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Bioremediation of Phenolic Pollutants by Fungi: A Perspective

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Abstract: Phenol is a priority pollutant that poses a significant risk to human health and ecological systems when released into aquatic environments. Consequently, numerous technologies have been developed and implemented to remove phenol from wastewater. These technologies can be classified into physical, chemical, and biological techniques. While conventional treatment methods can effectively remove phenol, some are more economical and less environmentally beneficial. This overview, which is based on a collation of relevant and comprehensive literatures, emphasizes various phenolic pollutants in wastewater and how mycoremediation can be implemented to address these issues. Mycoremediation research has been chiefly directed on investigating the effects of various conditions on phenol degradation and evaluating its effectiveness under controlled experiments. Moreover, mycoremediation enables a doable solution for mitigating pollution, improving water quality, and supporting biodiversity in aquatic ecosystems. These also mean that advancing mycoremediation encourages environmentally sustainable practice. However, the remaining gaps exist in current research including the toxicity assessment of degradation by-products, the application of synthetic biology methods for chassis modification, creation and development of innovative immobilization methods, improvement of remediation efficiency by integration of multiple technologies and scalability of mycoremediation for practical wastewater treatments. These areas warrant further research to advance the greater potential of mycoremediation.

Keywords: Fungi, mycoremediation, phenol, wastewater treatment

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1. Introduction

Water pollution has become a significant global concern due to several factors, including population growth, industrial expansion, urbanization, rising water usage, and agricultural practices. These issues have led to environmental degradation and contamination, adversely affecting water bodies, human health, and ecology. Phenolic compounds are a notable type of organic contaminants that significantly affect water quality due to their high toxicity and carcinogenic characteristics (Bibi *et al.*, 2023; Liu *et al.*, 2024). Phenol and its derivatives are among the most extensively utilized organic compounds. Simple phenolic molecules serve as intermediaries in the synthesis of specific polyphenolic secondary metabolites. They are also used as starting points for the industrial synthesis of numerous other chemical compounds. Consequently, industrial effluent from manufacturing organic chemicals, oil refining, and olive processing contains phenol and its derivatives (Wu *et al.*, 2022).

Persistent pollutants, such as phenols, are resistant to degradation by physical, chemical, or biological means (Mohd, 2022). Because of this, phenol has been listed as one of 129 priority pollutants by the US EPA and the Canadian National Pollutant Release Inventory (NPRI) that must be remedied before being released into the environment (EPA, 2014). Approximately 10 million tons of phenolic compounds are released into the environment annually by agrochemicals, leather, textiles, petrochemicals, and pharmaceuticals industries (Alshabib & Onaizi, 2019). In Indonesia, for instance, phenolic compound was detected around 0.013 ng/L in the tributary of Bengawan Solo River (Khoiriyah *et al*., 2019). Moreover, industrial processes such as making paint, paper, pulp, and pesticides are believed to release phenolic chemicals into the environment (Alshabib & Onaizi, 2019). The percentage of phenolic compounds in industrial effluents can vary from 1 mg/L to 7000 mg/L (Mohd, 2022; Bibi *et al*., 2023).

The discharge of untreated phenolic wastewater into the environment can cause significant health issues and pollute soil, surface water, and groundwater, disrupting the natural environment equilibrium (Anku *et al*., 2017). Moreover, it is common for phenolic wastewater to seep into the ground and contaminate surrounding lakes, rivers, water reservoirs, and agricultural areas (Panigrahy *et al*., 2022). As a result, the EPA sets a criterion for water filtration at fewer than 1 part per billion (ppb) for phenol in surface waters. This decision complies with the standards established by the European Union.

However, the permissible discharge limits for phenolic compounds are 0,5 mg/L for surface waters and 1,0 mg/L for effluents from sewage treatment systems as specified by Italy government, law no. 152/2006 (Mohd, 2022). The Indonesian government has established permissible phenol content limits for river water quality standards, ranging from 0,002 to 0,02 mg/L depending on the intended usage (Law No. 22/2021). Phenolic compounds, even at low concentrations, can adversely affect aquatic biota, and in drinking water, they can cause unpleasant tastes and odors at level as low as 5 g/L (Panigrahy *et al*., 2022). Thus, proper and effective treatment of phenolic wastewater is crucial before reuse or discharge (Alshabib & Onaizi, 2019).

Environmental exposure to phenol has a significant negative influence on human health as well as ecological systems. Even at modest levels, phenol can be lethal to aquatic life (Rittmann & McCarty, 2001). The human body can quickly absorb phenol through the skin, diet, and respiratory systems. Hanafee *et al*. (2019) stated that phenol exposure can result in a variety of health issues, including catastrophic skin damage, eye irritation, severe gastrointestinal problems, cardiovascular disorders, and, in the worst cases, death. Therefore, urgent intervention is required to mitigate the risks of phenol exposure and to remediate phenolic effluents in ecosystems.

A variety of physical and chemical approaches, including distillation, membrane separation, chemical and electrochemical oxidation, ozonation, advanced oxidation, and photocatalysis, have been suggested in treating phenolic wastewater (Wu *et al*., 2022; Bibi *et al*., 2023). Effective removal phenolic contaminants rely on the selection of suitable membrane and adsorbent materials. However, these materials often exhibit significant losses and inadequate regeneration (Crini *et al*., 2019; Dotto & McKay, 2020). The high chemical requirements of complex oxidation processes result in considerable running costs, even though they are frequently highly efficient (Tuan Tran *et al*., 2022). Some treatment technologies merely transfer pollutants from the water to another medium, potentially causing secondary pollution (Hodges *et al*., 2018). Limitations of physical and chemical wastewater treatment methods have driven the development of advanced, cost-effective, and sustainable technologies to reduce their environmental impact (Mehdi *et al*., 2021; Wu *et al*., 2022).

Mycoremediation is an environmental decontamination technique that utilizes fungi as a means of remediation. Fungi, alongside bacteria, are known for their diversity and remarkable capacity to decompose phenolic compounds. Unlike bacteria, fungi can thrive in ecologically challenging conditions, including environments with limited nutrient availability, reduced water activity, and low pH levels, where bacterial growth may be insufficient (Ibrahim & Al-Ghamdi, 2019). Fungi possess the capability to utilize phenol as a carbon source for their development, demonstrating remarkable adaptability to various ecosystems and the ability to thrive in extreme conditions (Hanafee *et al.*, 2019). This review describes the various types of phenolic pollutants present in aquatic ecosystems, their environmental impacts, and the utilization of fungal-based techniques for the remediation of phenol in these environments.

2. Methodology

This review employs a literature review methodology to explore the presence of phenolic pollutants in aquatic ecosystems, their environmental impacts, and the application of fungal-based remediation techniques. Relevant studies were sourced from reputable scientific databases such as ScienceDirect, Web of Science, and SpingerLink. Search terms included combinations of keywords such as mycoremediation, biodegradation of phenol, phenol environmental impact, and fungi enzymatic pathways. The inclusion criteria focused on peer-reviewed journal articles published in English that addressed phenolic pollution in aquatic environments and discussed fungal-based remediation approaches. Studies unrelated to aquatic ecosystems, phenolic pollutants, or fungi-based techniques were excluded. Extracted data encompassed the types and sources of phenolic pollutants, their ecological effects, and the specific fungal mechanisms used for phenol degradation. The review synthesizes findings into three primary themes: the type of phenolic pollutants, the environmental and ecological impacts, and the potential of fungal-based bioremediation as a sustainable solution. This review focuses on highlighting the advantages of fungi in bioremediation while recognizing, but not extensively addressing, challenges and limitations such as scalability and economic viability.

3. Result and Discussion

3.1. Types of phenolic pollutants

Phenolic compounds are introduced into aquatic environments through various pathways and can be detected in multiple environmental matrices, including surface water, seawater, and riverbed sediments. Common phenolic compound found in wastewater include simple phenols (phenol and cresols), chlorophenols (2,4-dichlorophenol and pentachlorophenol), nitrophenol (2-4 dinitrophenol and 4-nitrophenol), and bisphenol

3.1.1. Simple Phenols

Simple phenols consist of a benzene ring bonded to a hydroxyl group (OH) and commonly present in significant concentrations in industrial wastewater, particularly from refineries. In some cases, phenol concentration in wastewater can reach levels as high as 10 g/L (Wu *et al.*, 2022).

a. Phenol ($C6H5OH$): found in wastewater from the textile and pharmaceutical industries, phenol poses a threat to aquatic ecosystems, leading to reduced biodiversity (El-Naeb *et al.*, 2022; Ahmaruzzaman *et al.*, 2024).
b. Cresols ($C7H8O$): These methylated phenols, used in wood preservatives and disinfectants, exist in three isomeric forms (o-cresol, m-cresol, p-cresol). They are harmful to both soil and water environments (Gucbilmez, 2022).

3. 1.2. Chlorinated Phenols

Chlorinated phenols are phenol derivatives with one or more chlorine atoms covalently bonded. This compound are typically found in lake and river sediments, tannery waste and sewage sludge (Wu *et al.*, 2022).

a. 2,4-Dichlorophenol ($C6H4Cl2O$): Commonly used in pesticide production, this persistent pollutant adversely impacts both aquatic and terrestrial organisms (Gucbilmez, 2022).
b. Pentachlorophenol ($C6Cl5OH$): Utilized in wood preservation and as a pesticide, pentachlorophenol is highly toxic to aquatic life and contributes to long-term soil and groundwater contamination (Kahru *et al.*, 2002).

3.1.3. Nitrophenols

Nitrophenols are used in agricultural and industrial processes and are linked to respiratory and hematological health issues in humans. They also contribute to groundwater pollution (Maletta *et al.*, 2023)

a. 2,4-Dinitrophenol ($C6H4N2O5$): used in the manufacture of explosives and pesticides, this compound is toxic to aquatic life and humans and posing a significant risk of environmental risk if released into water bodies (Gucbilmez, 2022).

b. 4-Nitrophenol ($C6H5NO3$): A by-product of industrial activities such as pesticide production, it harms aquatic organisms and accumulates in the environment (Kahru *et al.*, 2002).

3.1.4. Bisphenols

Bisphenol A (BPA, $C15H16O2$), widely used in manufacturing plastics and epoxy resins, is recognized as an endocrine disruptor capable of interfering with hormonal functions in wildlife and humans. It contaminates water sources frequently (Kahru *et al.*, 2002; Gucbilmez, 2022).

3.2. Environmental Impacts

3.2.1. Aquatic Ecosystems

The highwater solubility of phenolic chemicals facilitates their contamination of aquatic habitats, thereby reducing biodiversity. These substances interfere with the growth and reproduction of aquatic organisms, primarily affecting algae, fish, and microbes. For example, phenol concentration ranging from 9 to 25 mg/L can be lethal to fish (Gucbilmez, 2022). When phenolic chemicals are present at level exceeding safe thresholds, they can alter phytoplankton diversity significantly and leading to ecological disruption (El-Naeb *et al.*, 2022). Furthermore, phenolic chemicals can disrupt the physiological functions of aquatic species, resulting in increased mortality rates and genotoxic effects (Gad & Saad, 2008). Phenolic pollutants also affect biodiversity by altering microbial populations and degrading water quality (Saratale *et al.*, 2020).

Table 1. Guidelines at both national and international levels regarding the presence of phenolic compounds in water

Compounds	National Water Quality Standards (mg/L)				Regulation of Drinking Water (mg/L)		
	Indonesia Government Regulation No. 22 of 2021				WHO	EPA 2023	EC 2020
	Class I[a]	Class II[b]	Class III[c]	Class IV[d]	Water for Human Consumption		
Phenol	0.002	0.005	0.01	0.02	0,001		0,001
Pentachlorophenol					0.009	0.001	
Dinitrophenol						0.007	0.001
2,4,6- trichlorophenol					0.2		0,025
Bisphenol							0.003

a= Water for raw drinking water and other applications that necessitate a specific level of water quality.
b= water for infrastructure and facilities, including recreational activities, freshwater fish cultivation, animal husbandry, crop irrigation, and other applications necessitating similar water quality standards.
c= water for cultivating freshwater fish, livestock management, irrigation of crops, and other applications that require identical water quality standards.
d= water for irrigation of crops and other applications that require a similar quality of water.

3.2.2. Soil Pollution

Pentachlorophenol is a chlorinated phenol that adheres to soil particles and persists in the environment for extended periods while inhibiting microbial growth. It reduces soil fertility and hinders plant development. Furthermore, leaching from contaminated soils poses a threat to groundwater quality (Kahru *et al.*, 2002).

3.2.3. The Effect of Bioaccumulation on the Food Chain

Many phenolic contaminants tend to bioaccumulate in organisms, transferring up the food chain and enhancing their harmful effects. This bioaccumulation can lead to long-term health risk for higher organisms, including reproductive and developmental disorders both in humans and wildlife (Gad & Saad, 2008).

3.2.4. Human Health Risk

Numerous phenolic derivatives are recognized for their -high toxicity and their tendency to produce hazardous by-products during water treatment, such as polychlorinated dibenzo-n-dioxins (Taneeva *et al.*, 2024). Humans' exposure to phenolic chemicals can result in severe health complication. Endocrine disruptors such as BPA are associated with developmental delays, cancer, and reproductive issues. Chronic exposure can also damage the kidneys and liver (Kahru *et al.*, 2002).

Chlorination of raw water increases the risks of exposure to phenolic chemicals. The production of chlorophenols in drinking water has been primarily attributed to the chlorination process (WHO, 2003). More stringent regulations are necessary because the elevated global levels indicate that current treatment methods are insufficient to completely eliminate phenolic compounds from water, posing significant risks to public health.

Water potability recommendations provide acceptable values for water quality standards intended for human consumption. These regulations, which are currently not sufficiently stringent regarding emerging toxins such as phenolic compounds, must be enforce by public water systems (Ladeia Ramos *et al*., 2024). Table 1 lists the phenolic compounds that have reached the Maximum Permitted Concentration (MPC) for surface and drinking water, as specified in the national guidelines of the Indonesia government (Law No. 22/2021) and relevant international standards.

3.3. Fungi-based strategies

Phenol compounds are organic pollutants that degrade water quality and belong to the class of aromatic organic substances with the molecular formula C_6H_5OH. These compounds can be produced naturally by various organisms or released into the environment as raw effluent by multiple industries. When water containing chlorine react with phenolic chemicals, it forms complexes with unpleasant tastes and odors. The substitution of chlorine enhances these undesirable characteristics with harmful consequences (Almasi *et al.*, 2019). Many phenolic compounds are dangerous due to their carcinogenic, mutagenic, teratogenic, and toxic properties. They can also disrupt the endocrine system. Even at low concentrations, they have a significant negative impact on aquatic ecosystems and human health (Alshabib & Onaizi, 2019; Singh *et al.*, 2021). Due to their persistent and resistance to degradation, phenolic contaminants represent the major environment risk and treatment challenge.

Table 2. Removal of phenolic pollutants by fungi and associated mechanisms

Fungal strain	Periods	Compound	Removal (%)	Mechanism	Reference
Pleurotus ostreatus (P. ostreatus)	10 days	p-chlorophenol (CP)	99.2	Biodegradation & Adsorption	(Batista-García *et al.*, 2017)
		phenol	98.7		
	8 days	Nonylphenol	70.0	Biotransformation& Biosorption	(Pezzella *et al.*, 2017)
		Bisphenol A	65.0		
	5 weeks	phenol	90.0	Enzymatic oxidation	(Ntougias *et al.*, 2015)
P. dryinus	30 days	chlorophenols,	>95.0	Biotransformation	(Ariste *et al.*, 2019)
Trametes hirsuta (T. hirsuta)	10 days	p-chlorophenol (CP)	99.0	Biodegradation & Adsorption	(Batista-García *et al.*, 2017)
		phenol	99.7		
	30 days	chlorophenols,	>80.0	Biotransformation	(Ariste *et al.*, 2019)
T. versicolor	8 days	Nonylphenol Bisphenol A	85.0 100.0	Biotransformation& Biosorption	(Pezzella *et al.*, 2017)
Tricoderma atroviride	8 days	Phenol 2, 4-dinitrophenol	92.0 91.0	Lignocellulolytic enzymes	(Kumar Vaidyanathan *et al.*, 2022)
Cadophora sp.	10 days	p-chlorophenol (CP)	73.0	Biodegradation & Adsorption	(Batista-García *et al.*, 2017)
		phenol	91.2		
Phanerochaetea chrysosporium	10 days	p-chlorophenol (CP)	99.2	Biodegradation & Adsorption	(Batista-García *et al.*, 2017)
		phenol	99.2		
	8 days	Nonylphenol	80.0	Biotransformation & Biosorption	(Pezzella *et al.*, 2017)
Pseudogymnoascus sp		Bisphenol A p-chlorophenol (CP) phenol	60.0 91.0 97.1	Biodegradation & Adsorption	(Batista-García *et al.*, 2017)
Aspergillus caesiellus (A. caesiellus)		p-chlorophenol (CP)	89.0	Biodegradation & Adsorption	(Batista-García *et al.*, 2017)
A. awamori	7-8 days	phenol phenol	92.2 85.0	Degradation	(Stoilova *et al.*, 2006)
A. biennis	5 weeks	phenol	>80	Enzymatic oxidation	(Ntougias *et al.*, 2015)

Mycoremediation, a fungi-based treatment strategy, offers considerable potential for addressing phenolic. Fungi are well-known for their ability to degrade aromatic xenobiotics through their highly effective enzymatic biodegradation processes on wide range structural diverse of contaminants. Both live and dead cells, as well as their enzymes, have been studied for treating wastewater contaminated with phenolic compounds. Fungal species, including Ascomycetes, *Aspergillus fumigatus*, *Debaryomyces, Aspergillus niger*, dark septate endophyte fungi (DSE), and various Basidiomycetes have been studied for their ability in phenol degradation (Melati *et al.*, 2021, 2023; Mtibaà *et al.*, 2020; Jiang *et al.*, 2017; Tebbouche *et al.*, 2016; Kües, 2015). Other fungi and their phenol reduction mechanism are summarized in Table 2.

Various fungal strains from diverse taxonomic groups, have shown the ability to eliminate, break down, and completely degrade phenols in liquid environments, primarily through co-metabolism. Fungi employ several mechanisms for phenol removal, including sorption, oxidative and reductive dechlorination, conjugation, ring cleavage, mineralization, and polymerization (Tomasini & Leon-santiesteban, 2019).

Table 2 shows that white rot fungi (WRF) groups such as *Pleurotus* sp., *Trametes* sp., and *Phaenorocytes* sp. are commonly reported as phenol degraders with high removal efficiency. Similarly, filamentous fungi such as *Aspergillus* sp. are frequently studied for phenol mycoremediation.

However, several factors, including pH, temperature, oxygen availability, substrate concentration, fungal species, and immobilization methods, influence the efficiency of mycoremediation in phenolic compounds removal from aqueous solution. Understanding these parameters is crucial to enhancing fungal growth, enzyme activity, and elimination of phenolic pollutants.

a. The pH of the Medium

The pH levels significantly impact fungi growth and the activity of ligninolytic enzymes responsible for phenol degradation by. For examples, *Aspergillus niger* and *Trametes versicolor* thrive in neutral pH settings (6-7.2) (Siva Kumar *et al.*, 2009; Supriya & Neehar, 2014). This neutral pH is optimal for the activity of the ligninolytic enzymessuch as laccases, manganese peroxidases, and lignin peroxidases (LiPs). Conversely, extreme pH level can denature enzymes and inhibit fungal metabolic processes. Additionally, under such condition, the positive charges on amino groups in fungal cell wall , allow them to act as potential absorbers of phenolic compounds (Siva Kumar *et al.*, 2009). These findings underscore the importance of maintaining appropriate pH levels in bioremediation processes.

b. Temperature

Temperature strongly affects fungal phenol degradation, with optimal range varying by species. Studies indicate that temperature is essential in improving the effectiveness of phenol degradation processes. It is necessary to regulate the fungal enzyme synthesis and the metabolism (Sivasubramanian & Namasivayam, 2015). Fungi associated with phenol cleanup often exhibit their most efficient degradation rates between 25°C and 35°C. Elevated or decreased deviations from this range may cause denaturation of the enzyme or inhibit fungus growth. For instance, *Aspergillus niger* inhibits peak degradation efficiency at 35°C, while a significant reduction is observed below25°C or above 40°C (Supriya & Neehar, 2014). Similarly, *Magnusiomyces capitatus* QWD1 and *Penicillium janthinellum* N12 P6C3 show optimal performance at 35 °C (Hanafee *et al.*, 2019; Wang *et al.*, 2019). In contrast, *Aspergillus flavus* and *Aspergillus nomius* SGFA1 achieve maximum phenol degradation at 25 and 28. 1 ^{o}C, repectiveely (Zanin *et al.*, 2014; Liu *et al.*, 2023).

c. Oxygen Availability

Optimal oxygen availability for phenol degradation depends on the fungal strain and environment conditions. Research has demonstrated that different types of fungi have distinct preferences for oxygen concentrations, which are essential to their ability to degrade phenol compounds. Aerobic environment generally enhance phenol breakdown, as demonstrated by *Candida tropicalis* SDP-1, which effectively degraded 1200 mg/L of phenol within 40 hours under optimal condition of pH 8, 35°C, and agitation (Gong *et al.*, 2021). Similarly, *Debaryomyces* species exhibit efficient phenol degradation at pH 6.0 and 200 rpm agitation (Jiang *et al.*, 2016). Furthermore, *Magnusiomyces capitatus* QWD1 demonstrated superior performance in activated sludge environments, suggesting that oxygen levels can optimize degradation process (Wang *et al.*, 2019). These findings highlight the need for tailored oxygenation strategies in fungal bioremediation.

d. Phenol Concentration

High concentrations of phenol can inhibit fungal growth due to its toxic effect on cellular membranes and metabolic processes. While certain fungi tolerate moderate phenol concentrations, their degradation efficiency diminishes at elevated levels. Stoilova *et al.* (2007) investigated the biodegradation of phenols and their derivatives by *Aspergillus awamori* at various concentrations (0.3, 0.6, 1.2, and 3 g/L) andfound that the fungus's ability to degrade phenol decrease significantly at concentration above 0.6 g/L. Conversely, fungal strains such as *Graphium* sp. and *Phanerochaete chrysosporium* effectively degrade phenol at concentrations of 0.3 and 0.05 g/L, respectively, (Kennes & Lema, 1994; Santos *et al.*, 2003;). Additionally, endophytic fungi demonstrated phenol tolerance and degradation at concentrations as high as 0.8% (Khalil *et al.*, 2021).

e. Fungal Species and Enzymes Involved

Different fungal species and strains exhibit varying levels of phenol tolerance and degradation capabilities, largely due to their enzymatic systems. Among various fungal species, Basidiomycetes have emerged as promising candidates for phenolic mycoremediation due to their ability to degrade a wide range of persistent aromatic pollutants. This ability is attributed to the secretion of intracellular enzymes, such ascytochrome P450 monooxygenases, and the activity of external peroxidases, including laccase, manganese peroxidase, and lignin peroxidase (Yan *et al.*, 2017; Mtibaà *et al.*, 2020). The enhanced capability of Basidiomycota for phenol biodegradation is largely due to their production of a diverse range of phenol-degrading enzymes, such as laccases, tyrosinases, and various forms of manganese and lignin peroxidases (Kües, 2015). Furthermore, Ascomycetous fungi surpass white-rot fungi (WRF) in pollutant degradation due to their ability to survive under low oxygen concentrations, acidic pH, or ligninolytic substrates, condition that often influence enzymatic activity (Aranda, 2016; Mtibaà *et al.*, 2020). The degradation of endocrine-disrupting chemicals (EDCs) has also been shown to require the presence of cytochrome P450 enzymes, which act as crucial oxidizing agents (Nowak *et al.*, 2019; Mtibaà *et al.*, 2020). Additionally, the biodegradation of 2,4-dichlorophenol (2-4-DCP), nonylphenols (NPs), and 4-tert-octylphenol (OP) was assessed using the Ascomycetous fungus *Thielavia* sp. HJ22. This strain efficiently degraded 100%, 95%, and 80% of 4-tert-OP, NPs, and 2,4-DCP in less than eight hours, respectively. Cytochrome P450 monooxygenase and laccase enzyme from Ascomycetous fungi play essential roles in breaking down these phenolic pollutants (Mtibaà *et al.*, 2020).

Numerous fungi enzymatic pathways that aid in the conversion of phenolic chemicals into less hazardous forms are the main component of the fungal enzymes' process of phenol degradation. Important enzymes that use various methods to accomplish degradation, such as phenol hydroxylases, catechol dioxygenases, laccase and peroxidase are essential to this process. Phenol hydroxylase catalyzes the first hydroxylation of phenol to catechol (van Schie & Young, 2000). Then, catechol dioxygenases break down catechol via ortho or meta routes, producing non-toxic byproducts. For example, catechol 2,3-dioxygenase is used by *Nocardia hydrocarbonoxydans* for meta cleavage (Shetty & Shetty, 2016). Additionally, phenol hydroxylases can also hydroxylate catechol to produce pyrogallol. Further, phenol hydroxylase activity can be inhibited by high phenol concentrations, but catechol dioxigenase showed no effect (Radziff *et al.*, 2021). The peroxygenase mechanism in certain fungi, such those that produce hemoglobin dehaloperoxidase, involves the Fe=O center abstracting hydrogen atoms, which aids in the breakdown of chlorophenols (Zhang *et al.*, 2021).

Laccases efficiently detoxify phenols by catalyzing the oxidation of phenolic compounds through electron transfer processes and promote the breakdown of harmful phenolic compounds (Shanmugapriya *et al.*, 2019; Li *et al.*, 2024). Laccases are found in many fungi and are especially good at breaking down phenolic contaminants and lignin (Shanmugapriya *et al.*, 2019). Two important peroxidases enzymes that use hydrogen peroxide to oxidize phenolic compounds are lignin peroxidase (LiP) and manganese peroxidase (MnP) (Terrazas-Siles *et al.*, 2005; Dashtban *et al.*, 2010). The LiP mechanism involved oxidative cleavage, electron ransfer and substrate versality. LiP catalyzes the oxidative cleavage of C-C and C-O-C bonds in aromatic non-phenolic compounds, which are generally more resistant to degradation (Wong, 2009). According to Higuchi (2004) the enzyme oxidizes lignin directly at the protein surface by long-range electron transfer. LiP's usefulness in detoxification procedures is increased by its ability to function on a range of substrates, including those with high redox potential (Wang *et al.*, 2018). While MnP involved manganese cycling and catechol-mediated mechanism. The manganese cycle is facilitated by MnP's oxidation of Mn(II) to Mn(III), which also oxidizes mediators that aid in the breakdown of non-phenolic substrates (Wong, 2009). A catechol-mediated cycle is involved in the early phases of phenol degradation by MnP, which results in the production of several oxidation products such benzoquinone and hydroquinone (Xu *et al.*, 2017)

f. Immobilization Techniques

Immobilized materials are of great interest in the biodegradation of phenolic pollutants due to their ability to prevent the formation of harmful by-products. Phenol biodegradation was assessed using *Debaryomyces* species encapsulated in calcium alginate beads and nanoscale Fe_3O_4. The results indicated that approximately 900 mg/L of phenol was degraded within 80 hours, with removal efficiency of over 99.9%. Furthermore, it was demonstrated that the encapsulated *Debaryomyces* species in the calcium alginate beads could be reused for up to 10 cycles (Jiang *et al.*, 2017). To enhance the efficacy of mycoremediation when applied to naturally occurring wastewater, the addition of co-substrate is often required. However, this approach is typically viewed unfavorably due to the associated increased cost (Ariste *et al.*, 2019).

4. Conclusion

The present review describes the types of phenol, their impact on various environment and a fungi-based treatment. Various types of phenols are found in wastewater, including simple phenols, chlorophenols, nitrophenol, and bisphenol. They are poisonous, dangerous, endocrine disrupting, mutagenic, teratogenic, and/or carcinogenic, and seriously harm the environment. Fungi can effectively remove dangerous phenolic chemicals from wastewater. As an eco-friendly and sustainable approach, it offers a viable solution for mitigating pollution, improving water quality, and supporting biodiversity in aquatic ecosystems. Mycoremediation technology provide a more economical, sustainable, and environmentally friendly alternative to physico-chemical methods for wastewater treatment. In recent years, research has primarily focused on analyzing the effects of various conditions on the phenol degradation and evaluating mycoremediation's effectiveness under controlled experiment environments. Effort have also been directed toward optimizing the degradation processes to enhance fungal performance. Apart from being able to remove phenolic pollutant, the integration of mycoremediation into management practices can promote water sustainability on a global scale.

However, significant gaps remain in the literature, particularly regarding the toxicity assessment of degradation by-products, the application of synthetic biology methods for chassis modification, development of innovative immobilization methods, creation of innovative immobilization methods, investigation of improving remediation efficiency by integrating fungal bioremediation with other technologies, including chemical oxidation, biochar, phycoremediation or phytoremediation and scalability of mycoremediation for practical wastewater treatments. These areas warrant further research to advance the field.

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Author Contribution

Irma Melati conducted the investigation, formal analysis of the literature review and preparation of the manuscript. **Miratul Maghfiroh**, **Nurul Setiadewi**, **Riky Kurniawan**, **Annisa Indah Pratiwi**, and **Rosidah** were involved in conceptualization as well as preparation and reviewed the manuscript. All the authors read and approved the final manuscript

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