

Phycoremediation of Phenolic Compounds in Wastewater: Ecological Impacts, Mitigation Strategies, and Process Mechanisms

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ABSTRACT

The elevated concentrations of phenolic compounds in effluent have significant detrimental effects on aquatic organisms, posing a notable environmental concern. Algae-based remediation of organic wastewater has gained substantial attention due to its cost-effectiveness, efficiency, and environmental compatibility. Industrial processes, notably petroleum processing, are major sources of phenolic compounds, emphasizing the urgency for their remediation. Conventional wastewater treatment methods are costly and may contribute to secondary pollution, necessitating the development of advanced techniques to mitigate the adverse impacts of insufficiently treated phenolics. Algae offer environmentally friendly processes such as adsorption, bioaccumulation, biodegradation, and photodegradation for phenolic bioremediation. Additionally, algae possess carbon fixation capabilities and the potential to produce high-value products, thus enhancing the economic feasibility of algal wastewater remediation technology. This review evaluated the ecological consequences of various phenolic pollutants in effluent and explored diverse approaches to mitigate them, including the optimization of bioremediation processes. Furthermore, the article examined the progress in understanding the mechanisms involved in phenol removal using algae. This technology exhibits considerable promise, and further research is required to practically implement industrial-scale wastewater remediation.

INTRODUCTION

Algae encompass a wide range of organisms, comprising over 30,000 species from various phylogenetic groups. They are typically categorized into multicellular macroalgae and unicellular microalgae. Microalgae consist of single-celled organisms, but it is crucial to acknowledge the remarkable heterogeneity observed within the algae kingdom (Ariede *et al.*, 2017). Algae represent eukaryotes' most abundant photosynthetic organisms (Anastopoulos & Kyzas, 2015) that play a crucial role in supporting life.

Phytoplankton, a type of microalgae, can be found in diverse ecosystems (**Wang *et al.*, 2015; Bwapwa *et al.*, 2017**). Algae are further classified based on color, with brown, red, and green algae being the most prevalent types. There are remarkably more than fifty edible algae species (**Wang *et al.*, 2019**).

In recent years, there has been a growing interest in utilizing microalgae in cosmetics, particularly for their moisturizing properties and potential to treat skin degeneration, sunburn, and pigment disorders. Microalgae have gained attention in cosmetics due to their potential to develop anti-ageing, whitening, and pigmentation-reducing products (**Wang *et al.*, 2015**). Moreover, microalgae exhibit the ability to generate oxygen necessary for the degradation of various pollutants, including phenol, pharmaceuticals, polycyclic aromatic hydrocarbons, and organic solvents (**Peng *et al.*, 2014; Gentili & Fick, 2017; Xiong *et al.*, 2018**).

Cyanobacteria and microalgae have demonstrated remarkable adaptability throughout evolutionary history, enabling them to utilize renewable energy sources such as solar energy and adapt to autotrophic, heterotrophic, or mixotrophic culture conditions (**Subashchandrabose *et al.*, 2013**). Although the utilization of microalgae in the biodegradation process was initially proposed by Oswald and Gotaas (**Papazi *et al.*, 2012**), there has been a recent surge of interest within the scientific community.

The degradation/ deterioration of surface water has emerged as a prominent concern within environmental issues (**Younis, 2019; Taher *et al.*, 2023**). Globally, two significant and persistent sources of pollution threaten water quality. The first is the presence of high concentrations of organic matter in aquatic ecosystems, leading to organic contamination and eutrophication. The second is the pollution caused by various sources, resulting in the discharge of organic compounds into rivers, lakes, and oceans (**Hanafy *et al.*, 2021; Younis *et al.*, 2022**). This organic pollution originates from agricultural water, industrial effluents, urban discharge, and sewage, ultimately impacting water quality and limiting its usability for diverse purposes (**Amin *et al.*, 2018; Younis, 2020**).

Organic pollution can have detrimental effects on water quality through various mechanisms (**El-Naggar *et al.*, 2021; Younis *et al.*, 2023**). Among the numerous chemicals of concern, phenol stands out as one of the 129 chemicals with specific significance. It is considered toxic under the Clean Water Act Amendments of 1977, and the Environmental Protection Agency (EPA) has established water quality standards for its regulation (**Kumar, 2011**). Phenol is an aromatic hydrocarbon with an OH group attached to the benzene ring. It serves as a fundamental structural unit for numerous synthetic organic compounds. Being an organic substance, phenol is soluble in most

organic solvents and exhibits mild solubility in water at room temperature (**Agarry, 2008**).

As major environmental pollutants, phenols can exist as natural or synthetic nonaromatic compounds in various environments. Due to its aromatic structure, phenol is inherently resistant to biodegradation, and phenolic compounds are known for their high stability, primarily due to the challenge of benzene ring cleavage.

Initially discovered in 1841 by the German scientist Ferdinand Runge (**Tyman, 1996**), phenol occurs naturally in coal tar. It represents one of the most prevalent pollutants discharged by various industries, including plastics manufacturing, oil refineries, dye and pesticide production, and the pharmaceutical sector. Phenol (C_6H_5OH) serves as the fundamental building block of phenolic compounds. These compounds are characterized by organic substances featuring one or more aromatic rings with a hydroxyl group ($-OH$) attached. Moreover, phenol is known as hydroxybenzene, benzophenol, and carboic acid (**Anku et al., 2017**). Other significant phenolic compounds include butylhydroxytoluene, nonylphenol, methyl phenols, alkylphenols, aminophenols, nitrophenols, chlorophenols, and bisphenol A.

Phenolic compounds can be produced as byproducts in the course of produce processing activities. For instance, during the mass production of olive oil, a substantial volume of water is employed for fruit washing and machine cleaning following the processing stage. Depending on the specific extraction method employed, the production of olive oil can generate wastewater ranging from 10 to 120 litres per 100 kilograms of olives (**Dermeche et al., 2013**). This wastewater has been reported to contain phenolic concentrations ranging from 1 to 10 grams per liter (**Faraloni et al., 2011; Di Capri et al., 2018**).

Given that phenolic compounds possess toxicity toward various organisms (**Fiorentino et al., 2003**), it is crucial to prevent their release into the environment and, if possible, find effective ways to utilize these compounds. **Obied et al. (2005)** identified ten significant phenolic compounds in OMW, characterized by intricate chemical structures and notable functionalities. These compounds include tyrosol, hydroxytyrosol, oleuropein, rutin, catechol, vanillic acid, p-coumaric acid, caffeic acid, elenolic acid, and verbascoside. Their environmental toxicity primarily arises from their antimicrobial properties.

The remediation of water contaminated with phenolic pollutants presents a challenge due to the diverse origins and variable concentrations of these chemicals resulting from various industrial processes. The high solubility of phenolic compounds in water and their limited biodegradability can lead to significant detrimental effects when

present in wastewater (**Massalha *et al.*, 2010; Subramaniam *et al.*, 2020**). Consequently, numerous wastewater treatment methods have been developed to eliminate phenolic chemicals from municipal, industrial, and domestic effluents. It is crucial to devise strategies that mitigate phenol's harmful impacts on aquatic organisms and human well-being. The escalating levels of water pollution necessitate the development of sustainable approaches to restore environmental balance by addressing the issue of phenolic contaminants. Recently, there has been a growing emphasis on ecologically friendly solutions aimed at combating water pollution and restoring equilibrium within the aquatic ecosystem (**Wu *et al.*, 2010; Wu *et al.*, 2011**).

Various effective methods exist for removing hydrocarbons and phenols, such as chemical oxidation, ion exchange, activated carbon adsorption, and liquid-liquid extraction. However, these approaches often have significant drawbacks, including high costs and potential harmful side effects. Moreover, most of these methods merely transfer the organic chemicals to a different phase rather than breaking them down, generating hazardous byproducts and secondary pollution. In contrast, biodegradation is considered a more economically viable and environmentally friendly alternative. Consequently, biological treatment has emerged as a crucial step in the battle against pollution (**Younis *et al.*, 2019**).

Many microorganisms possess the ability to tolerate phenol and utilize it as a carbon and energy source. The biological degradation occurs through the cleavage of the benzene ring, facilitated by specific enzymes produced by these microorganisms (**Feng *et al.*, 2011**). This enzymatic breakdown allows for the efficient removal of phenolic compounds, contributing to the remediation of contaminated environments. Harnessing the potential of microbial degradation offers a promising avenue for sustainable and eco-friendly pollution control.

The employment of algae in bio-removal processes offers several advantages, including (a) cost-effective production and maintenance, (b) utilization of readily available and inexpensive energy through photosynthesis, (c) production of high-value products, (d) growth facilitated by inorganic nitrogen and phosphorus, and (e) the potential for algal biomass reproduction for biofuel production (**Voloshin *et al.*, 2016; Papazi *et al.*, 2019**).

Algae play a vital role in a process known as phycoremediation, which involves the detoxification of chemically contaminated water (**Phang *et al.*, 2015**). One significant advantage of this method is that it ensures the absence of harmful substances being transported to treatment sites, thanks to the adsorption capabilities of algae (**Krishnamoorthy & Manickam, 2021**). Phycoremediation has gained prominence in environmental remediation due to algae's remarkable ability to absorb various hazardous

contaminants, viz. heavy metals, phenols, aromatic hydrocarbons, and organochlorines, surpassing traditional physiochemical approaches (**Ke et al., 2012; Al-Jabri et al., 2020; Soliman et al., 2020; Younis et al., 2020**). The inherent capacity of algae to remove organic, metal, and nutrient components has made them invaluable for wastewater treatment (**Laurens et al., 2017; Mahana et al., 2021**). Interestingly, algae can utilize phenol as their sole carbon source (**Van Schie et al., 2000; Krastanov et al., 2013; Lee et al., 2015**). Among the non-pathogenic microalgae widely recognized for their efficacy in phycoremediation of phenolic compounds are *Chlorella*, *Spirulina*, *Scenedesmus*, and *Chlamydomonas* species (**Brar et al., 2017**). Algae-based wastewater treatment systems are particularly suitable for widespread implementation and on-site oxygen generation (**Garrett et al., 2017**).

Extensive research has been conducted to elucidate algae's breakdown of phenolic compounds. The mechanisms underlying this degradation process have been investigated, considering the factors influencing degradation and highlighting the cellular modifications induced by excessive phenol exposure. This article presented an overview of the latest advancements in algae-mediated removal of phenolic compounds, paving the way for future progress in this field.

Recent studies have indicated that algae exhibit the potential to metabolize and eliminate phenol and its derivatives. The efficacy of phenolic chemical removal by algae is influenced by various factors, including the type of algae or substrate employed, the degradation rate, and the initial pH conditions. Algae display a limited tolerance range to phenol, and as the concentration of pollutants increases, the phenol degradation rate decreases. This decline can be attributed to the heightened toxicity of phenol at higher concentrations, impacting cellular function.

Notably, algae offer a long-term protective shield for the environment against harmful substances. In this review, we delved into the mechanisms employed by algae in the breakdown of phenol and explored related topics in depth.

Sources of phenol

Phenol can be synthesized through both chemical processes and natural pathways. The predominant method for synthetic phenol production globally is cumene oxidation, which accounts for approximately 95% of the total production. Various industrial sectors contribute to the generation of phenolic waste, including petroleum refineries, petrochemical plants, steel mills, coke oven facilities, coal gas production, synthetic resin manufacturing, paint and plywood industries, mine discharges, explosives production, rubber products manufacturing, textile industries, and the food and beverage sector (**Field**

& Lettinga, 1991; Aggelis *et al.*, 2002; Zhang *et al.*, 2017; Kadir *et al.*, 2018; Lellis *et al.*, 2019).

Table (1) displays detailed information on the specific sources of phenol. Phenol serves multiple purposes including its use as a chemical analysis reagent and disinfectant. In addition, it can enter the environment through automobile exhaust, with a population of 580,000 individuals residing in the United States alone (**Bruce *et al.*, 1987**). Phenol exposure is prevalent among individuals working in industries where it is utilized.

Chemical processes contribute to the production of phenol, which can occur through various pathways. One such pathway involves the formation of phenol during the condensation of water vapor, leading to cloud formation in the atmosphere. Additionally, hydroxybenzene is generated through organic processes, such as plant biosynthesis and the breakdown of organic matter. Ultraviolet (UV) radiation exposure can produce phenol from amino acids in plant hemicelluloses (**Davi *et al.*, 1996**). Furthermore, tyrosine modification in the digestive tracts of mammals including humans can generate phenol (**Tsuru *et al.*, 1996**).

Table 1. Industrial sources and applications of phenolic compounds

Industry/ Source	Compound used in application	Reference
Textile	Intermediate compounds of Phenol employed in synthetic yarn	(Hong <i>et al.</i>, 2016)
Pharmaceutical	Utilized as an antiseptic, slimicide, lotion, ointment, mouthwash, and oral spray for treating sore throat	(Anku <i>et al.</i>, 2017) (Anku <i>et al.</i>, 2017)
Construction	Essential for concrete forming, insulation, beams, and molding compounds	(Weber <i>et al.</i>, 2010)
Agriculture	Essential for producing pesticides, fungicides, and herbicides	(Sueoka <i>et al.</i>, 2009)
Cosmetic	Commonly found in sunscreens	(Downs <i>et al.</i>, 2016)
Household	Essential ingredients in the production of soaps, paints, toys, lacquers, and perfumes	(Barlow <i>et al.</i>, 2007; Downs <i>et al.</i>, 2016)
Automotive	Utilized in manufacturing filters, tires, insulation, and coating additives	(Weber <i>et al.</i>, 2010; Hirano <i>et al.</i>, 2013)
Food and beverage	Applied as coatings for cans, cups, and polycarbonate containers	(Barlow <i>et al.</i>, 2007)

The phenol content in surface water exhibits variability. In undisturbed marine environments, the range typically falls between 0.01 and 2.0 $\mu\text{g/L}$ (**Mich Ałowicz & Duda, 2004**). However, water bodies exposed to higher levels of anthropogenic pollution may contain elevated phenol concentrations. For instance, surface water in the Netherlands has phenol concentrations ranging from 2.6 to 5.6 $\mu\text{g/L}$, while river water contaminated with refinery sewage can have phenol content exceeding 40 mg/L (**Bruce et al., 1987**). In addition, phenol has been detected in residential water supplies in the United States, albeit at a lower level of 1.0 $\mu\text{g/L}$. In the air, background levels of phenol are expected to be modest, measuring only one ng/m^3 (**RIVM, 1986**). However, higher phenol concentrations can be found near facilities involved in wood impregnation, reaching levels as high as 9.7 $\mu\text{g/m}^3$ (**Alle et al., 1997**).

Phenol is also present in various food items. Modest phenol concentrations (5 $\mu\text{g/kg}$) have been detected in honey (**Gyroik et al., 2003**). In coffee, phenol is produced from ferulic acid, resulting in its presence in the beverage. Corn, a natural substance, converts from ferulic acid to guaiacol, vinyl-guaiacol, and phenol (**Dor Fner et al., 2003**).

Processed foods can sometimes contain dangerously high levels of phenol. For example, grilled sausage and pork have been found to contain 7 and 28.6 $\mu\text{g/kg}$ of phenol, respectively (**US EPA, 1980**). Other studies have detected phenol in the outer layer of smoked meat at levels ranging from 37 to 70 mg/kg .

Determining the extent of phenol exposure in the general population remains challenging due to insufficient exposure statistics. However, individuals regularly consuming smoked foods with high phenol content or inhaling air in heavily industrialized areas may be exposed to hazardous phenol levels, estimated to be around 4 and 2 mg daily, respectively. Furthermore, it has been calculated that each burned cigarette releases approximately 0.3– 0.4 mg of phenol. Accidental phenol exposure can also occur, as exemplified by Delfino and Dube, who reported a case of phenol contamination in groundwater used for human consumption. In this scenario, it was estimated that each person would be exposed to 10- 240 mg of phenol daily, resulting in statistically significant symptoms, such as darkened urine, mouth ulcers, a burning sensation in the mouth, and diarrhoea (**Del Fino & Dube, 1976**).

Phenolic pollutant types as identified by the U.S. Environmental Protection Agency (EPA)

Phenol pollutants originating from oil refineries are commonly detected in the wastewater they discharge. These pollutants can also be found in various sectors, such as coal processing, pharmaceutical industries, and petrochemicals (**Othmani et al., 2022**;

Duan *et al.*, 2018). The concentration of total phenols in wastewater typically ranges from 10 to 300mg/ L.

The European Union (EU) and the U.S. Environmental Protection Agency (EPA) have identified a list of priority chemicals, including nitrophenols and chlorophenols. Fig.(1) illustrates eleven phenols that the EPA recognizes as significant pollutants. EU Directive 2455/2001/EC has established a specified limit of 0.5µg/ L for the total concentration of these phenols in drinking water, with a further requirement of less than 0.1µg/ L. **Al-Zuhair and Co. (2018)** emphasized the criticality of addressing the presence of these contaminants, particularly phenolic compounds in sewage-based wastewater. The chemical structures of phenolic compounds vary, with phenol, cresol, and other related substances being frequently encountered in wastewater. In the supplementary materials, examples of such compounds include 2, 4, 6-trichlorophenol and 2, 4-dinitrophenol.

Phenol, the fundamental phenolic compound, is formed by the combination of a hydroxyl group (OH) and a benzene ring. It is commonly present in high concentrations in industrial wastewater, particularly from refineries. Some wastewater streams exhibit phenol concentrations as high as 10g/ L (**Krastanov *et al.*, 2013**). According to **Xiong *et al.* (2021)**, phenol is highly carcinogenic, corrosive, and toxic. In wastewater, when the phenol content exceeds 50mg/ L, the biodegradation rate may be hindered (**Saputera *et al.*, 2021**).

Chlorophenols, the largest and most prevalent group of phenols, are primarily formed through the chlorination of mono and polyaromatic compounds present in soil and water. This environmental synthesis of chlorophenols involves the participation of chloroperoxidases found in plants and microbes, facilitated by the presence of inorganic chlorine and hydrogen peroxide. Notably, certain species of the *Hypholoma* fungus such as the *Hypholoma* genera produce chlorinated phenols (**Sw Arts *et al.*, 1998**; **Verh Age *et al.*, 1998**). Chlorophenol concentrations in oceanic waters typically range from 5 to 10ng/ L, while river waters exhibit higher levels, varying between 2 and 2000µg/ L. It is worth mentioning that, chlorophenols can also be found in drinking water due to the replacement of organic materials and low molecular weight compounds by chlorine atoms from inorganic chlorine oxidants, even after the water has undergone filtration processes.

Pentachlorophenol (PCP), 2,4,5-trichlorophenol (2,4,5-TCP), and 2,4,6-trichlorophenol (2,4,6-TCP) represent notable examples of chlorophenol pollutants that have been classified by the International Agency for Research on Cancer (IARC) as potentially carcinogenic to humans (**Cooper & Jones, 2008**).

Methyl phenols are commonly detected in the environment, often occurring at high concentrations. An example can be seen in the Hayashida River located in Tatsuno town, Japan, where elevated levels of 4-methylphenol (204 $\mu\text{g/L}$) were identified, primarily attributed to industrial effluent pollution. Areas adjacent to coal tar (creosote) manufacturing plants exhibit the highest levels of methyl phenols, with groundwater containing over 2mg/ L of 4-methylphenol. Some studies have also reported the presence of methylated phenols in the atmosphere.

Shale oils and rock oils commonly contain alkylphenols with low molecular weight. These chemicals, primarily substituted in the para position, arise from geochemical reactions occurring within geological formations, involving processes such as methylation, butylation, and alkylation (**Kahl *et al.*, 1997**). Furthermore, certain technological processes also contribute to the formation of these chemicals. For example, nonylphenols are generated by using surfactants known as nonylphenol ethoxylates, which find applications in agriculture and various industries. Nonylphenols serve as dispersants, wetting agents, and emulsifiers. Industries involved in textile processing, paper and pulp production, paint manufacturing, oil and resin production, and steel manufacturing utilize nonylphenol polyethoxylates. Additionally, alkylphenols can be produced through agricultural activities, industrial wastewater discharge, and the breakdown of pesticides (**Berryman *et al.*, 2004**).

Bisphenols, particularly bisphenols A and F, are widely used in rubber, epoxy resins, lubricants, and various synthetic products as essential components or byproducts (**Sinkkonen *et al.*, 2003**). Significant levels of brominated bisphenols such as tetrachlorobisphenol can be found in the ash produced during aluminium production (**Stachel *et al.*, 2003**). The average concentration of bisphenol A (BPA) across 13 states was measured at 0.5 $\mu\text{g/ L}$, while in 21 European countries, it was recorded as 0.016 $\mu\text{g/ L}$. In the United States, only two streams exhibited BPA concentrations exceeding 1 $\mu\text{g/ L}$, with a median concentration of 0.14 $\mu\text{g/ L}$ observed in numerous streams.

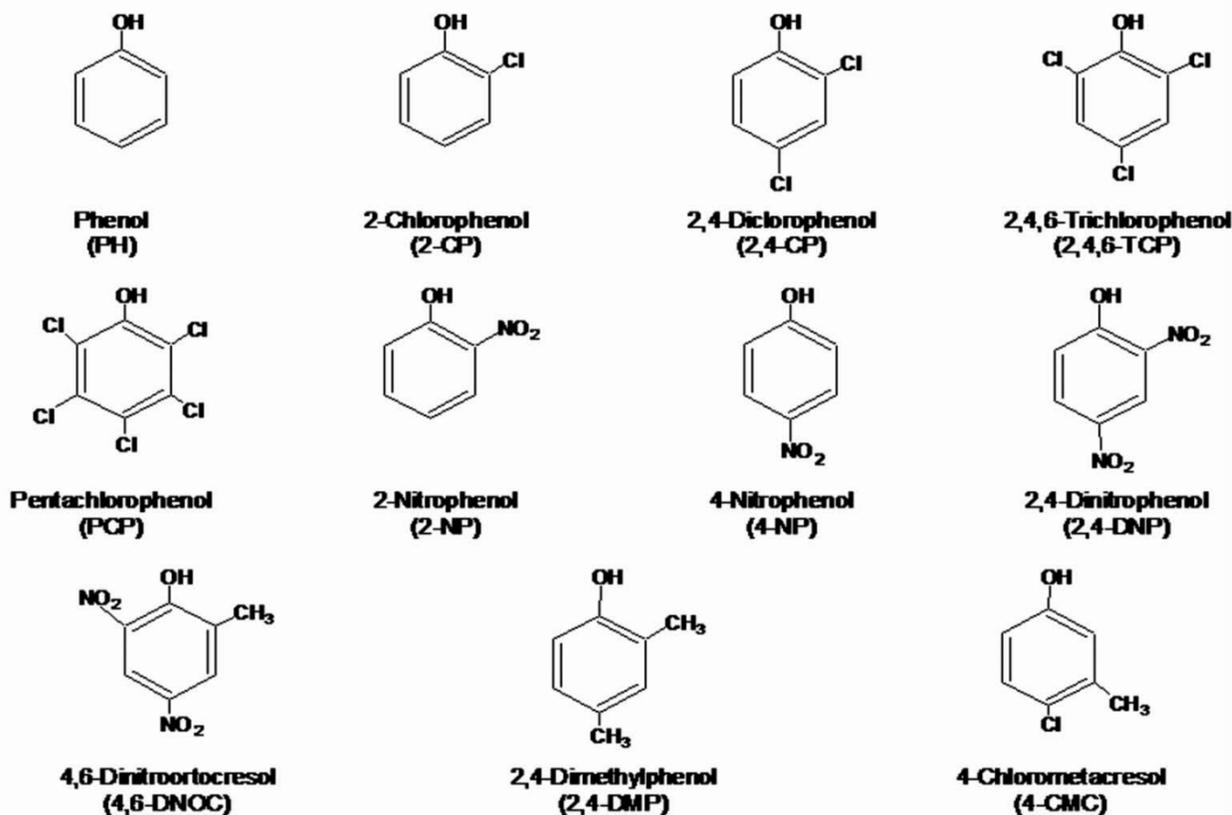


Fig. 1. Structural characteristics of priority phenolic pollutants as identified by the U.S. Environmental Protection Agency (EPA)

Acute toxicity of phenol and phenolic compounds

Phenol and its derivatives are primarily classified based on their hazardous properties. According to **Boyd *et al.* (2001)**, the toxicity of phenolic compounds increases with the substitution of chlorine atoms in phenol. Phenol toxicity is primarily attributed to the production of organic and free radical species and the hydrophobic nature of phenolic compounds. The hydrophobicity of phenolic compounds is influenced by two key parameters: P_{ow} (the octanol-water partition coefficient of undissociated acids) and pK_a (the compound dissociation constant).

Reactivity, which indicates the strength of toxicity, is associated with the ease of electron migration within the benzene ring when exposed to oxidase enzymes like peroxidase. Increased hydrophobicity, as indicated by higher $\log P$ and lower pK_a values, enhances the toxicity of phenol by promoting solubility, membrane penetration, and interaction with cellular structures. The position of the substituent atom in the chemical structure and the interaction of substituents affecting the condensation of aromatic rings

also influence toxicity. Substitution at the ortho position is generally less hazardous compared to the meta position. Additionally, the presence of a hydroxyl group in the ring makes phenol more susceptible to oxidizing agents and enables various chemical reactions, including etherification, esterification, oxidation, and substitution (**Michalowicz & Duda, 2007**).

Hydrogen atoms in the phenol ring and hydroxyl group can be replaced or removed, and the chemical groups attached to phenol, and their positions on the ring determine its stability under environmental conditions. Phenol undergoes an active transformation in the presence of oxygen, facilitated by oxygenase in cytochrome p450, a key component of the electron transport chain. This transformation can lead to the formation of potentially harmful compounds, such as phenoxy radicals and intermediate metabolites, viz. semiquinones and quinone methides, which can bind to DNA or proteins within cells, causing damage. Phenol reactivity influences the generation of reactive oxygen species, including superoxides, radicals, and hydrogen peroxide, which promote lipid peroxidation in membranes. As a result, membrane permeability decreases, allowing penetration into cell organelles such as the endoplasmic reticulum, mitochondria, and nucleus, as well as components including enzymes and nucleic acids (**Barlow *et al.*, 2007; Michalowicz & Duda, 2007; Basha *et al.*, 2010**).

Industrial waste contains phenol, and consuming just one gram of phenol can harm life (**Mohammadi *et al.*, 2015**). Additionally, even at relatively low concentrations (around 5µg/ L), phenolic chemicals in drinking water can impart an unpleasant taste and odor. Researchers have detected phenol in industrial waste at concentrations ranging from 50 to 10,000mg/ L (**García *et al.*, 1997; Jusoh *et al.*, 2008**). Moreover, due to its higher density than water and the formation of hazardous compounds even after dilution, the process of diluting phenol is slow. In contaminated fishing areas, the concentration of phenol in seawater is typically very low, around 0.13mg/L. However, in the event of an accidental phenol leak into the sea, the phenol content can increase significantly to 8.28mg/ 100mL due to its high solubility in water (**Wei *et al.*, 2016**).

Phenolic compounds encompass bisphenol A (BPA), a chemical plasticizer that produces epoxy resin, polycarbonate polymers, and plastics (**Gorini *et al.*, 2020; Kim *et al.*, 2020**). BPA is found in water at parts per trillion (ppt) levels and exhibits resistance to biodegradation (**Luo *et al.*, 2014**).

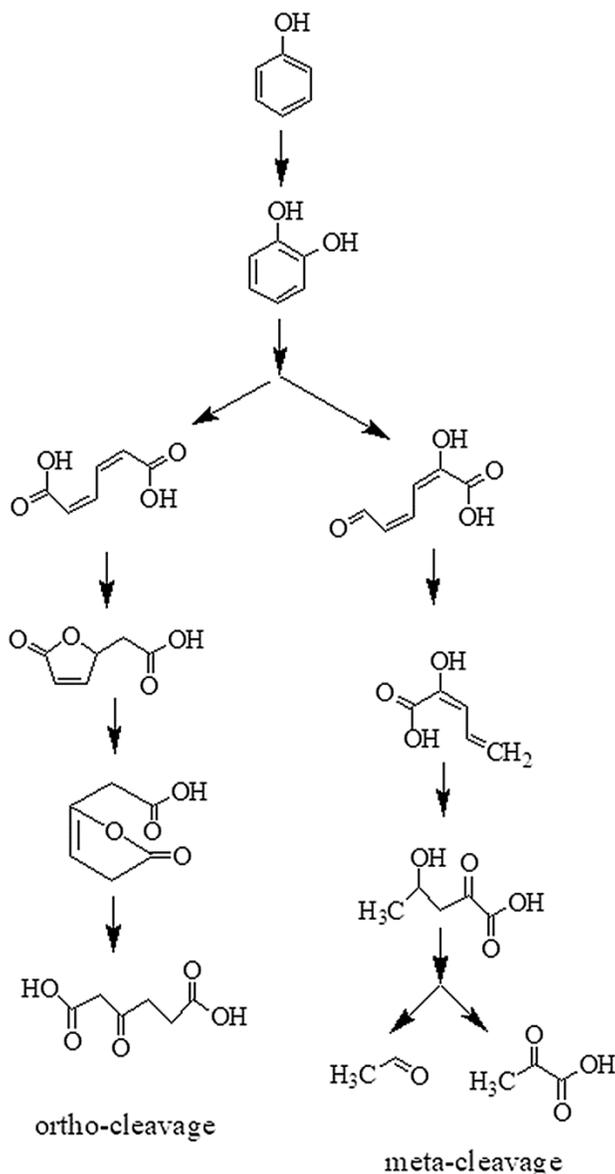


Fig. 2. The pathway of phenol degradation

At concentrations of 1 to 2% in an aqueous solution, phenol is considered a safe disinfectant suitable for treating non-critical medical devices with minimal risk of infection spread. However, exposure to this disinfectant can counteract skin irritation. At a concentration of 5mg/ L, phenol is a hazardous pollutant that can cause long-term cell damage (Mohammadi *et al.*, 2015). The typical toxic limits for both aquatic life and humans range from 9 to 25mg/ L (Kulkarni *et al.*, 2013). The presence of antibiotic-resistant genes in bacteria due to phenolic waste raises concerns about public health (Menz *et al.*, 2019).

Most phenols are volatile and release offensive odors into the water, threatening aquatic life. Furthermore, they can disrupt endocrine systems, impede the oxidative phosphorylation response, hinder ATP synthesis, and accumulate in various trophic levels within the biological food chain (Tišler *et al.*, 1997; Duan *et al.*, 2017; Kong *et al.*, 2019).

Phenol exposure can occur through various pathways, such as workplace exposure, environmental contact, contaminated food or beverages, and phenol-containing products (ATSDR, 2008). The International Agency for Research on Cancer (IARC) classified phenols as Group 3, indicating that there is inadequate information to determine their carcinogenicity in humans or animals. Similarly, the Environmental Protection Agency (EPA) categorized phenols as Group D due to insufficient data on their carcinogenic potential. Before widespread distribution, phenol undergoes absorption, distribution, and excretion processes in humans, crossing various barriers and membranes through diverse transport mechanisms.

Factors like molecular weight/shape, charge, lipid solubility, membrane composition, and membrane thickness influence the transport of toxicants throughout the body. Once extensively circulated, phenol can penetrate the placenta, cross the blood-brain barrier, and even enter human breast milk (Barlow *et al.*, 2007). According to Michalowicz and Duda (2007), phenol accumulates primarily in the muscles, liver, brain, and kidneys. It can either be eliminated or undergo conjugation during the detoxification process within two days (Barlow *et al.*, 2007; Basha *et al.*, 2010). Due to its presence in both gaseous and particulate forms in the atmosphere, as well as direct skin contact and ingestion, phenol is readily absorbed through inhalation. Phenol exposure has various adverse effects on living organisms. The biological response to a chemical, cell, or tissue dose is referred to as a biological effect. The significance of these biological effects and their relationship to further negative health consequences is not fully understood. Adverse effects, on the other hand, result in modifications to morphology, physiology, growth, development, or lifespan, impairing the body's ability to withstand additional stress or increasing its susceptibility to other toxic substances (Barlow *et al.*, 2007).

Even in diluted solutions (1-2%), short-term dermal contact with phenol can cause skin irritation (Basha *et al.*, 2010), while prolonged contact can lead to severe skin damage (HPA, 2007). Phenol reacts with collagen and keratin-containing amino acids in the epidermis, causing coagulation and damage to the skin. Its acidic and irritating properties can result in burns upon acute skin exposure. Skin exposure is often associated with occupational exposure, particularly among workers handling phenolic compounds in chemical factories or agricultural settings, who face the highest risk of phenol absorption compared to workers in other industries. Skin contact with phenol can also lead to

necrosis, a sign of systemic poisoning, temporary central nervous system stimulation and depression that can result in coma (**Basha *et al.*, 2010**). The impact of human exposure to phenols depends on individual tolerance, similar to scenarios involving ingestion, direct skin contact, or inhalation exposures. Prolonged exposure can cause skin eruptions, skin irritation, and onychomycosis. Additionally, catechol, an intermediate breakdown product of phenol, is a potent toxin (**Basha *et al.*, 2010**).

Approaches for eliminating phenols in industrial wastewater

Industrial wastewater can be categorized as industrial runoff, and its characteristics vary significantly across different industries. Therefore, diverse treatment methods are often employed to address industrial wastewater based on its specific composition and regulatory requirements for discharge into public sewers (**Molva & Polat, 2004; Busca *et al.*, 2008**).

Proper treatment of agricultural runoff containing phenols is crucial to prevent their release into open waters, as these compounds pose risks to both human health and the quality of drinking water and food processing environments. Recognizing the toxicity associated with certain phenolic compounds, the Environmental Protection Agency has established a water purification standard specifying a phenol threshold of less than 1 part per billion (ppb) in surface waters. These regulations require comprehensive and highly efficient treatment methods to achieve commercial-scale removal of phenols from wastewater. This typically involves a combination of biological and physicochemical treatment technologies. For instance, the petroleum industry employs chemical oxidation or biological treatment methods to eliminate organic pollutants from wastewater. Specific treatment techniques tailored to those substances may be necessary when phenolic waste contains other contaminants. Selecting effective and appropriate treatment methods depends on the wastewater's unique properties and cost-effectiveness considerations.

Different techniques are employed to remove phenol from wastewater, each offering specific advantages and disadvantages. Many wastewater treatment plants employ a combination of physical, chemical, and biological processes to achieve comprehensive treatment. Integrated treatment systems offer advantages, such as improved removal efficiency, flexibility in handling varying influent characteristics, and the potential for resource recovery. However, combined treatment systems can be complex, requiring significant infrastructure, skilled operation and maintenance, and increased operational costs.

Solvent extraction is the predominant method employed to remove phenol from wastewater. This technique facilitates the purification of wastewater by selectively extracting phenol from it. Subsequently, carbon or biological adsorption techniques are utilized to achieve complete phenol removal. Solvent extraction is also known as liquid-

liquid extraction or solvent abstraction. During this process, constituents present in the wastewater are selectively recovered by coming into contact with an organic solvent, as they exhibit greater solubility in the solvent compared to the wastewater itself. The primary objective of the solvent extraction procedure is to separate organic compounds from wastewater including phenolic compounds (Molva & Polat, 2004). However, one of the disadvantages of solvent extraction is the need for significant quantities of solvents and ligands.

Frequently, adsorption is a remediation technique for treating polluted wastewater and contaminated waterways. Traditional fixed-bed adsorption processes require additional steps such as desorption, elution, or regeneration to address saturation, adsorption, or loading. In cases where recovery is challenging or impractical, the saturated adsorbent bed is either discarded or disposed of through controlled incineration in appropriate furnaces (Saleh *et al.*, 2019).

One commonly used method by scientists for extracting liquid organic substances is the adsorption onto activated carbon. Activated carbon is derived from various carbonaceous materials, including wood, pulp-mill char, peat, and lignite, and it has proven to be one of the most effective adsorbents for water remediation to date. The superior adsorption capabilities of these materials can be attributed to their exceptionally high surface areas, which enhance their efficacy in removing organic contaminants from water.

The utilization of membrane engineering for phenol removal demonstrates both efficiency and economic viability. This approach offers a range of advantages, including reduced energy usage, a compact footprint, production of high-quality effluent, and simplified scaling of membrane systems. However, it is crucial to address the issue of membrane fouling, which can result in particle damage and the presence of colloids in the feed streams (Mohammadi *et al.*, 2015; Laura *et al.*, 2016).

Several prominent membrane techniques have been employed to extract phenols from effluent. These techniques include removal through extractive membrane bioreactors and porous fiber membranes, removal of phenol using photocatalytic membrane reactors, and removal of phenol through reverse osmosis and nanofiltration.

The utilization of extractive membrane bioreactors (EMBRs) employing an aqueous-aqueous extractive membrane cycle, along with biodegradation, demonstrates significant potential for efficiently removing phenol from wastewater. In a study conducted by Loh *et al.* (2016), composite hollow fiber membranes with different degrees of polydimethylsiloxane (PDMS) intrusion were created by depositing a PDMS layer onto a polyetherimide (PEI) hollow fiber substrate. The researchers investigated

phenol removal from wastewater using hollow fiber membranes impregnated with trioctylphosphine oxide. Immobilization of phenol within the hollow fiber membrane was achieved, leading to its effective removal. This system offers advantages such as portability and adaptability, making it readily applicable in environmental engineering (Praveen *et al.*, 2013).

Photocatalytic membrane reactors represent a hybrid approach where the membrane separator acts as a physical barrier for the photocatalyst and functions as a functional barrier for the molecules to be degraded. After degradation, the photocatalyst particulates need to be separated and removed from the treated water (Mohammadi *et al.*, 2015).

Nanofiltration is a commonly employed technique for extracting organic compounds, inorganic salts, color, and hardness from aqueous solutions (Mohammadi *et al.*, 2015). Conversely, reverse osmosis is a membrane-based demineralization technique primarily used to separate dissolved solids, such as ions, from aqueous solutions. Nanofiltration can be used as a pre-treatment step before reverse osmosis to reduce the pressure associated with organic materials. However, these systems can be complex, requiring significant infrastructure, skilled operation and maintenance, and increased operational costs.

The concept of sustainable biomaterials explores the intricate relationship between renewable natural resources and biomaterials, offering promising opportunities for advancing innovative sustainable development approaches in the near future. There is a noticeable emphasis on developing and producing materials derived from renewable resources, gradually replacing traditional materials. In the modern era, we find ourselves at a critical juncture where achieving sustainable energy is of utmost importance, a goal that can only be accomplished through advancements in green technologies. The utilization of biomaterials has experienced a steady rise in recent years, surpassing the use of conventional materials, indicating a progressive shift towards sustainable practices.

Algae-based phenol removal

Algal-mediated degradation of phenol

The advancement in the breakdown of phenol by algae has enabled the isolation, culture adaptation, and enrichment of algal strains that can exclusively thrive on phenols as their carbon and energy source (Klekner & Kosaric, 1992). Although phenol possesses antibacterial properties, certain phenol-resistant microalgae, as shown in Fig. 2, have the capability to degrade phenol.

Phenol and its derivatives inhibit the growth of many green microalgae, requiring significant energy for their breakdown. Even at low concentrations, as low as 0.05%,

phenol can be detrimental to microalgae, as highlighted by **Kahru *et al.*, (2002)**. Microalgal bioremediation, through photosynthesis and pollutant breakdown, can simultaneously sequester carbon dioxide.

Despite the fact that mixotrophic microalgae can mineralize phenolic compounds, phototrophic and heterotrophic microalgae are susceptible to phenolic derivatives (**Tikoo *et al.*, 1997**). **Semple and Cain (1996)** reported that eukaryotic microalgae demonstrate the ability to degrade aromatic molecules such as phenol. Strains like *Scenedesmus* and *Chlorella* are frequently employed to biodegrade phenolic chemicals (**Lutzu *et al.*, 2015; Cheng *et al.*, 2016**). Various phenolic compounds, including 4-nitrophenol, 4-chlorophenol, 2,4-dinitrophenol, bisphenol (**Klekner & Kosaric, 1992; Hirooka *et al.*, 2003; Tsuji *et al.*, 2003; Lima *et al.*, 2004**), 2,4-dimethylphenol (**Klekner and Kosaric, 1992; Pinto *et al.*, 2002**), pentachlorophenol (**Tikoo *et al.*, 1997**), and nonylphenol (**Gao *et al.*, 2011**) can be effectively biodegraded by these strains. Initially identifying phenol-degrading strains in cultures includes *Spirulina maxima*, *Scenedesmus obliquus*, and *Chlorella* sp. (**Klekner & Kosaric, 1992**). Additionally, it was discovered that *Ochromonas danica* can grow heterotrophically in the presence of phenol, utilizing p-cresol as its sole carbon substrate (**Semple & Cain, 1996**) (Table 2).

In *Chlamydomonas* cells, phenol biodegradation occurs only when algae require carbon stores to maintain homeostasis, as indicated by **Nazos *et al.* (2020)**. The adaptable bioenergetic apparatus of *Chlamydomonas reinhardtii* regulates its metabolism to achieve a balance between phenol biodegradation and growth (**Nazos *et al.*, 2020**). This mechanistic understanding opens avenues for using freshwater and marine microalgae in phenol biodegradation. Consequently, microalgae are considered effective agents for removing hydrophobic organic contaminants.

Two distinct categories exist for the biodegradation pathway of phenolic compounds. The first category is metabolic degradation, where these compounds serve as carbon sources for algae or act as donors or acceptors of electrons. The second category is co-metabolism, where additional organic substrates support biomass formation and serve as electron donors for non-growth purposes (**Xiong *et al.*, 2021**). Adding more phenol to enhance the process can accelerate the biodegradation of p-cresol through co-metabolism (**Xiao *et al.*, 2019**) (Table 2). In this respect, **Hena *et al.* (2021)** suggested that biodegradation relies on various enzymatic processes within the cellular metabolism of algae.

Desmodesmus sp. eliminates bisphenol A from the culture medium through oxidative hydroxylation, glycosylation, and oxidation processes. Transcriptome analysis of the biodegradation process revealed significant upregulation of oxidoreductase and

glycosyltransferase coding genes involved in the oxidative degradation of bisphenol A in microalgae. This promotes adding glycosyl groups for detoxification (Wang *et al.*, 2017).

Algae utilize a variety of enzymes including those from the Phase I and Phase II enzyme families to metabolize harmful chemicals (Xiao *et al.*, 2019). Cytochrome P450 enzymes, such as monooxygenase, dioxygenase, hydroxylase, carboxylase, and decarboxylase are involved in the initial phase. These enzymes employ oxidation, reduction, or hydrolysis to convert hydrophobic contaminants into more hydrophilic substances (Leng *et al.*, 2020). The second phase involves enzymes such as superoxide dismutase, catalase, glutathione S transferase, malate/pyruvate dehydrogenase, mono(di)oxygenase, pyrophosphatase, and hydrolase, among others. These enzymes contribute to the breakdown of organic substances that induce stress in algae cells and aid in cell defence. However, the specific roles of these enzymes may slightly vary among different algal species (Sutherland & Ralph, 2019).

Table 2. Summary of laboratory experiment procedures for phenolic contaminant removal using algae in previous studies

Compound	Algae species	Initial concentration	Removal efficiency (%)	Reference
Phenol	<i>Chlorella vulgaris</i>	100mg/L	55.8	Xiao <i>et al.</i> , (2019)
Phenol	<i>Ankistrodesmus braunii</i>	1.5g/L	70	Pinto <i>et al.</i> , (2003)
Bisphenol A	<i>Chlorella pyrenoidosa</i>	10mg/L	15	Guo <i>et al.</i> , (2017)
Phenol	<i>Chlorella pyrenoidosa</i>	200mg/L	60	Stephen <i>et al.</i> , (2017)
p-Nitrophenols	<i>Chlorella</i> sp.	400mg/L	50.24	Zheng <i>et al.</i> , (2017)
Phenol	<i>Chlorella vulgaris</i>	100mg/L	98	Baldiris-Navarro <i>et al.</i> , (2018)
Phenol	<i>Arthrospira platensis</i>	240mg/L	10	Nur <i>et al.</i> , (2021)
Phenol	<i>Chlorella</i> sp.	100mg/L	100	Wang <i>et al.</i> , (2016)
Phenol	<i>Chlorella pyrenoidosa</i>	200mg/L	97.4	Dayana and Bakthavat salam (2019)
Phenol	<i>Scenedesmus quadricauda</i>	1.5g/L	50	Pinto <i>et al.</i> , (2003)
Phenol	<i>Scenedesmus regularis</i>	30mg/L	40	Kankılıç <i>et al.</i> , (2018)
Bisphenol A	<i>Desmodesmus</i> sp.	1mg/L	57	Wang <i>et al.</i> , (2017)
Phenol	<i>Spirulina maxima</i>	50mg/L	97.5	Lee <i>et al.</i> , (2015)
Phenol	<i>Chlorella</i>	200mg/L	97.6	Dayana and Bakthavat

	<i>pyrenoidosa</i>			salam (2019)
Phenol	<i>Tribonema minus</i>	250mg/L	94.6	Cheng et al., (2018)
Phenol	<i>Lyngbya lagerlerimi</i>	166mg/L	64.4	(El-Sheekh et al., (2012)
2,4-dinitrophenol	<i>Anabaena variabilis</i>	40µM	86	Hirooka et al., (2003)
2,4-Dichlorophenol	<i>Chlorella pyrenoidosa</i>	0.15mg/L	100	Li et al., (2018)
Bisphenol A	<i>Chlorella pyrenoidosa</i>	10mg/L	15	Guo et al., (2017)
Phenol	<i>Ulva lactuca</i>	1mg/L	90.13	Abbas et al., (2019)
Phenol	<i>Caulerpa prolifera</i>	50mg/L	78	Younis et al., (2020)
Bisphenol A (BPA)	<i>Chlorella vulgaris</i>	1mg/L	23	Ji et al., (2014)
p-Nitrophenols	<i>Chlorella</i> sp.	400mg/L	50.24	Zheng et al., (2017)
Phenol	<i>Chlorella</i> sp	95mg/L	100	Surkatti and Al-Zuhair(2018)
Nonylphenol (NP)	<i>Ankistrodesmus acicularis</i>	0.5mg/L	83.77	He et al., (2016)
Bisphenol A (BPA)	<i>Stephanodiscus hantzschii</i>	0.10mg/L	99	Li et al., (2009)
Phenol	<i>Chlorella pyrenoidosa</i>	25mg/L	100	Das et al., (2015)
Phenol	<i>Chlorella</i> VT-1	100mg/L	100	Scragg (2006)

Photolysis

Both direct photolysis and indirect photodegradation, facilitated by the active components of algae under light, are involved in the degradation of phenolic pollutants (Xiong et al., 2021). In natural environments, photodegradation primarily drives the transformation of surface-bound phenolic compounds (Wei et al., 2021). Numerous phenolic compounds can undergo direct breakdown and elimination via light exposure, even in the absence of algae. Direct photolysis has also been observed as the mechanism for the elimination of bisphenol A (Guo et al., 2017), triclosan (Bai & Acharya, 2019), and phenol (Nur et al., 2021) in various algal wastewater treatment systems.

Algae act as efficient photosensitizers, generating reactive oxygen species (ROS) in response to radiation during the process of indirect photodegradation. This enables algae systems to enhance the removal of specific phenols through indirect photodegradation (Mullineaux et al., 2018). The type of oxidant involved, such as hydrogen peroxide (H₂O₂), singlet oxygen (O₂), superoxide (O²⁻), and hydroxyl radicals (·OH), among others influences the process of indirect photodegradation (Wei et al., 2021).

However, certain phenols exhibit resistance to degradation, and light-induced algal active compounds are unable to completely eliminate these chemicals (**Yang *et al.*, 2021**).

In addition to the mentioned mechanisms, other processes that may reduce phenolic compounds include hydrolysis, evaporation, precipitation, adsorption onto glassware, and aqueous substrate conversion (**Yang *et al.*, 2021**). Nonetheless, these mechanisms are often not the primary focus of most research, as they only play a minor role in the degradation of contaminants.

Factors influencing algal phenol degradation

The degradation profile of microorganisms is influenced by various elements that must be understood to comprehend the biodegradability of phenol. Selecting appropriate physiological conditions poses a significant challenge, as conventional experimental designs require numerous runs to achieve reliable results. Several variables affect phenol decomposition, including temperature, oxygen availability, phenol concentration, initial algal density, light intensity, and alternative carbon sources (**Nazos *et al.*, 2016**; **Priyadharshini & Bakthavatsalam, 2016**). For microalgal cells to degrade phenols, they require a different carbon source and sufficient light.

Furthermore, the addition of diverse organic carbon sources mitigates the toxicity of phenolic chemicals and promotes algal growth (**Megharaj *et al.*, 1992**; **Kong *et al.*, 2019**). Alternative carbon sources also alleviate the stress response induced by phenol toxicity. Phenol acts as the sole carbon source in the medium, leading to the generation of carbon reserves for cellular homeostasis and structure. *Chlamydomonas* cells exhibit higher phenol uptake within the first 48 hours of incubation when acetic acid is absent (**Nazos *et al.*, 2020**). *Anabena variabilis* and *Chlorella fusca* var. *vacuolata* microalgae strains can degrade phenolic compounds even in the absence of organic carbon sources (**Hirooka *et al.*, 2003**).

The presence of exogenous glucose has been shown to enhance halophenol breakdown. However, **Lika and Papadakis (2009)** found that glucose inhibits phenol degradation by competing with phenol for oxygen, resulting in slower phenol degradation. The availability of alternative carbon sources that promote microalgal growth may limit biodegradation since substrates require sufficient oxygen for metabolism.

When maritime microalgae are cultivated, phenol induces the expression of genes associated with reactive oxygen species (ROS) generation and a decrease in chlorophyll content (**Hirooka *et al.*, 2003**). The biodegradability of *Scenedesmus obliquus* for various monosubstituted phenol forms is influenced by the types of phenolic compounds

investigated and the culture conditions employed (Papazi & Kotzabasis, 2007). Cultures grown in phenol-free tris-acetate-phosphate (TAP) medium exhibit less acetic acid-induced microalgal development.

Higher phenol concentrations induce more biodegradation in *Chlamydomonas reinhardtii* under stress conditions. Conversely, decreased phenol and monosubstituted methylphenol content and the removal of other carbon sources from the culture media enhance biodegradability (Nazos *et al.*, 2016). Increased nonylphenol concentration in *Cyclotella caspia* reduces chlorophyll content and cell proliferation rate (Liu *et al.*, 2013). While low concentrations of phenol are not toxic to microalgae and can serve as a potential carbon source, high phenol concentrations inhibit algal growth by damaging photosynthetic pigments and membrane-bound organelles by producing phenol-induced phenoxy radicals (Cho *et al.*, 2016).

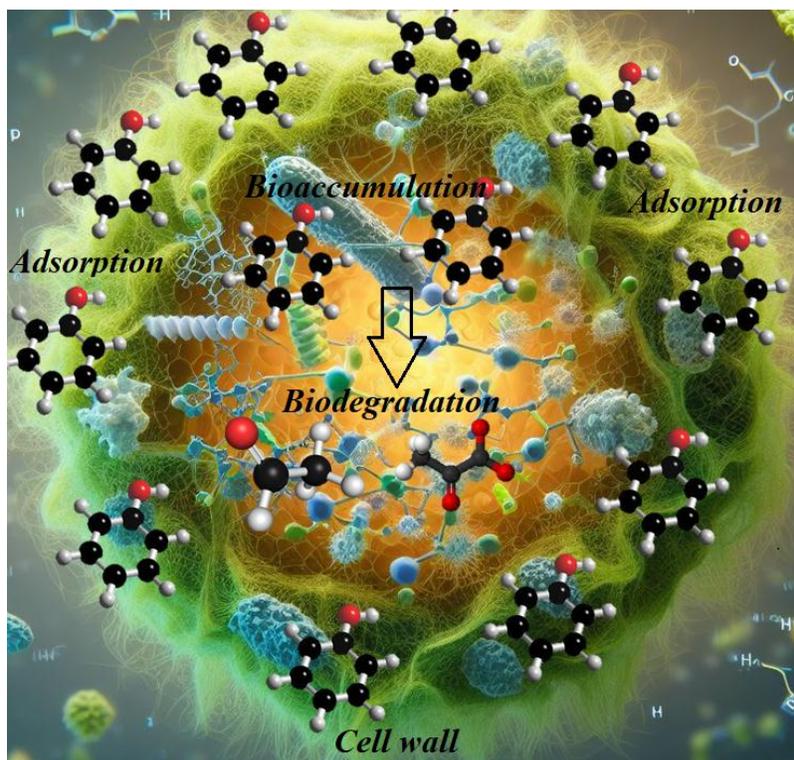


Fig. 3. Phenol degradation mechanism utilizing algae

Light is another crucial factor in the phenol degradation process of microalgae. High light intensities slow down phenolic compound breakdown as they exacerbate the toxicity of light-enhanced autoxidation (Nakai *et al.*, 2001). Phenol degradation occurs only in the absence of light, not under photoautotrophic and photoheterotrophic conditions, as observed in *Synechococcus* PCC 7002 by Wurster *et al.* (2003). Likewise, *Scenedesmus* sp. performs better under heterotrophic conditions compared to mixotrophic

conditions, possibly due to reduced light penetration in the latter, emphasizing the critical role of light in phenol degradation (**Di Caprio *et al.*, 2018**).

Temperature is also a significant parameter affecting phenol biodegradation by microorganisms. Lower temperatures (e.g., 10°C) hinder the removal process by *Isochrysis galbana* due to enzyme inhibition, which retards growth and metabolism (**Li *et al.*, 2019**). Higher temperatures enhance the activity of photosynthesis-related enzymes and key processes like carbon dioxide diffusion (**Raven *et al.*, 1988**). Elevated temperatures accelerate cellular metabolism, promoting microalgal growth. However, exceeding the optimum temperature leads to irreversible physiological reactions in cells, negatively impacting algae growth and photosynthetic rates.

Other mechanisms of phenolic pollutant removal

Algae employ a range of mechanisms to remove detrimental phenolic pollutants and ensure their survival after exposure. These mechanisms encompass hydrolysis, photodegradation, adsorption, accumulation, and biodegradation. Table (2) provides a comprehensive overview of the laboratory experiment procedures involving algae for phenolic contaminant removal.

Adsorption

Adsorption is a passive method for removing pollutants by binding them to solid materials (**Bilal *et al.*, 2018**). Various adsorbents including activated carbon and nanomaterials have effectively removed phenolic pollutants (**Fu *et al.*, 2019**; **Kartikadevi *et al.*, 2021**; **Alminderej *et al.*, 2022**). The microalgae cell wall, composed of polymer components such as protein and cellulose, contains functional groups, which include carboxylate, amine, imidazole, phosphate, sulfhydryl, sulfate, and hydroxyl groups, that actively participate in biosorption (**Redha, 2020**) (Fig. 4).

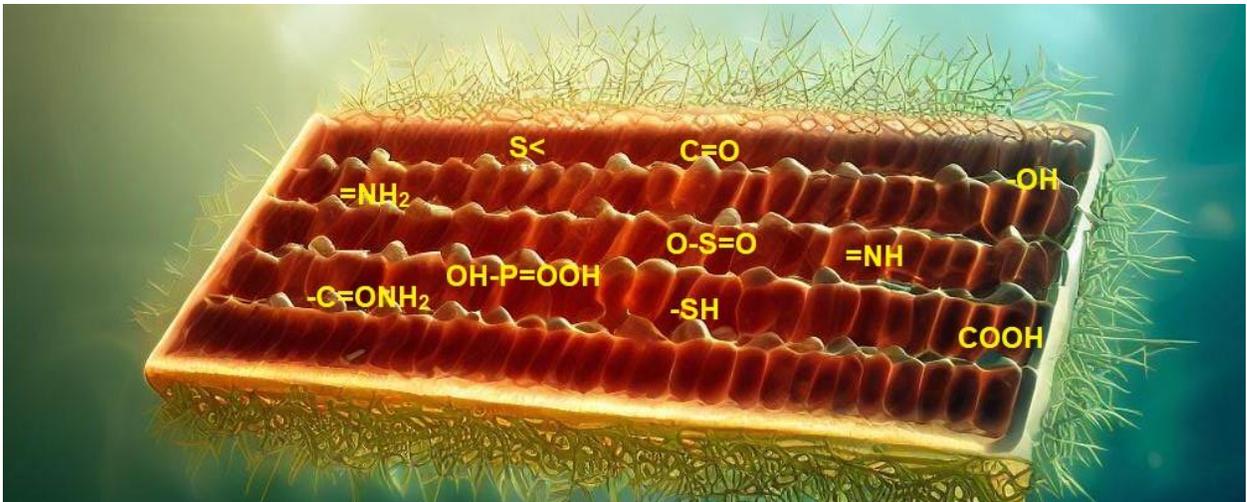


Fig. 4. Functional groups involved in phenol adsorption on algal cell wall surfaces

In comparison to the cultivation of fresh algae over a long period, dried algae powder and fresh seaweed obtained from algae-based wastewater treatment plants or residual algal biomass after oil extraction can be directly employed as adsorption materials, saving time and resources (Abbas *et al.*, 2019).

Certain algae efficiently remove specific phenolic compounds through adsorption (Fig. 5). For instance, *Ulva lactuca*, when dried and processed into 0.5 to 1mm fragments, can eliminate 90.125% of 1mg/ L phenol in simulated wastewater (Abbas *et al.*, 2019). Additionally, Zheng *et al.*, (2017) reported that Chlorella-derived biochar has a potential adsorption capacity for p-nitrophenol that is 140% higher than that of activated carbon. Thus, adsorption may not be the primary mechanism for phenol removal in some studies, it can still serve as an initial stage for bioaccumulation, biodegradation, and other processes (Bilal *et al.*, 2018).

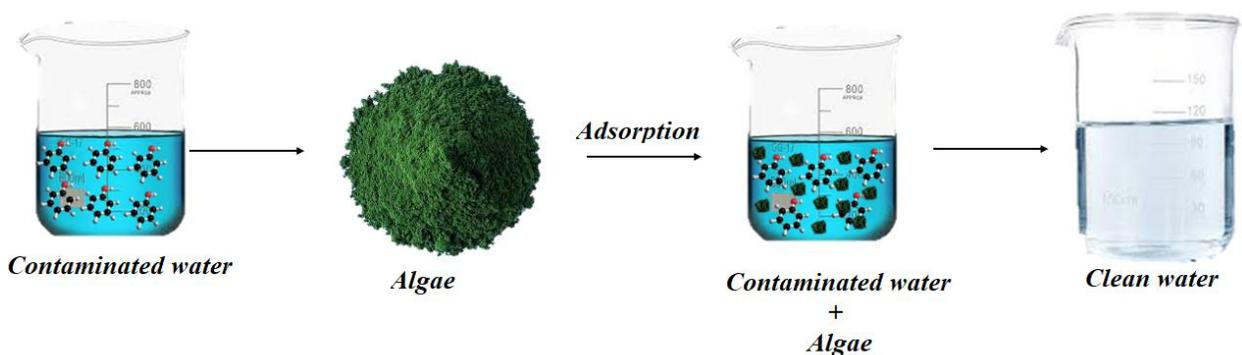


Fig. 5. Adsorption mechanisms for phenol removal using algae: A schematic diagram

Bioaccumulation

Bioaccumulation, or uptake, refers to the process in which certain contaminants permeate the algal cell membrane and become absorbed within the cell (Xiong *et al.*, 2021; Elkady & Younis, 2023).

Dichloromethane: methanol (1:2, v/v) extraction combined with ultrasonic treatment is the most commonly used method for extracting phenolic substances from microalgae. Some studies utilize radioactive substance labels to directly measure the bioaccumulation of substances (Ding *et al.*, 2018; Lv *et al.*, 2019).

Algae-mediated absorption has proven to be one of the most effective methods for removing hydrophobic substances (Bai & Acharya, 2016). For instance, *Desmodesmus subspicatus*, a green algal, was found to accumulate nearly 23% of radiolabeled 17 α -ethinyl estradiol within 24 hours (Maes *et al.*, 2014). Bioaccumulation often exhibits a two-stage release pattern: the first stage involves rapid elimination, while the second stage is characterized by slower removal. After exposure to triclosan, *Cymbella* sp. showed intracellular triclosan levels of 24.37mg/ gDW at 24 hours and 4.02mg/ gDW at 144 hours (Ding *et al.*, 2018).

Furthermore, the gradual decrease in intracellular phenolics may be attributed to the release of microalgae cells into the culture media or the biotransformation occurring within the cells (Ding *et al.*, 2018). Suppose hazardous and harmful molecules accumulated in algal cells are not promptly converted into low-toxic and innocuous compounds. In that case, they can continue accumulating, propagating through the food chain, and ultimately enriching the human body.

Integration of algal biomass production for effective treatment of phenolic compound-containing wastewater

Nutrient-rich wastewater holds significant potential for utilization as an abundant and easily accessible resource for the cultivation of microalgae (Williamset *al.*, 2010). Microalgae, a diverse group of photosynthetic microorganisms, offer valuable prospects to produce various commodities, including food, feed, biofertilizers, biofuels, biopolymers, and other high-value goods (Williams *et al.*, 2010; Stiles *et al.*, 2018).

It is important to acknowledge that although concerns regarding human consumption exist, microalgae cultivated on wastewater have shown promise in applications such as animal feed/nutrition, biofuel production, and biofertilizer development (Olguín, 2012; Ación Fernández *et al.*, 2018). Microalgae, as microscopic photosynthetic organisms, belong to the diverse group of algae.

Microorganisms possess the capability to assimilate carbon dioxide (CO₂) and essential nutrients, particularly nitrogen and phosphorus. These microorganisms are well known for their involvement in bioremediation processes.

The wide range of habitats and the broad tolerance of microorganisms contribute to their effectiveness in treating wastewater from various sources. Environmental conditions, specifically nutrient levels, have been extensively documented in previous studies (**Williams *et al.*, 2010; El-Sheekh & Abomohra, 2021**).

To achieve effective phenolic compound removal while maximizing algal biomass production, several factors should be considered. Nutrient management plays a crucial role in algal cultivation, as it affects both biomass growth and phenolic compound uptake. Balancing the nutrient supply, particularly nitrogen and phosphorus, is essential to prevent excessive algal growth and to promote the synthesis of high-value biomass products. Optimizing light exposure through photobioreactors or open ponds is necessary to enhance algal photosynthesis and biomass productivity.

Extensive research has been dedicated to investigating the production of microalgae using wastewater as a growth medium. As previously mentioned, this approach has demonstrated high efficacy in pollutant removal from diverse wastewater sources, including residential and industrial sources (**Williams *et al.*, 2010; El-Sheekh *et al.*, 2020; El-Sheekh *et al.*, 2022**). Microalgae cultivation has been successfully carried out using different stages of residential wastewater treatment, including raw sewage, settled sewage, anaerobically digested wastewater, and centrate obtained from digestate dewatering (**El-Sheekh *et al.*, 2022**). Moreover, microalgae growth has been achieved utilizing agro-industrial wastewater from various origins, such as tanneries (**Sekaran *et al.*, 2013**), digestate derived from agro-industrial waste (**Zuliani *et al.*, 2016**), piggery effluent (**Raeisossadati *et al.*, 2019**), and anaerobically digested abattoir effluent (**Vadiveloo *et al.*, 2020**).

Algal biomass exhibits inherent capabilities for phenolic compound removal from wastewater. The mechanisms involved include physical adsorption, biodegradation, and enzymatic transformations. Algal cells possess surface binding sites that can adsorb phenolic compounds, effectively removing them from the water phase. Furthermore, algal enzymes, such as peroxidases and laccases, participate in the degradation of phenolic compounds, converting them into less toxic byproducts. Understanding these removal mechanisms is crucial for optimizing the integration process.

To further enhance phenolic compound removal efficiency, integrating algal biomass production with other wastewater treatment processes can be advantageous. For instance, combining algal cultivation with adsorption techniques using activated carbon

or other adsorbents can provide complementary removal mechanisms. Additionally, advanced oxidation processes, such as ozonation or photocatalysis, can be integrated to enhance the degradation of recalcitrant phenolic compounds. These synergistic approaches capitalize on the strengths of different treatment technologies, resulting in more comprehensive and efficient wastewater treatment.

Despite the potential benefits of integrating algal biomass production with phenolic compound removal, several challenges need to be addressed. These include the selection of suitable algal strains with high phenolic compound tolerance and uptake capacities, optimization of cultivation conditions for simultaneous biomass production and removal efficiency, and economic feasibility at a larger scale. Furthermore, the fate of accumulated phenolic compounds within the algal biomass, such as their potential release during biomass harvesting or downstream processing, requires careful consideration.

CONCLUSION

The elimination of phenolic compounds is essential for environmental protection. Biological treatment is the most effective and environmentally sustainable approach among the available methods. This treatment has gained increasing interest in the field of pollution control. Algae play a crucial role in natural ecosystems, contributing to the biodegradation of phenol. Their ability to thrive in harsh environments provides advantages for efficient and rapid removal of phenolic contaminants.

Algae have the potential to eliminate hazardous phenolic compounds present in wastewater effectively. Algae-based technology offers a sustainable, environmentally conscious, cost-effective alternative to conventional wastewater treatment techniques. Recent research efforts have primarily focused on optimizing the degradation process by investigating the effects of various factors on algae performance under controlled experimental conditions. However, there are significant research gaps regarding the bioremediation of real wastewater by algae, the determination of toxicity of degradation products, and the modification of chassis through synthetic biology strategies. Therefore, further relevant research is needed to address these gaps and advance the field.

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