hospital waste, where the presence of plastic is becoming an increasing environmental concern. A common thermoplastic polymer, polypropylene (PP), as well as the material from which PP is made, is found throughout the medical field in syringe manufacture, surgical mask manufacture, IV bags, and plastic disposables. Because of its high molecular weight and hydrophobicity, PP is highly resistant to degradation by natural means; however, *A. sinuosa* SPF21 has been shown to degrade PP through the release and function of oxidative and hydrolytic enzymes. This fungal strain is a promising bioremediation agent for degrading plastic pollution from health care waste (Figure 5).

The table below gives a summary of the different fungal species that are involved in degradation of plastic, along with the enzymes involved in the mechanism.

3.2 Mode of Action and Mechanism of Plastic Degradation

Plastic degradation by fungi proceeds through sequential biochemical phases (Figure 6). Initially, spores attach to microplastic surfaces

Table 2: Comparative analysis of Fungal degraders

Fungal Species	Target Plastic	Enzymes Involved	Notable Features
Pleurotus ostreatus	PU, PET	Laccases, MnP, LiP	Utilizes organic waste for bioremediation
Acremonium strictum	PE, PS, PU	Esterases, Hydrolases	Thrives in microplastic-contaminated environments
Cladosporium sphaerospermum	LDPE	Laccases, MnP	Effective in oxidative degradation of polyethylene
Penicillium chrysogenum	PE, PU	Peroxidases, Esterases	Decomposes plastic in soil and marine settings
Ascotricha sinuosa SPF21	PP (Hospital Waste)	Peroxidases, Hydrolases	Efficient in medical waste degradation

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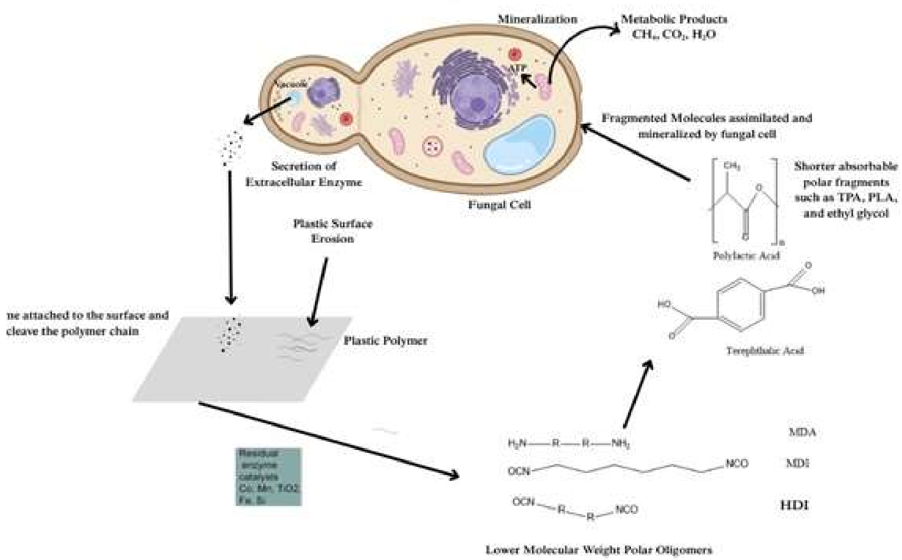

Fig. 6: Schematic diagram showing the different steps involved in the process of degradation of plastics

via hyphal elongation and biofilm formation, aided by the hydrophobic nature of fungal cell walls, particularly on nonpolar plastics like PE and PS. This is followed by enzymatic attack, where species such as *Acremonium* and *Penicillium* secrete laccases, esterases, cutinases, and peroxidases, generating free radicals and reactive oxygen species that destabilize polymer backbones. Subsequent fragmentation introduces oxygenated groups (carbonyl, hydroxyl, carboxyl), enhancing hydrophilicity and breaking polymers into smaller oligomers and monomers, which are further disintegrated by abiotic factors. Finally, these degradation products are assimilated into fungal metabolism, with some entering the TCA cycle, leading to mineralization. Under aerobic conditions, this process yields CO_2 and H_2O, while anaerobic conditions produce CH_4 and organic acids. Understanding these mechanisms underscores the potential of fungal species in bioremediation, with future applications focusing on optimizing growth conditions, enhancing enzyme production, and genetic engineering for large-scale plastic waste treatment.

3.3 Case Studies and Experimental Evidences

Case Study 1: Fusarium spp. — Powerhouse of PU Degraders

Researchers: Sabreen S. Ibrahim, Danny Ionescu, Hans-Peter Grossart *Fungal Strains:Fusariumsolani* MA14, *Fusarium tricinctum* MA24, MA17 *Plastics Tested:* Polyurethane (PU), Polyethylene (PE), Rubber (Ru), Low-Density Polyethylene (LDPE-PB). The *Fusarium* species demonstrated outstanding capability in degrading PU, consuming up to 98.6% of oxygen within 14 days and generating 300–500 ppm CO_2. They showed the ability to colonize and utilize PU as the sole carbon source without any pretreatment or priming with sugars. FTIR spectroscopy confirmed oxidative degradation, and SEM revealed morphological changes such as hyphal twisting and surface deformation (Table 3).

Case Study 2: *Penicillium* spp. — Versatile Biodegraders

Researchers: Sabreen S. Ibrahim and team *Fungal Strains: Penicillium*

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Table 3: Summary of the takeaways from the case studies (Plastic types: PU, PE, Ru, LDPE-PB)

Fungal Strain	Degradation Efficiency	Key Observations (SEM/FTIR)	Remarks
Fusarium solani MA14	Very High (PU: 98.6% O_2 consumed)	Twisting hyphae, oxidative enzyme activity	PU specialist; strong metabolic activity
Fusarium tricinctum MA24, MA17	Very High	Deformed mycelia, high CO_2 production	Fast-growing PU degrader
Penicillium brevicompactum FBP5	High	Indentations on hyphae, ester and aldehyde peaks (FTIR)	Multi-polymer efficient, strong oxidative profile
P. crustosum FBSL1	High	Altered morphology, sulfonate and ether group presence	Excellent for PU and Ru degradation
Botryotiniacinerea EN41	High	Twisted hyphae, sulfonate and alcohol group formation	Versatile and consistent performer
Trichoderma harzianum IS2	High	Hyphal protrusions, amines and alcohols detected	Robust and fast colonizer
Alternaria alternata EN22	Moderate	Mycelial shrinkage, oxidative degradation signs (PE)	Potential PE colonizer
Cladosporium tenuissimum IS28	Moderate to High	Swollen nodes, ester hydrolysis observed	Variable efficiency among strains
Cladosporium cladosporioides FBP8	Moderate	Indented surface, alcohol/ester breakdown	Mild PU degradation, lower overall impact
Scedosporium boydii A1	Low to Moderate	Decrease in protoplasm, aldehyde functional groups	Limited degradation capacity
Psathyrella sp. A18	Low	Minimal activity, slight deformation	Weakest PU activity in study

brevicompactum FBP5, *Penicillium crustosum* FBSL1*Plastics Tested:* PU, PE, Ru, LDPE-PB

These strains performed efficiently across all tested plastics, especially PU and Ru. They exhibited high oxygen consumption and CO_2 production, indicating active degradation. FTIR analysis highlighted functional groups such as esters and sulfonates, supporting enzymatic cleavage activity. SEM imaging demonstrated surface indentations and loss of protoplasm.

Case Study 3: Botryotinia cinerea EN41 — A High-Potential Generalist

Researchers: Sabreen S. Ibrahim and team*Fungal Strain:Botryotinia cinerea* EN41 *Plastics Tested:* PU, PE, Ru, LDPE-PB *Findings:* This strain was effective in degrading PU, Ru, and LDPE. It showed significant oxygen consumption and CO_2 output. SEM revealed mycelial deformation, and FTIR spectra identified multiple degradation-related functional groups. Its

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versatility across various polymers makes it a strong candidate for bioremediation applications.

Case Study 4: Strain-Specific Fungal Biodegradation of Plastics

Researchers: Sabreen S. Ibrahim and team

Sabreen S. Ibrahim et al. evaluated the plastic-degrading potential of multiple fungal isolates *(Trichoderma harzianum IS2, Alternaria alternata EN22,* and several *Cladosporium spp.)* against PU, PE, Ru, and LDPE-PB. *T. harzianum IS2* exhibited the highest efficacy, with robust PU degradation, elevated CO_2 release, and distinctive hyphal adaptations confirmed by SEM and FTIR. A. alternata EN22 demonstrated moderate activity, notably against PE, with evidence of limited oxidation and morphological stress responses. *Cladosporium* isolates displayed variable performance; *C. tenuissimum IS28* showed significant activity on PU and PE, while *C. herbarum FB7* was less effective. Overall, the findings highlight the strain-specific nature of fungal plastic biodegradation, with *Trichoderma, Alternaria,* and *Cladosporium* representing promising taxa for bioremediation applications, particularly in PU and PE degradation.

4. Fungal Strains In Pharmaceutical Industry and Waste Management

The pharmaceutical sector is influential in the world economy due to the widespread use of drugs, antibiotics, and hormones in medicine, agriculture, and biotechnology. The use of pharmaceutically active compounds (PhACs) raises environmental issues(14). For example, non-steroidal anti-inflammatory drugs (NSAIDs) such as diclofenac (DCF) are common in healthcare, which leads to their omnipresence in water bodies(4). As one of the most popular analgesics, DCF's proliferation across the globe its environmental burden. The long-term consequences of NSAIDs in ecosystems is troublesome and needs further study concerning their environmental impact(7). Pharmaceutical substances, vital for medical care, are progressively contaminating aquatic environments, leading to ecological damage and the emergence of drug resistance. They pose a threat to the environment by contributing to antibiotic resistance and disrupting endocrine functions. Fungi, especially filamentous and lignin-decomposing varieties, present a viable bioremediation approach owing to their capacity to break down pollutants through specific enzymes(15).

Fungi are essential in the bioremediation of wastewater, owing to their diverse enzymatic capabilities and their ability to thrive in extreme conditions.Bioremediation and biosorption through the use of fungi and algae offer environmentally sustainable and economically viable options. Pharmaceutical contaminants remain in aquatic environments due to the inefficacy of traditional wastewater treatment facilities (WWTPs) in eliminating them(16). Expensive techniques such as membrane filtration and oxidation often produce harmful by-products. (6) Fungi possess the ability to break down a wide range of contaminants, such as metals, oils, plastics, and pharmaceuticals, while also generating beneficial by-products.

4.1 Processes For Management of Pharmaceutical Industry Waste

Fungi, particularly those from the *Basidiomycota* and *Ascomycota* divisions, are essential in the bioremediation of pharmaceutical waste. For instance, Trametes versicolor can effectively eliminate diclofenac within three hours, while a consortium of *Ganoderma applanatum* and *Laetiporussulphureus* can degrade non-steroidal anti-inflammatory drugs (NSAIDs) in 72 hours(25). Additionally, white-rot fungi such as T(17). versicolor and *Hypholomafasciculare* can significantly reduce vincristine levels in just four days(15).The enzyme system of *Basidiomycota*, especially cytochrome P450, plays a vital role in enhancing biotransformation processes. Treatment using whole-cell fungi proves to be more efficient than methods relying solely on enzymes, owing to factors such as bioabsorption,

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immobilization, reactive oxygen species (ROS) effects, and overall enzymatic activity(15). Fungal genetic engineering improves bioremediation by increasing the efficiency of enzymes and the breakdown of pollutants. Modified fungi, such as Aspergillus and Trichoderma, demonstrate a greater capacity to decompose contaminants, thereby making bioremediation more efficient and cost-effective(15). Mycoreactors employed in fungal bioremediation can function as either suspended or immobilized systems, and they may operate in batch or continuous modes under aerobic or anaerobic environments. Typical configurations include stirred tank reactors, air-lift reactors, and fluidized-bed reactors, each offering distinct benefits for the degradation of pollutants(18). A bioremediation device utilizing fungi for wastewater treatment plants (WWTPs) improves the degradation of pharmaceutical compounds by encapsulating a fungal consortium within a porous matrix during the secondary treatment phase. This method promotes stable fungal growth, optimizes enzymatic activity, and facilitates effective pollutant degradation (Figure 7). The device is designed for straightforward installation and replacement, and it accommodates fungi that are pre-adapted to the conditions of wastewater, rendering it a cost-efficient and sustainable option for addressing emerging contaminants(16).

4.1.1 Non-Enzymatic Process

Filamentous fungi employ various bioremediation strategies, such as bioadsorption, the production of biosurfactants, and biomineralization. Bioadsorption refers to the process where toxic substances adhere to the cell walls of fungi, a phenomenon observed in species like Trichoderma, Penicillium, and Aspergillus, particularly for the removal of heavy metals. Biosurfactants, including lipopeptides, facilitate the bioremediation of crude oil; however, their high production costs pose a challenge to widespread application. Biomineralization, which is influenced by the secretion of oxalic acid, enables fungi such as Aspergillus niger and Penicillium to convert toxic metals like lead, zinc, and copper into insoluble forms, thereby mitigating environmental toxicity(13). These processes underscore the significant role fungi can play in the mycoremediation of pollutants.

4.1.2 Enzymatic Process

Filamentous fungi employ enzymatic bioremediation through both extracellular and intracellular enzymes. Extracellular enzymes such as laccases, peroxidases, and hydrolases are responsible for breaking down toxic substances, synthetic dyes, crude oil, and plastics. On the other hand, intracellular enzymes like cytochrome P450 and

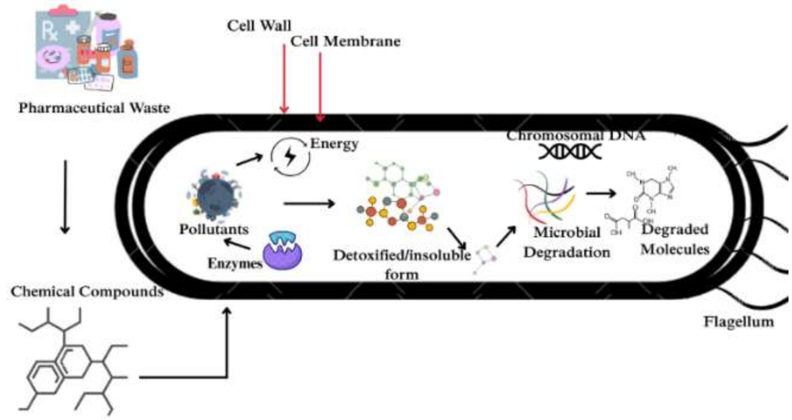

Fig. 7: Process of degradation of pharmaceutical waste through fungal strains

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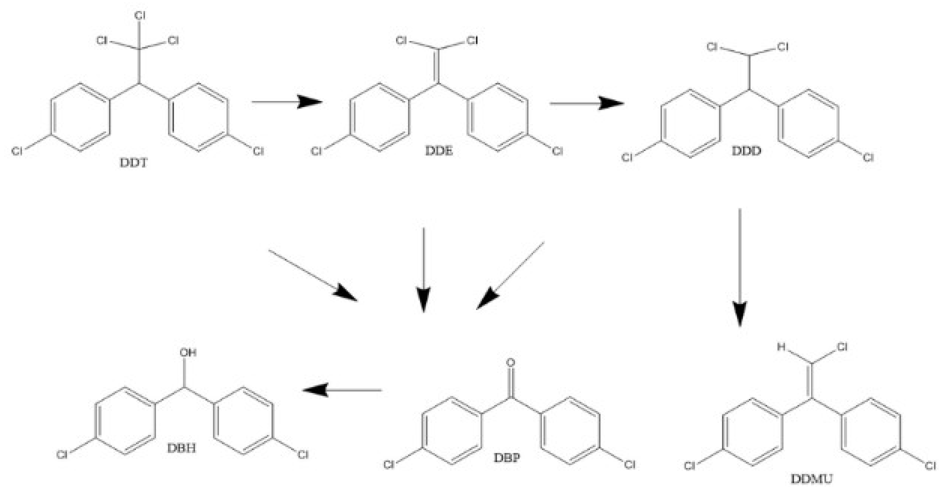

Fig. 8: Different types of pharmaceutical waste present in environment. DDT degradation pathway of brown-rot fungi.

glutathione S-transferases play a crucial role in detoxifying heavy metals and other pollutants. These enzymes facilitate various reactions, including oxidation, reduction, and conjugation, which allow fungi to effectively degrade hydrocarbons, plastics, and xenobiotics(16). Notably, fungal enzymes derived from genera such as Aspergillus, Fusarium, and Phanerochaete demonstrate significant potential for bioremediation, particularly in the degradation of persistent environmental contaminants.

4.2 Fungal Strains Involved in Pharmaceutical Waste Degradation

The application of fungi in the bioremediation of pharmaceutical waste has gained substantial momentum due to their ability to secrete extracellular enzymes and adapt to a variety of environmental conditions. Numerous fungal strains have demonstrated remarkable efficiency in degrading pharmaceutically active compounds, particularly non-steroidal anti-inflammatory drugs (NSAIDs), antibiotics, and endocrine-disrupting substances (Figure 8). Below is a summary of key fungal strains and their target pharmaceutical pollutants (Table 4):

4.2.1 *Bjerkanderaadusta* has shown exceptional ability in degrading diclofenac sodium (DCF), a widely used anti-inflammatory drug resistant to conventional wastewater treatment methods. The strain produces high levels of lignin peroxidase (LiP) and manganese peroxidase (MnP), along with moderate laccase activity, facilitating oxidative degradation pathways. Studies have reported up to 93.7% removal of DCF from synthetic solutions and over 90% removal from actual pharmaceutical wastewater. Moreover, detoxification was confirmed via phytotoxicity and FTIR analyses, suggesting the breakdown of harmful intermediates.

4.2.2 *Fomitopsismeliae*, another ligninolytic white-rot fungus, also degrades DCF effectively through MnP activity, although it lacks laccase production. While it exhibits slightly reduced efficiency at higher pollutant concentrations compared to *B. adusta*, it remains highly effective for moderate DCF levels, achieving degradation rates close to 90%.

4.2.3 *Penicillium brevicompactum* is notable for its broad-spectrum degradation

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Table 4: Comparative analysis of Fungal degraders in pharmaceutical waste

Fungal Strain	Target Pollutants	Degradation Mechanism	Efficiency	Application Notes
Bjerkander aadusta	Diclofenac sodium (DCF)	Lignin peroxidase, MnP, moderate laccase	Up to 93.7% (synthetic); >90% (real effluent)	Confirmed detoxification; suitable for oxidative degradation in complex matrices
Fomitopsis meliae	Diclofenac sodium (DCF)	Manganese peroxidase (no laccase)	~90% at moderate concentrations	Effective at lower concentrations; potential for real effluent application
Penicillium brevicompactum	Acetaminophe, Ketoprofen, other NSAIDs	Laccases, peroxidases	Broad-spectrum activity	Works well in acidic conditions; suitable for batch reactor integration
Fusarium solani	Tetracyclines, Diclofenac	Hydrolytic & oxidative enzymes; biosorption	80–90%	Functions under nutrient-limited conditions; robust for field application
Aspergillus niger	Ciprofloxacin, Ibuprofen, Paracetamol	Diverse enzymatic activity; biosorption	60–85%	Scalable; fast-growing; potential for industrial bioreactor integration
Pleurotus ostreatus	Estradiol, Diclofenac, Carbamazepine	Laccases, MnP	High degradation potential	Cultivation protocols well established; strong bioreactor performance

capabilities. It has been reported to degrade multiple NSAIDs, including acetaminophen and ketoprofen, through the action of oxidative enzymes such as laccases and peroxidases. This strain performs optimally under acidic conditions and is well-suited for integration into batch reactor systems used in pharmaceutical effluent treatment.

4.2.4 *Fusarium solani* has demonstrated degradation of antibiotics like tetracyclines, as well as NSAIDs including diclofenac. The strain employs both hydrolytic and oxidative mechanisms, along with biosorption, to achieve removal rates of up to 80–90%. Its resilience in nutrient-limited conditions makes it a promising candidate for real-world pharmaceutical wastewater applications.

4.2.5 *Aspergillus niger*, a commonly studied industrial fungus, has been employed for the degradation of ciprofloxacin, ibuprofen, and paracetamol. It produces a diverse array of enzymes and has notable biosorptive properties, achieving moderate to high degradation efficiency ranging from 60% to 85%. Its rapid growth and scalability make it favorable for bioreactor-based applications.

4.2.6 *Pleurotus ostreatus* is another white-rot fungus capable of degrading endocrine-disrupting compounds such as estradiol and pharmaceutical pollutants like diclofenac and carbamazepine. It utilizes a robust ligninolytic enzyme system, particularly laccases and MnP, to degrade complex pharmaceutical structures. Its established cultivation protocols and strong performance in bioreactor setups make it a leading candidate for scale-up in industrial wastewater treatment.

Together, these fungal strains offer a diverse and powerful toolkit for mitigating pharmaceutical pollution in wastewater streams. Their mechanisms—primarily based on oxidative degradation, biosorption, and enzymatic transformation—position fungi as pivotal agents in sustainable and eco-friendly wastewater remediation strategies.

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Table 5: Summary of the takeaways from the case studies

Aspect	*Bjerkanderaadusta* (Fungal Strain 1)	*Fomitopsismeliae* (Fungal Strain 2)
Research Team	Nikita Dhiman et al.	Nikita Dhiman et al.
Laboratory	Dept. of Environment Studies, Panjab University, Chandigarh	Dept. of Environment Studies, Panjab University, Chandigarh
Fungal Strain	*Bjerkanderaadusta*	*Fomitopsismeliae*
Origin of Fungi	Forest soil, Nurpur, Himachal Pradesh	Forest soil, Nurpur, Himachal Pradesh
Pharmaceutical Waste Targeted	Diclofenac Sodium (DCF)	Diclofenac Sodium (DCF)
Maximum Removal Efficiency	93.7% (at 50 ppm)	90% (at 25 ppm)
Enzyme Activity (Key)	High LiP, MnP, moderate laccase	High MnP, no laccase
FTIR/SEM Observations	Hyphal distortion, rough surface, elemental uptake confirmed	Hyphal flattening, porous texture, chemical bonding change
LC-MS/GC-MS Findings	Hydroxylation, decarboxylation; intermediates identified	Similar metabolic products with lower yield
Tolerance Index (25 ppm)	1.7	0.77
Seed Germination Results	100% seed germination	100% seed germination
Phytotoxicity (%)	8.1%	16.2%
Performance in Real Wastewater	91% removal from real effluent	85% removal from real effluent
Overall Efficiency & Application	Superior degradation and detoxification	Moderate performance; useful in consortia

4.3 Case Studies and Real-World Applications

Here are outline case studies demonstrating how different fungal strains are capable of degrading pharmaceutical waste. Two fungal strains were mainly used. The experiments were conducted in the Laboratory: Department of Environment Studies, Panjab University, Chandigarh, India(4).

Case Study 1:*Bjerkanderaadusta* – A Potent Degrader of Diclofenac Sodium

*Researchers: Nikita Dhiman, Savita Chaudhary, Avtar Singh, Archana Chauhan, Rajeev Kumar*Laboratory: Department of Environment Studies, Panjab University, Chandigarh, India (Table 5).

To explore sustainable bioremediation of pharmaceutical waste, particularly diclofenac sodium (DCF)**,** the research team employed the white-rot fungus *Bjerkanderaadusta*. Isolated from forest soils in Himachal Pradesh, this strain was cultured and tested for its potential to break down DCF under controlled conditions. Using 2 g of fungal biomass in a defined glucose-peptone medium, the experiment was carried out in amber bottles at 28°C for five days.

Advanced analytical techniques including UV–Vis spectrophotometry, FTIR, SEM-EDS, LC-MS, and GC-MS confirmed significant structural changes in the xenobiotic compound. The removal efficiency reached 93.7% at 50 ppm concentration, with enzyme assays indicating strong production of lignin

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peroxidase and manganese peroxidase, key enzymes for breaking down complex organic compounds. FTIR spectra showed the transformation of functional groups post-treatment, and SEM revealed noticeable morphological alterations in the fungal hyphae due to DCF adsorption. Toxicity studies, including bacterial inhibition and wheat seed germination assays, showed a remarkable reduction in toxicity, indicating successful detoxification. The tolerance index was 1.7 at 25 ppm DCF, showing high adaptability.

Case Study 2: *Fomitopsismeliae* – A Supportive Agent in Mycoremediation

Researchers: Nikita Dhiman et al. Laboratory: Department of Environment Studies, Panjab University, Chandigarh, India

Alongside *B. adusta*, the brown-rot fungus *Fomitopsismeliae* was tested for its DCF degradation capabilities. Cultured under identical conditions, this strain demonstrated a90% removal efficiency at 25 ppm and produced a slightly different enzyme profile, withelevated manganese peroxidase activity but no measurable laccase production (Table 5).

FTIR and SEM-EDS analyses confirmed adsorption and subsequent degradation of DCF. Notably, the elemental composition of fungal biomass changed post-adsorption, and SEM micrographs showed transformation from smooth to rough, porous hyphae. LC-MS and GC-MS confirmed multiple hydroxylation and decarboxylation 0reactions leading to transformation products such as 4- and 5-hydroxy DCF and various other intermediates. Despite slightly lower removal efficiency than *B. adusta*, *F. meliae* proved effective in reducing DCF toxicity, achieving complete seed germinationand only 16.2% phytotoxicity. The tolerance index was 0.77 at 25 ppm, indicating moderate resilience under xenobiotic stress.

Field Validation: Real Wastewater Treatment

Both fungi were tested on real effluent collected from a pharmaceutical plant in Baddi, Himachal Pradesh. When supplemented with 25 ppm of DCF, the effluent treated with *B. adusta* showed a 91% reduction, while *F. meliae* achieved 85% degradation. Statistical analyses confirmed a significant difference ($p < 0.05$) in degradation performance. The results validated the fungi's applicability in real-world wastewater treatment scenarios, showing potential for integration into bioreactors.

These case studies demonstrate the effective degradation of pharmaceutical waste—specifically DCF—by two fungal strains with differing enzymatic mechanisms. The research underscores the significance of *Bjerkanderaadusta* for its superior degradation and detoxification performance, while also recognizing *Fomitopsismeliae* as a strong complementary agent.

5. Challenges and Future Prospects

Fungal bioremediation faces several challenges that limit large-scale use. Scalability remains a hurdle, as lab results are difficult to reproduce in industrial settings due to requirements for controlled growth, enzyme stability, and consistent degradation. Strain specificity, slow breakdown of resistant polymers like polyethylene, and the risk of toxic intermediates further constrain efficiency. Integration into existing waste treatment systems also demands technical adaptation, while environmental factors such as pH, temperature, and co-contaminants add complexity.

Despite these barriers, future prospects are promising. Advances in synthetic biology and genetic engineering can enhance enzyme activity and substrate range, while fungal consortia or hybrid systems with bacteria may improve efficiency. Incorporation into circular economy models—such as converting fungal biomass into bioenzymes or biofertilizers—can strengthen economic feasibility. With rising environmental policies and interest in green technologies, fungal bioremediation is poised to become a sustainable strategy for managing persistent pollutants.

6. Conclusion

The use of fungi for the degradation of plastic and pharmaceutical waste represents a sustainable and eco-friendly

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alternative to conventional waste management methods. Through their enzymatic machinery and adaptability to diverse environments, fungi such as *Bjerkanderaadusta*, *Fomitopsismeliae*, *Fusarium*, and *Penicillium* have demonstrated significant potential in breaking down complex pollutants into less harmful by-products. The studies reviewed underscore not only the environmental benefits but also the economic feasibility of fungal bioremediation, especially when integrated into industrial treatment systems. However, challenges related to scalability, degradation rates, and operational optimization must be addressed through further research and technological innovation. As awareness around environmental pollution grows and policies increasingly favour green technologies, fungal-based systems are well-positioned to play a critical role in future waste management strategies. With continued scientific and industrial support, mycoremediation could become a cornerstone of global efforts to mitigate plastic and pharmaceutical contamination.

7. Acknowledgement

We would like to acknowledge Amity Institute of Biotechnology for providing the necessary resources to carry out the research work.

8. Conflict of 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.

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