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Mycodegradation of Pesticides in Agricultural Soils: A Systematic Review

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Abstract

Introduction: Pesticides are extensively used in agriculture, but their persistence in soil poses environmental and health risks. Mycodegradation, a process where fungi enzymatically break down pesticides into less harmful compounds, offers a promising solution. Despite interest in bioremediation, fungal contributions to pesticide degradation remain underexplored compared to bacterial or chemical methods. This systematic review examined the role of mycodegradation in reducing pesticide contamination and its potential for sustainable environmental management.

Methods: A comprehensive search was conducted in the Web of Science, Embase, PubMed, and Scopus databases, focusing on English-language studies from January 2013 to December 2024. Studies were included if they explicitly reported fungal-mediated degradation of pesticides in agricultural soils.

Results: The initial search identified 901 articles. After removing duplicates and screening for relevance, 601 articles (239, 127, 137, and 98 from Web of Science, Embase, PubMed, and Scopus, respectively) were selected for full-text evaluation. Finally, 40 studies met the inclusion criteria. These studies reported insecticide destruction efficiencies ranging from 26% to 100%, herbicide destruction efficiencies from 24% to 96.1%, and fungicide destruction efficiencies from 11% to 30%. The measured pesticide concentrations ranged from 10 to 2000 mg/L.

Conclusion: Fungi show strong potential for pesticide degradation, with Aspergillus species showing robust activity. Harnessing fungal biodegradation could reduce pesticide pollution, promote healthier ecosystems, and support sustainable agriculture. Further research is needed to optimize and scale these processes for practical applications, offering a viable solution to global environmental challenges.

Keywords: Biodegradation, Bioremediation, Soil, Pesticide, Fungi

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Introduction

Pesticides, both natural and synthetic chemicals, are indispensable tools in modern agriculture for managing pests and plant diseases (1). In 2019, global pesticide consumption reached approximately 3.5 million tons, underscoring their critical role in safeguarding agricultural productivity (2). However, pesticides enter the environment through various sources, including agricultural practices (e.g., crop spraying and soil treatment), industrial activities (e.g., manufacturing waste and chemical spills), and household applications (e.g., garden pest control and insect repellents) Figure 1 (3). Despite their benefits, excessive use and inherent toxicity can lead to environmental contamination, as pesticides and their metabolites infiltrate soil, water, and food chains, posing significant risks to biodiversity and human health (4,5). Consequently, there is an urgent need for sustainable strategies to mitigate these adverse effects (6).

Biodegradation, defined as the process of breaking down organic pollutants into less harmful substances using microorganisms, offers a promising solution (7). Among microorganisms, fungi have shown remarkable potential in degrading persistent pesticides—a process known as mycodegradation (8). Mycodegradation refers to the degradation of toxic compounds by fungi through mechanisms influenced by various environmental and biological factors (9). These factors include soil pH, temperature, nutrient availability, and fungal strain specificity, all of which play a crucial role in determining the efficiency of pesticide degradation (10).

Recent studies have emphasized the importance of optimizing these parameters to enhance mycodegradation

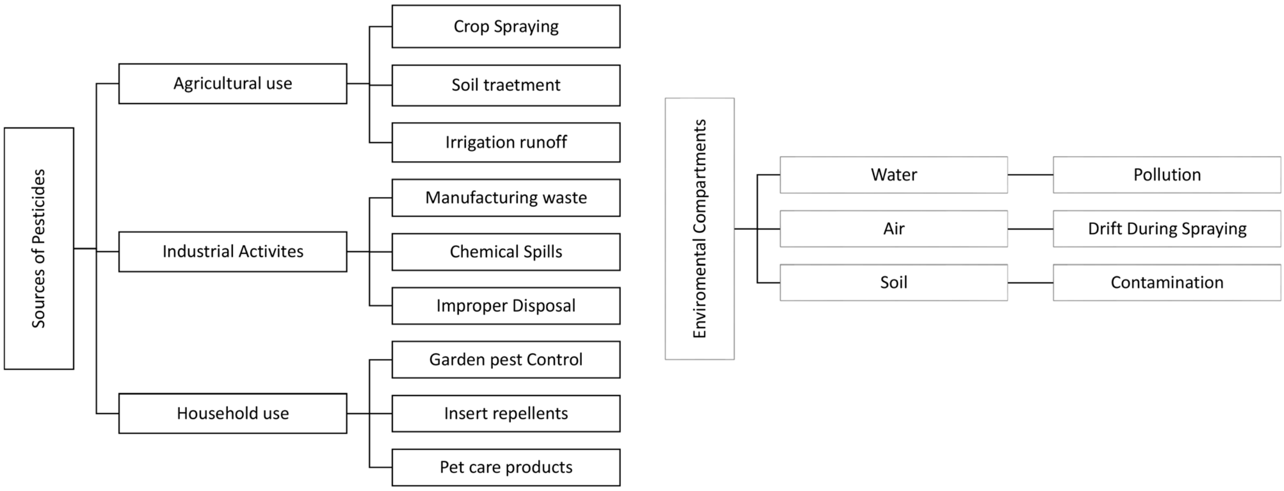

Figure 1. Major sources of pesticide introduction into the environment and their impacts on environmental compartments. Pesticides from agricultural, industrial, and household sources can contaminate water, air, and soil through mechanisms such as runoff, drift, and improper disposal

efficiency. For instance, acidic to neutral pH levels (pH 5–7) are often optimal for fungal activity, whereas extreme temperatures can inhibit enzyme secretion and metabolic processes (11). Additionally, the presence of specific nutrients, such as nitrogen and carbon sources, can significantly influence fungal growth and degradation rates (3). Furthermore, different fungal strains exhibit various levels of tolerance and adaptability to environmental conditions, making strain selection a key factor in bioremediation strategies. Although bacterial degradation has been extensively studied due to its well-understood metabolic pathways. Recent findings have highlighted the importance of further investigating the interplay between environmental parameters and fungal activity to optimize mycodegradation processes.

Recent research also has underscored the underexplored yet significant role of fungi in pesticide bioremediation. Fungi, particularly species such as *Aspergillus niger* and *Trichoderma harzianum*, have demonstrated robust capabilities in degrading a wide range of pesticides under diverse environmental conditions (12). These findings emphasize the need to investigate how environmental factors interact with fungal activity to improve mycodegradation efficiency.

Despite this potential, research on fungal-mediated pesticide degradation remains limited compared to bacterial approaches (13). This gap highlights the necessity for systematic evaluations of the factors influencing mycodegradation efficiency. By understanding how parameters such as pH, temperature, and fungal strain specificity affect degradation rates, more effective and sustainable strategies for environmental remediation can be developed (14).

This systematic review aims to consolidate and evaluate existing literature on the use of fungi for pesticide degradation, with a specific focus on identifying key parameters that influence mycodegradation efficiency. By synthesizing current knowledge and highlighting gaps in the field, this review seeks to encourage further research into the untapped potential of fungi for sustainable environmental management.

Materials and Methods

Research question

Does fungal pesticide degradation occur more efficiently under specific environmental conditions, such as particular pH levels or temperature ranges?

Search strategy

The search strategy was designed to identify both published and unpublished studies. This review employed a three-step search strategy. Initially, a limited search was performed on PubMed, followed by an analysis of the text words in the titles and abstracts, as well as the index terms associated with the articles. A second search utilizing all identified keywords and index terms (“Mycodegradation”, “biodegradation”, “bioremediation”, “biotransformation”, “degradation”, “herbicide”, “fungicide”, “insecticide”, “pesticide”, “fungi”, and “soil”) and Boolean operators (AND, OR) was applied to combine search terms. The search was updated in November-December 2024 across databases: PubMed, Scopus, Web of Science, and Embase. For unpublished studies and gray literature, Google Scholar was also included in the search. Finally, the reference lists of all reports and articles selected for critical appraisal were examined for additional studies. The complete search strategies for each database (PubMed, Scopus, Web of Science, and Embase), along with the PRISMA checklist used to ensure transparency and reproducibility of the review process, are provided in Figure 2.

Inclusion and exclusion criteria

This study included original research published in English that focused on pesticide degradation using various fungi. Articles were excluded if they were abstracts, duplicates, presentations, conference papers, meta-analyses, review articles, unrelated topics, letters to the editor, or books.

Screening process and study selection

Duplicate records were removed using EndNote X9 software. Two independent reviewers screened the titles and abstracts of the remaining articles based on the inclusion criteria. Studies published between January 2013 and September 2024 were considered. Any disagreements between the reviewers were resolved through discussion to reach consensus. If necessary, a third reviewer was consulted to resolve discrepancies.

Quality assessment of selected studies

The methodological quality of the included studies was independently assessed by two reviewers using a modified version of the CAMARADES study quality checklist. This tool was adapted to evaluate the internal validity of the selected studies, considering potential biases such as selection bias, attrition bias, performance bias, and detection bias, as well as other quality indicators, including reporting completeness and statistical power.

The checklist included criteria such as publication in a peer-reviewed journal, blinded outcome evaluation, randomization based on treatment or control groups, allocation concealment, reporting of animal inclusion and exclusion criteria, calculation of sample size, compliance with monitoring requirements, and disclosure of potential conflicts of interest. Studies scoring 50% or higher were classified as high or moderate quality and were included in the analysis. Disagreements between reviewers were resolved through discussion or consultation with a third reviewer.

Data extraction

Data were extracted using tables designed to record relevant information from the selected articles, including authors and publication date, pesticide type and name, microorganism involved, pesticide concentration (mg/ml), temperature (°C), pH, and degradation percentage (%) (Table 1).

Results

Characteristics of the literature

The details of all studies at various stages of selection and exclusion are summarized in the PRISMA flow diagram (Figure 2). A total of 901 articles were initially identified, of which 300 articles were removed due to duplication. The remaining 601 studies (PubMed: 137; Scopus: 98; Web of Science: 239; Embase: 127) were screened based on titles, abstracts, and full texts. Ultimately, 40 studies met all the

Table 1. Summary of the articles selected for the review

	Author/date	Pesticide type	Pesticide	Microorganism name	Degradation	Conc.	Temperature	pH
Insecticides List								
1	Alrahman et al. (2014) (15)	OP	CPF	*Trichoderma. viride*	70.61	10	30 ± 2	7.2
				Trichoderma. harzianum	60.31			
				Aspergillus. niger	63.96			
				Aspergillus. oryzae	50.79			
				Penicillium. citrinum	25.93			
2	Lie-Zhong et al. (2014) (16)	OP	CPF	12 Fungal strains and two bacterial strains of Enterobacter *sp.*	> 80	50	Bactria 37 Fungi 30	6.8
3	Jain et al. (2013) (17)	OP	MCP	*Aspergillus. flavus*	91.59 ± 4.31	150	28 ± 2	8
				Fusarium Pallidoroseum	75.02 ± 5.6			
				Macrophomina sp.	79.03 ± 7.6			
4	Gajendiran et al. (2015) (18)	OP	MCP	*Aspergillus. oryzae SJA1*	100	500	30 ± 2	7.2
5	Dudeja et al. (2017) (19)	OP	MP	O1	65	25	30	8
				M1	70			
6	Abraham et al.(2018) (20)	OP	CPF	*Aspergillus. terreus JAS1*	100	0.3	Room T	-
				Ganoderma sp.	100			
7	Abd-Alrahman et al. (2014) (21)	OP	FNT	*Trichoderma viride*	73.32	10	30 ± 2	7-8
				Aspergillus niger	66.52			
				Brady rhizobium sp.	60.44			
8	Peter et al. (2015) (22)	OP	MLT	*Fusarium oxysporum JASA1*	100	0.4	Room T	6.8
9	Shi et al. (2018) (23)	NNI	ACE	*Fusarium sp CS-3*	98	0.05	20-40	5-8
10	Silambarasan et al. (2013) (24)	OP	CPF	*Ganoderma JAS4*	100	0.5	30 ± 2	6.8
11	Silambarasan et al. (2013) (25)	OP	CPF	*Aspergillus. terreus JAS1*	100	0.3	30 ± 2	6.8

Table 1. Continued.

	Author/date	Pesticide type	Pesticide	Microorganism name	Degradation	Conc.	Temperature	pH
12	Jiang et al. (2016) (26)	OP	TCF	*Aspergillus. sydowii PAf2*	75.31	0.1	28	7
13	Huang et al. (2017) (27)	OP	Six OPs	*Aspergillus. oryza (ZHJ8)* *Cladosporium. cladosporioides* (ZHJ10)	~80	2	25	7
14	Bhatt et al. (2020) (28)	PYR	ALR	Fusarium proliferatum	100	1	26	6
15	Abraham et al. (2014) (29)	OC	ESL	Fungus strain *Lasiodiplodia sp. JAS12* Bacteria Strain *Klebsiella pneumoniae JAS8*	Together ~60	1	Room T	7
16	Kaur et al. (2023) (30)	OC	LND	*9 strains of Ascomycetes fungi*	~57-94	10	28 ± 2	-
17	Purnomo et al. (2014) (31)	OC	HPC	*Pleurotus ostreatus*	89	20	25	-
18	Ahmad (2020) (32)	OC	ESL	Bacteria Strain *Bacillus subtilis* Fungus strain *Aspergillus. Niger* *Aspergillus. Flavus* *Penicillium chrysogenum*	 95 77 72 69	10	29 ± 2	~7-6
19	Abraham et al. (2014) (33)	OC	ESL	Bacterial strain *Halophilic bacterium JAS4* *Klebsiella. pneumoniae JAS8* *Enterobacter asburiae JAS5* *Enterobacter cloacae JAS7* Fungi strain *Aspergillus. tamarii.*	100 (Total)	1	bacteria 37 ± 2 for 3 days fungi 28 ± 2 for 7 days	7 6.8
20	Russo et al. (2019) (34)	OC	DDT	*Trichoderma hamatum FBL 587* *Rhizopus arrhizus*	100	1	25	-
21	Mariana et al. (2014) (35)	OC	ESL	*Penicillium sp.*	94.87	150	30	7
22	Islas-García et al. (2015) (36)	OC	HPC, ALR, ESI and DDT	*Hydrocarbonoclast bacteria and fungi*	-	200	28	6-7
23	Royata (2018) (37)	OC	DLR & ESL	*Mucor racemosus DDF* *Mortierella sp. W8* *Mortierella sp. Cm1-45*	>90 70 50	50	25	2
24	Kaur et al. (2020) (38)	Carb	CF CBL	*Acremonium sp.*	97.65 99.6	0.2-0.6	28	7
25	Meng et al. (2023) (39)	PP	FPN	*Cunninghamella elegans ATCC36112*	92	10	28	7
Herbicides List								
26	Erguven et al. (2018) (40)	CAA	ACT	*Tolypocladium geodes* *Cordyceps cicadae* *Metacordyceps owariensis* *Metarhizium cylindrosporae* *Verticilium chlamydosporium*	91 87 87 69 55	11	25	-
27	Yadav et al. (2014) (41)	SU	SUL	*Trichoderma sp*	-	0.2	25	7
28	Correa et al. (2023) (42)	OP	GLY	*Penicillium 4A21* *Aspergillus 2B112* *Penicillium 2A31*	~43 ~37 ~35	2.35	30	6

Table 1. Continued.

	Author/date	Pesticide type	Pesticide	Microorganism name	Degradation	Conc.	Temperature	pH
29	Pandey et al. (2020) (43)	SU	OSM	*Aspergillus niger*	50 96.1	2.5 0.5	30 ± 2	7
				Cunninghamella sp.	46			
30	Jing Guo et al. (2022) (44)	OP	GLY	*Fusarium verticillioides*	sterilized soil 72.17 unsterilized soil 89.07	0.9	28	7
31	Wongputtisin et al. (2021) (45)	QAC	PQ	*Aspergillus tamarii*	24	0.01	30	7.3
32	Xu et al. (2024) (46)	-	DUR/IMID	*Simplicillium sp. QHSH-33*	70	-	-	-
33	Nguyen et al. (2022) (47)	-	2,4-D 2,4,5-T	*Rigidoporus sp. FMD2*	-	150-180 60-120	30	4-7
34	Lizano-Fallas et al. (2017) (48)	Triazine/OP	(ATR, TBR, TRN)/CPF	*Trametes versicolor*	84.7	-	25	6.4
35	Ahmad et al. (2020) (49)	Triazole	TCM	*Aspergillus flavus* *Penicillium chrysogenum* *Aspergillus niger* *Aspergillus terrus* *Aspergillus fumigatus*	74 95 81 98 74	0.01	29 ± 2	7
36	Ahmad et al. (2020) (50)	CAA	Alachlor	*Aspergillus flavus* *Penicillium chrysogenum* *Aspergillus niger* *Aspergillus terrus* *Aspergillus fumigatus*	17.1	0.01	29 ± 2	7
37	Belovezhets et al. (2024) (51)	IMI/SU	IMZ/CSU	Without identification of bacteria and fungi	Bacteria 25-57 fungi 23-37	30	25	7
Fungicides list								
38	Sharma et al. (2016) (52)	BZI	CBZ	Trichoderma harzianum Trichoderma viride Trichoderma atroviride	60 83 93	100 150 200	25	-
39	Kumar et al. (2020) (53)	IPP	IPP	*Aspergillus flavus* *Penicillium chrysogenum* *Aspergillus niger* *Aspergillus terreus* *Aspergillus fumigatus*	21 27 21 11 30	0.01	29	7.4
40	Martins MR et al. (2017) (54)	ACYN	MET	*Gongronella sp.* *Rhizopus oryzae*	97 98	1.360 2.430	25	7

OP: Organophosphate; CPF: Chlorpyrifos; MCP: Monocrotophos; MP: Methyl Parathion; FNT: Fenitrothion; MLT: malathion; NNI: Neonicotinoid; ACE: Acetamiprid; TCF: Trichlorfon; PYR: Pyrethroids; ALR: Allethrin; OC: Organochlorine; ESL: Endosulfan; LND: Lindane; HPC: Heptachlor; DDT: Dichloro-Diphenyl-Trichloroethane; DLR: Dieldrin; ALR: Aldrin; Carb: Carbamate; CF: Carbofuran; PP: Phenylpyrazole; CBL: Carbaryl; FPN: Fipronil; CAA: Chloroacetanilide; ACT: Acetochlor; SU: Sulfonylurea; SUL: Sulfosulphuron; GLY: Glyphosate; OSM: Orthosulfamuron; QAC: Quaternary Ammonium Compounds; Paraquat: PQ; DUR: Diuron; IMID: Imidaclopride; 2,4-D: 2,4 Dichlorophenoxyacetic acid; 2,4,5-T: 2,4,5 Trichlorophenoxyacetic acid; ATR: Atrazine; TBR: Terbuthylazine; TRN: Terbutryn; TCM: Thiencarbazone Methyl; IMI: Imidazolinone; CSU: Chlorsulfuron; IMZ: Imazamox; BZI: Benzimidazole; CBZ: Carbandazim; IPP; Isopyrazam; ACYN: Acylanilide; MET: Metalaxyl.

inclusion criteria for this review. The key characteristics and quantitative findings of these studies are summarized in Table 1.

Characteristics of the included studies

Pesticides encompass several classes of chemicals, including insecticides, herbicides, fungicides, rodenticides, and nematicides, which are used to control or eliminate pests (55,56). In this systematic review, we analyzed the distribution of published studies across these pesticide groups. The results revealed that the majority of studies focused on insecticides (62.5%), followed by herbicides

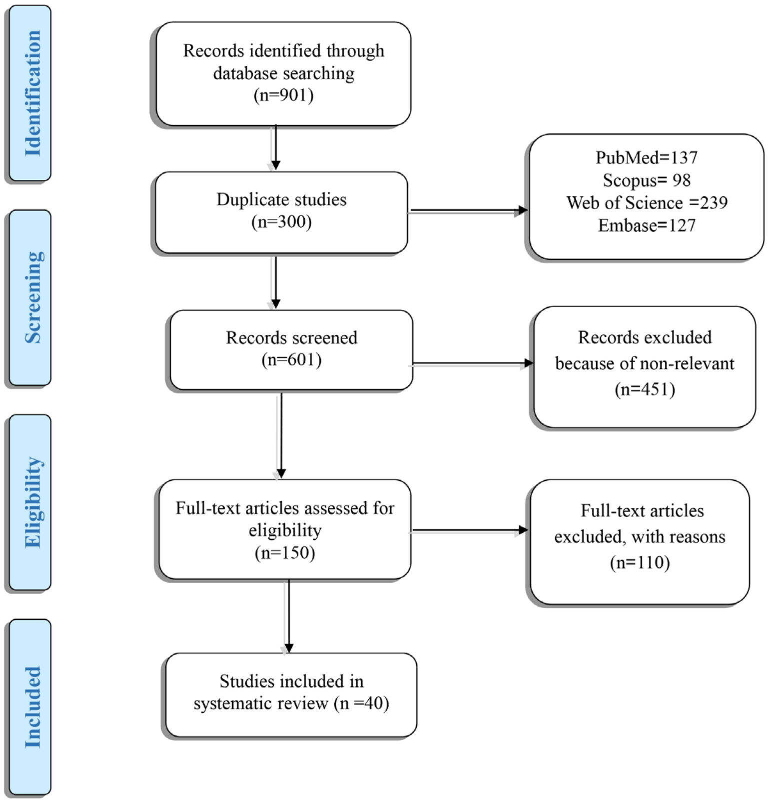

Figure 2. Flow diagram of the study selection process for the systematic review. A total of 901 records were identified through database searching, with 300 duplicates removed. After screening 601 records, 150 full-text articles were assessed for eligibility, leading to the inclusion of 40 studies in the final review

(30%) and fungicides (7.5%). These studies were conducted in agricultural soils from various regions, emphasizing the widespread concern about the environmental impact of these pesticides (Figure 3).

The predominance of insecticide-focused studies reflects their extensive use in agriculture and the associated environmental challenges. Although less studied, herbicides and fungicides remain significant due to their persistence in soil and potential ecological effects. The regional diversity of the included studies further underscores the global relevance of pesticide degradation research.

Figure 4 illustrates that various fungi can facilitate the biodegradation of different pesticides. In this context, the highest efficiency in environmental remediation was achieved by *Aspergillus species* (36.1%), followed by *Penicillium* (11.1%), *Trichoderma* (11.1%), and *Fusarium* (6.9%). Other fungal species (34.8%) also demonstrated activity, as detailed in Table 1.

Given the notable ability of *Aspergillus* fungal strains to degrade pesticides, Figure 5 shows that *Aspergillus Niger* (31%) and *Aspergillus Flavus* (19%) exhibit the highest degradation capabilities among *Aspergillus* species.

As shown in Table 2, based on the fungi's optimal growth conditions, the temperature and pH parameters can be classified within a specific range tailored to each pesticide group.

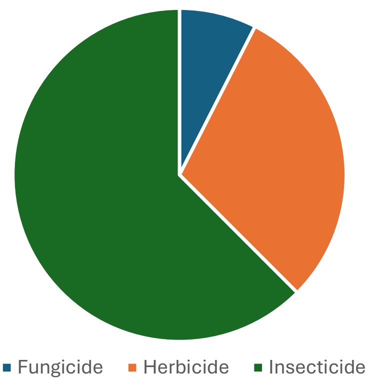

Figure 3. Distribution of pesticide types used, showing that insecticides (62.5%) are the most commonly used, followed by herbicides (30%) and fungicides (7.5%).

Role of Fungi in the degradation of insecticides

Insecticides containing toxic compounds are a major cause of various health disorders, including neurological issues, allergic reactions, reproductive diseases, skin conditions, and cancer (57). Therefore, researching methods to degrade insecticides in soil is a key goal for policymakers concerned with both environmental and human health.

Insecticides can be classified into several categories: The two most widely used groups are organophosphates (OPs) and Organochlorines (OCs), while other groups include Carbamates (Carb), pyrethroids (PYR), and Neonicotinoids (NNI), etc. This review examined 11 studies focusing on the degradation of OPs (15-17,19-22,24-27), 9 studies on OC (29-37), as well as additional studies on Carb (38), Fipronil (FPN) (39), Acetamiprid (ACE) (23), with a particular

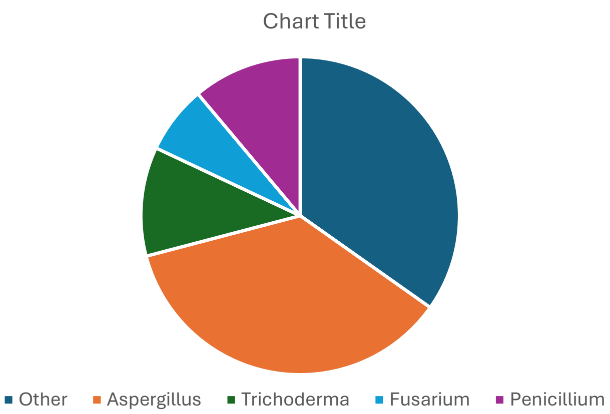

Figure 4. Contribution of Major Fungal Species to Pesticide Biodegradation (*Aspergillus* species (36.1%), *Penicillium* (11.1%), *Trichoderma* (11.1%), *Fusarium* (6.9%), and other fungal species (34.8%))

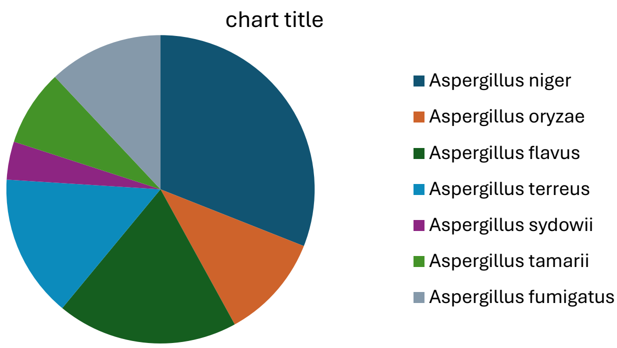

Figure 5. Activity Percentage of Different Aspergillus Species in Mycoremediation

Table 2. The optimal pH and temperature for the Mycoremediation of pesticides

	Insecticides	Herbicides	Fungicides
pH	2-8	4-7	7-8
Temperature (°C)	20-37	25-30	25-29

emphasis on the role of fungi in this process (Table 1).

Fungal degradation of OP insecticides

The degradation efficiency of insecticides ranged from 25.93% to 100%. Various OP insecticides such as Chlorpyrifos (CPF) (15,16,20,24,25), Trichlorfon (TCF) (26), Monocrotophos (MCP) (17, 18), Methyl Parathion (MP)(19), Fenitrothion (FNT) (21), Malathion (MLT) (22), and Six OPs (Folimat, Phoxim, and Methamidophos) (27) were studied.

According to the study by Silambarasan et al. (24), a fungal strain identified as *JSA4* belonging to the genus *Ganoderma* can degrade CPF into its primary metabolite, 3,5,6-trichloro-2-pyridinol (TCP). The optimal incubation conditions for CPF degradation were found to be 30 ± 2°C and pH 6.8. One of the important aspects of this strain is its ability to degrade more TCP, which is noteworthy due to the higher toxicity of TCP compared to CPF, as well as its antimicrobial effects.

In another study, Silambarasan et al. (25) isolated and identified a new CPF-degrading fungus, *Aspergillus terreus*. This strain can uniquely degrade both CPF and TCP in various culture media and soil. It is the first reported case of *A. terreus JAS1* effectively degrading CPF and its metabolite TCP in nutrient-depleted soil within 24 and 48 hours of incubation, respectively. Similar to the previous study, the optimal conditions for CPF degradation were 30 ± 2°C and pH 6.8. However, due to the differences in enzyme capacities among fungal strains such as *Ganoderma* and *A. terreus*, the incubation conditions for CPF degradation cannot be uniformly extended to all strains.

Huang et al. (27) evaluated two fungal strains capable of degrading organophosphorus pesticides, including flufenoxuron. The identified strains were *Aspergillus oryzae* and *Cladosporium cladosporioides*. These fungi require an external source of carbon to facilitate degradation and can utilize nitrogen and phosphorus from the pesticides themselves. Both strains grow in acidic conditions and can efficiently degrade organophosphorus pesticides at 25°C.

Additionally, Lie-Zhong et al. (15) isolated and confirmed five fungal strains from soils contaminated with CPF as capable of degrading this pesticide. Among them, *Trichoderma viride* was the most effective, achieving a degradation rate of 70.61%. *Aspergillus niger*, *Trichoderma harzianum*, and *Aspergillus oryzae* showed moderate biodegradable activity, with degradation rates of 63.96%, 60.79%, and 50.39%, respectively. In contrast, *Penicillium Citrinum* exhibited the lowest degradation rate at only 25.93% after 15 days of incubation. The optimal conditions for all strains in this study were a temperature of 30 ± 2 and pH 7.2.

According to the study by Abraham et al. (20) on the biodegradation of CPF and its metabolite 3,5,6-trichloro-2-pyridinol (TCP) by a fungal consortium comprising *Aspergillus terreus JAS1 and Ganoderma sp. JAS4*, it was observed that 300 mg/L of CPF was entirely degraded within 12 hours of incubation in soil. Additionally, FTIR and HPLC analysis indicated that TCP was completely degraded after 48 hours in a nutrient-depleted environment.

In another study, Jiang et al. (26) isolated a fungus (PAF-2) from soil contaminated with TCF, which was identified as *Aspergillus sydowii* based on sequencing of the internal transcribed spacer ribosomal DNA (rDNA). This fungus could utilize TCF as its sole carbon, phosphorus, or both in a mineral salt medium. The study demonstrated that, under optimal conditions, 75.31% of 100 mg/L TCF was metabolized within seven days at 28°C and pH 7.

In a further investigation into the biodegradation of MCP, Jain et al. (17) identified three fungal strains from agricultural soil contaminated with this pesticide. These isolates degraded MCP via hydrolytic cleavage of the vinyl phosphate bond, accompanied by the release of extracellular alkaline phosphatases, inorganic phosphates, and ammonia. The optimal degradation occurred at a temperature of 28 ± 2°C and pH 8. The isolates were ranked by degradation efficiency as: *Aspergillus flavus* > *Macrophomina sp.* > *Fusarium pallidoroseum.*

Gajendiran et al. (18) investigated the potential of *Aspergillus oryzae SJA1* for MCP biodegradation. They found that the enzymes active in this strain could degrade 100% of MCP within 120 hours of incubation at 30 ± 2°C and pH 7.2 in the presence of nutrients such as carbon, nitrogen, and phosphorus. When inoculated into the soil and minimal medium without added nutrients, SJA1 still achieved complete degradation of MCP after 168 hours. This indicates that strain SJA1 can efficiently degrade MCP both in nutrient-rich and nutrient-deprived condition.

Dudeja et al. (19) highlighted the high toxicity of MP in soil and water due to its persistence and stability. The researchers examined 20 fungal strains under various parameters affecting viability. The results showed that increased pH and inoculum size improved MP degradation, while higher glucose concentrations decreased degradation. According to the studies, the maximum biodegradation of MP was reported to be about 65–70% at 30°C and pH 8. This study primarily focused on the conditions influencing the biodegradation of MP by fungi rather than on the identification of the fungi themselves.

Research on the biodegradation of FNT by different fungal and bacterial isolates has also been reported. Among the tested strains, *Trichoderma viride* exhibited the highest degradation efficiency (73.22%) over 14 days of incubation period at 30 ± 2°C, followed by *Aspergillus niger* (66.52%) and *Brady rhizobium* sp. (60.44%), all of which played a significant role in the biodegradation process (21).

In a separate investigation conducted by Peter et al, *Fusarium oxysporum* strain JASA1, originally isolated from sugarcane fields, was evaluated for its ability to mineralize MLT. Using an enrichment technique, the researchers isolated fungal strains capable of degrading MLT from contaminated soil samples. Strain JASA1 successfully degraded up to 400 mg/L of MLT in a mineral salts medium. In experiments where the soil was supplemented with nutrients (carbon, nitrogen, and phosphate), complete degradation was achieved within 8 days. The isolate could degrade MLT by the eighth day of incubation. Conversely, under nutrient-deficient conditions, full degradation occurred by the ninth day of incubation (22).

Fungal degradation of OC insecticides

This section summarizes the findings from nine studies (29-35,37) that investigated the biodegradation of OC pesticides including Endosulfan (ESL) (29,32,33,35), Chlorinated cyclodiene and ESL (37), Lindane (LND) (30), Heptachlor (HPC) (31), Dichloro-Diphenyl-Trichloroethane (DDT) (34), and Alltherin.

Several studies have focused on the biodegradation of ESL; Abraham et al. (33) and Ahmad et al. (32) explored the use of bacterial and fungal consortia for the bioremediation of ESL-contaminated soils. Abraham et al. assessed various bacterial isolates, such as *Halophilic bacterium*, *Klebsiella pneumoniae*, *Enterobacter asburiae*, and *Enterobacter cloacae*, as well as fungal isolates like *Aspergillus tamarii*. Ahmad et al. investigated the environmental transformation of ESL through biodegradation by soil microbes that were isolated and cultured, such as *Aspergillus flavus, Bacillus subtilis*, *Aspergillus Niger*, and *Penicillium chrysogenum*. Their results showed complete degradation of ESL and its metabolites within 6 and 4 days, respectively, in nutrient-enriched soil inoculated with the bacterial and fungal consortium.

Mariana et al. (35) further evaluated the biodegradation potential of a soil-isolated strain of *Penicillium sp*. against ESL. Under controlled conditions (30°C, pH 7), this fungus could completely remove 50 mg/L of ESL from Minimal Salt Medium (MSM), using it as the sole carbon source over the six-day incubation period. Notably, the genotoxic properties of ESL were also significantly reduced following fungal treatment. These findings suggest that the *Penicillium sp*. *CHE 23* can effectively process ESL residues in both soil and water environments without producing toxic metabolites, making it a promising candidate for environmental remediation.

Furthermore, research by Abraham et al. (29) demonstrated that a novel fungus, *Lasiodiplodia sp. JAS12,* and the bacterium *Klebsiella pneumoniae JAS8* can decompose ESL as a nutrient source in the environment. This was the first report on ESL degradation by *Lasiodiplodia sp*. In this degradation pathway, the main metabolite, ESL sulfate, was ultimately transformed into non-recyclable acidic forms, as confirmed by FTIR. Therefore, these fungal and bacterial species offer significant potential as green technologies for cleaning up sites contaminated with ESL or ESL sulfate.

Additionally, Royata et al. (37) reported the biodegradation of Dieldrin (DLR) and ESL by two fungal species, *Mucor racemosus* strain *DDF* and *Mortierella sp. W8*, originally isolated from pesticide-contaminated soils. Under controlled conditions (25°C, pH 2), strain *DDF* degraded more than 90% of DLR over a 10-day incubation period. During this process, transdiol Aldrin (ALR) was detected as a minor metabolite. Notably, DDF further reduced the level of ALR transdiol while producing several unidentified secondary metabolites. In contrast, *Mortierella sp. W8* demonstrated the ability to degrade over 70% of ESL, primarily converting it into its sulfated metabolite. This transformation raises concerns regarding potential environmental toxicity due to the persistence or bioactivity of the resulting metabolites.

Other studies have investigated various OCs, including LND, DDT, and HPC. According to a report conducted by Kaur et al. in 2023, strains of *ascomycetes* isolated from agricultural soil are highly effective in the bioremediation of LND. Notably, *Pleurostoma richardsiae (FN5)* is the first fungus shown to degrade LND using a pathway similar to bacterial biodegradation (30).

Russo et al. (34) found resistant species such as *Trichoderma hamatum FBL 587* and *Rhizopus arrhizus FBL 578* against DDT. However, there are no reports on their ability to actually break down DDT, as this study focused on evaluating their tolerance.

Purnomo et al. (31) reported that inoculating with *Pleurotus ostreatus* reduced HPC levels by nearly 89% after 28 days at 25°C, with chlordane as the main metabolite. *Pleurotus ostreatus* also significantly degraded HPC epoxide by 32% over the same period, with HPC Diol identified as a byproduct. Because *Pleurotus ostreatus* can convert HPC into less harmful substances and effectively degrades HPC Epoxide, it was chosen for use in contaminated agricultural soils.

One study focused on Carb pesticides (38), specifically the bioremediation of Carbaryl (CBL) and Carbofuran (CF) using the fungus *Acremonium sp.* The degradation efficiencies were impressive: 97.65% for Carbofuran and 99.06% for CBL. In this study, the optimum conditions for biodegradation were 28°C and pH 7.

Regarding Allethrin (ALR) biodegradation, a new strain of *Fusarium proliferatum* CF2 was capable of tolerating high concentrations up to 1000 mg/L in a minimal salt medium. Using response surface methodology, the optimal conditions for degradation were found to be 26°C and pH 6.0. Under these conditions, strain CF2 completely degraded ALR within 144 hours (28).

According to the study by Shi et al. (23) on the biodegradation of ACE by *Fusarium sp.* strain CS-3, the strain could degrade high concentrations of ACE (50 mg/kg) across a wide pH range (5.0–8.0) and temperature (20–42°C). Strain CS-3 efficiently degraded 99.6% of ACE within 96 hours.

Role of fungi in the degradation of herbicides

Fungal degradation of herbicides varies, with removal rates between approximately 24% and 96.1%. For Acetachlor, different fungal strains achieved the following removal efficiencies (40).

- *Tolypocladium geodes*: 91%
- *Cordyceps cicadae*: 87%
- *Metacordyceps owariensis*: 78%
- *Metarhizium cylindrosporae*: 69%
- *Verticillium chlamydosporium*: 55% (lowest at 40%)

Research by Yadav et al. (41) showed that some *Trichoderma* species tolerate sulfosulfuron well, degrading it via specific metabolic pathways, decarboxylation at the sulfonylurea bridge, and hydrolytic cleavage of the sulfonylamide bond. These fungi grew well in media containing up to 0.2 mg/ml of Sulfosulfuron, with optimal growth at 25–30°C. They could use Sulfosulfuron as the sole carbon and nutrient source, but growth was inhibited at 35°C, indicating sensitivity to higher temperatures.

A study in 2023 (42) investigated the biodegradation potential of glyphosate by 50 fungal isolates, most from the *phylum Ascomycota*. All isolates could utilize glyphosate as a phosphorus source. Some showed increased biomass in glyphosate-enriched medium (2.35 mg/mL). The best conditions were 30°C and a pH of 6. Under these conditions, *Penicillium 4A21*, *Aspergillus 2B112*, and *Penicillium 2A31* achieved degradation rates of approximately 43%, 36%, and 35%, respectively, over 14 days. These results suggest these fungi are promising candidates for glyphosate bioremediation.

Additionally, Pandey et al. (43) reported that *Aspergillus niger* degraded the rice herbicide orthosulfamuron by 50% within 10 days and up to 96.1% after 40 days.

In 2021, Wongputtisin et al. studied the degradation of paraquat, a highly toxic herbicide, by two fungi: *Aspergillus tamarii* PRPY-2 and *Cunninghamella sp*. PFCM-1. They found that 8–10% paraquat remained on the mycelium, while 24–46% was degraded (45). Another study evaluated a bio-mixture for degrading three Triazine herbicides (Atrazine (ATR)/Terbuthylazine (TBR)/Terbutryn (TRN)) plus CPF, an insecticide, using *Trametes versicolor*. The degradation rates were 82.8% for the non-augmented mixture, 43.8% for the fungal bio-augmented mixture, and 84.7% for soil (48).

Another study investigated the degradation of two herbicides from different chemical groups: Imazamox (IMZ) and Chlorsulfuron (CSU). The researchers used 20 fungal strains and six bacterial strains. The results showed that bacteria were more effective at degrading IMZ, while fungi degraded CSU well. Both microorganisms demonstrated significant potential in the degradation of these pesticides. The highest biodegradation rates ranged from 28% to 57% for bacteria and 23% to 37% for fungi. Optimal performance for both groups occurred at 25°C and pH 7 under controlled conditions (51).

The degradation of the Triazole herbicide was tested with five fungal strains: *Aspergillus flavus*, *Penicillium chrysogenum*, *Aspergillus niger*, *Aspergillus terrus*, and *Aspergillus fumigatus*. After 42 days at 29 ± 2°C and pH 7, degradation percentages were: *Aspergillus flavus* 74%, *Aspergillus fumigatus* 81%, *Aspergillus niger* 95%, *Penicillium chrysogenum* 98%, and *Aspergillus terreus* 90% (49).

Biodegradation experiments with one bacterial strain, *Xanthomonas axonopodis*, and three fungal strains (*Aspergillus flavus*, *Penicillium chrysogenum*, and *Aspergillus niger)* showed the following degradation rates of Alachlor after 35 days: 17.1% *Aspergillus flavus*, 5.5% *Penicillium chrysogenum*, 72.6% *Aspergillus niger*, and 82.1% *Xanthomonas axonopodis*, respectively (50).

In 2022, Guo et al. studied the degradation of glyphosate by *Fusarium verticillioides* C-2 in sterilized and non-sterilized soils contaminated with 60 mg/kg. Under optimal conditions (28°C, pH 7), glyphosate degradation was 72.17% in sterilized soil and 89.07% in non-sterilized soil, with the highest rate in non-sterilized soil. When sterilized soil was treated with the strain, the degradation remained at 72.17% (44).

The herbicides 2,4-dichlorophenoxyacetic acid (2,4-D) and 2,4,5-trichlorophenoxyacetic acid (2,4,5-T), used as synthetic auxins in agriculture, were tested with three fungi. The study focused on the roles of laccases and cytochrome P450 enzymes. A positive correlation was found between the white-rot fungus *Rigidoporus sp. FMD2* laccase activity and herbicide degradation (47).

In 2024, Xu et al. (46) evaluated the genetic potential of *Simplicillium* sp. isolated from agricultural soil to biodegrade Imidacloprid (IMID) and Diuron (DUR). After seven days, degradation rates were 50.19% for IMID and 70.57% for DUR. The main degradation reactions involved nitro-reduction, hydroxylation, and other processes. They also identified multiple degradation pathways and products, providing new insights into microbial genetics (Table 1).

Role of fungi in the degradation of fungicides

Kumar et al. (53) studied the biodegradation of Isopyrazam (IPP), a Pyrazole Carboxamide fungicide inhibiting succinate dehydrogenase. Fungal strains degraded it in the following orders: *Aspergillus flavus* 21%, *Penicillium chrysogenum* 27%, *Aspergillus niger* 21%, *Aspergillus tereus* 11%, and *Aspergillus fumigatus* 30%. Additionally, *Gongronella sp*. and *Rhizopus oryzae* degrade the fungicide MET at approximately 1.0 mg·kg^{-1} d^{-1} (54)

Sharma et al. (52) looked at how different *Trichoderma* isolates degrade Carbendazim. The fungi showed various tolerance and degradation levels at 25°C and 200 rpm, over 5 days: 85% in *T. Harzianum*, 47% in *T. viride*, and 21% in *T. atroviride* (Table 1).

Discussion

Mycoremidiation via fungi as a sustainable strategy

The use of fungi for pesticide degradation, known as mycoremediation, has emerged as a sustainable and eco-friendly strategy to mitigate the adverse effects of pesticide contamination in soil ecosystems. Fungi secrete specialized extracellular enzymes, such as laccases, peroxidases, and cytochrome P450, which can break down complex chemical structures into less harmful compounds (55).

Among various fungal genera, white-rot fungi have been extensively studied for their robust metabolic capabilities. However, other genera, including *Aspergillus*, *Penicillium*, and *Trichoderma*, also demonstrate significant potential in pesticide degradation (42). The efficiency of mycoremediation depends on several environmental factors, including soil pH, temperature, nutrient availability, and pesticide concentration. Typically, optimal pH levels range from slightly acidic to neutral, while moderate temperatures (20–37°C) generally enhance fungal activity. Understanding these parameters is essential for optimizing mycoremediation processes and achieving effective pesticide degradation (56).

In this systematic review, we highlighted the role of fungi in degrading pesticides across three major classes: Insecticides, herbicides, and fungicides. The results indicate that most studies have focused on the biodegradation of insecticides, with less emphasis on herbicides and even less on fungicides (Table 1). This distribution reflects the widespread use of insecticides in agriculture and their associated environmental challenges, while also pointing to important research gaps for herbicides and fungicides.

Impact of essential parameters on fungal pesticides degradation in soil environments

Various factors can influence microbial activity and pesticide breakdown, including temperature (58), moisture (59), chemical structure (60), soil oxygen levels, pH, and nutrients (61). Temperature and pH are especially important, significantly affecting biodegradation efficiency (62,63). Fungi generally tolerate higher contaminant concentrations than bacteria, with white-rot fungi being particularly adept due to their ability to detoxify complex chemical mixtures (64). A thorough understanding of how environmental conditions affect fungal growth is key to advancing soil bioremediation strategies.

Optimizing environmental factors

The degradation of pesticides by fungi is greatly affected by environmental parameters such as temperature, pH, and pesticide concentration. These factors play a crucial role in regulating microbial activity, enzymatic efficiency, and overall biodegradation performance. Below, we investigate the influence of each parameter in detail.

Temperature

Temperature is one of the most vital factors impacting microbial activity and pesticide degradation. Studies have shown that optimal temperature ranges vary among fungal species and the specific pesticide targeted. For example, Bhati et al. (2019) observed that fungi like *Aspergillus terreus*, *Aspergillus fumigatus*, *Alternaria alternata*, and *Aspergillus flavus* exhibited enhanced biomass growth at 30°C. Seasonal temperature variations between 20°C and 38°C were also found to influence biodegradation rates significantly (65). Similarly, Fang et al. (2009) identified 35°C as optimal for CPF degradation by *Verticillium sp.,* while other studies reported 30°C as ideal for degrading cymoxanil, pendimethalin, carbofuran, and ESL using fungal strains such as *Aspergillus versicolor*, *Pichia anomala*, and *Aspergillus terreus* (66). Interestingly, *Ganoderma australe* demonstrated the highest LND degradation efficiency at 18°C, highlighting the specific temperature (60).

pH

pH significantly influences fungal enzymatic activity and growth. Most research suggests that neutral to slightly acidic conditions are optimal (67). For instance, Fang et al. (2009) found that a pH of 7.0 was ideal for CPF degradation by *Verticillium sp.*, with deviations reducing efficiency (66). Similar results were seen with cymoxanil and pendimethalin, which also favored pH 7.0 (60). Conversely, *Mucor racemosus* showed strong adaptability, degrading DLR across a pH range of 4.0–8.0, indicating its potential for diverse environmental conditions (60). For carbofuran degradation by *Pichia anomala*, the optimal pH was slightly alkaline at 7.5. Some studies suggest that slightly acidic conditions may further enhance degradation for specific pesticides (58)

Pesticide concentration

High pesticide concentrations can inhibit microbial activity by toxicity, thus reducing degradation efficiency. Zhao et al. found that optimal degradation of methamidophos by *Penicillium oxalicum ZHJ6* occurred at glucose concentrations up to 1% and with higher nitrogen content (68). Farhan et al. reported maximal CPF degradation at 250 mg/L, beyond which higher concentrations increased lag phases and lowered efficiency (69).

Implication for sustainable agriculture and future research

The optimal conditions for biodegradation vary widely across different pesticide classes, including insecticides, herbicides, and fungicides. Factors such as temperature, pH, chemical structure of the pesticide, and the enzymatic capabilities of fungi are also critical. Proper optimization enhances enzyme activity and degradation pathways, promoting complete mineralization and reducing the risk of toxic intermediates, thereby minimizing environmental pollution and preserving ecological balance (Table 2).

Our commitment, "Green Earth," embodies our dedication to sustainable environmental solutions. By deepening our understanding of fungal-mediated pesticide degradation, we aim to develop eco-friendly strategies that protect both soil and water resources. Continued research in this field is vital for minimizing pesticide pollution and fostering a cleaner, safer planet for future generations.

Conclusion

This study systematically reviewed the role of fungi in degrading pesticides in soil, emphasizing the influence of key environmental factors, including temperature, pH, and pesticide concentration, on biodegradation efficiency. Our findings align with the detailed analysis presented in the discussion section, where we highlighted how these factors significantly regulate fungal activity and degradation outcomes. Among the fungal species investigated, *Aspergillus niger* and *Aspergillus flavus* demonstrated exceptional biodegradation potential across multiple pesticide classes. Their broad enzymatic activities—such as laccase, oxidase, protease, and amylase—play a pivotal role in breaking down pesticide residues into less toxic or non-toxic products. These results underscore the critical importance of optimizing environmental conditions to maximize the efficiency of fungal-mediated bioremediation.

The discussion also revealed that optimal degradation conditions vary depending on the fungal species and pesticide type. Neutral to slightly acidic pH levels and moderate temperatures (20–37°C) generally enhance enzymatic activity and fungal growth. However, the absence of a clear correlation between these factors and the percentage of biodegradation across different pesticides suggests that strain-specific adaptations require further investigation. This highlights the complexity of the biodegradation process and the need for tailored approaches to optimize conditions for specific fungal strains and pesticide types.

To address the gaps identified in this study, future research should focus on several key areas:

1. Elucidation of Degradation Mechanisms: A deeper understanding of the molecular and enzymatic mechanisms underlying pesticide degradation can facilitate strain optimization through genetic engineering or adaptive evolution techniques, as discussed in the analysis of enzymatic activities.
2. Cost-Effectiveness and Scalability: Developing cost-effective and scalable reactor designs is essential for translating laboratory findings into large-scale applications, enabling practical implementation of fungal-based bioremediation strategies.
3. Alternative Pesticide Management Practices: Complementary approaches, such as reducing pesticide use through Integrated Pest Management (IPM) strategies, can minimize environmental pollution and reduce the burden on biological treatment systems, as emphasized in the discussion of environmental sustainability.
4. Management of Intermediate Products: Toxic intermediates formed during the degradation process may pose greater risks than the parent compounds. Strategies to ensure complete mineralization are therefore critical to mitigating potential environmental hazards, as noted in the discussion of degradation pathways.

In conclusion, this study highlights the immense potential of fungi as natural agents for pesticide degradation, offering sustainable solutions to mitigate environmental contamination. By addressing the identified gaps and advancing research in these areas, we can pave the way for more effective and eco-friendly strategies to protect soil and water ecosystems, ultimately contributing to a cleaner and healthier environment for future generations.

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Competing Interests

The authors state that they have no known financial conflicts or personal relationships that could have influenced the work reported in this study.

Ethical Approval

There are no ethical issues associated with this study. The authors confirm that all data collected during the research are accurately represented in the manuscript and that no data from the study will be published separately elsewhere.

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