Biodegradation of Phenol and Its Derivatives in Industrial Effluent: A Review on Status and Perspective

Mishu Singh
HOD,
Dept. of Chemistry,
Maharana Pratap Govt. P.G.College,
Hardoi, U.P., India

Abstract

Organic pollutants comprise of potentially carcinogenic and mutagenic substituted aromatic compounds that are dreadfully perilous to human health out of which phenol and its higher molecular homologous derivatives are hazardous to the environment. Being highly toxic these molecules and their derivatives tend to accumulate into water and soil and persist there for long as they are discharged without any proper treatment. These are even proficient of long-range haulage and bioaccumulation in human and animal tissue. Phenol and its derivatives make a class of potentially toxic pollutants in water and soil which are mainly used and produced in a wide variety of industrial processes. The industrial submission for biodegradation of industrial waste has become an important issue in recent years. In this paper, the current situation, properties, and characteristics of phenolic water, the factors affecting the biodegradation of phenol and its derivative, biodegradation methods and microbes helping in degradation is discussed.

Keywords: Phenol, Carcinogenic, Pollutants, Biodegradation, Ion Exchange, Activated Carbon, Bacteria, Ozonolysis.

Introduction

Water, the most valuable natural recourse, covers 70% of the earth's surface and without it, the life on the Earth would not exist. Water pollution is a common problem that is being recognized for the last many decades. With rapid urbanization and extensive industrialization, environmental pollution has become a major problem [Ghisalba, 1983]. The natural water bodies are constantly being contaminated by hazardous and toxic pollutants. Due to depletion and exhaustion of freshwater bodies, the demand for clean and drinking water is becoming an imperative concern for the countries all over the world. Soil and water bodies are highly contaminated with many toxic compounds such as phenol, ammonia, cyanides, thiocyanate, phenol-formaldehyde, Acryl & Aceto- nitriles and heavy metals like Cr, Zn, Cd, Hg, Cu, Ni, etc. Thirty monoaromatics are on the EPA priority pollutant list and 11 of these compounds are among the top of hundred chemicals on the priority list of hazardous substances published by the agency for toxic substances and disease registry [Y. Q. Huang, et al, 2012]. Monoaromatics like benzene, toluene, and phenol are obvious choices for studies on biodegradation. Among these, phenol and its derivatives are the most common toxic, recalcitrant and hazardous environmental pollutants which are used and produced in many of the industrial processes. They are even highly toxic at a relatively low concentration and hence, USEPA has set a limit of 0.1mg/L of phenol as the permissible limit in the water bodies.

Phenolic compounds mainly include chlorophenols, alkyl-phenols, and natural steroid hormones, which are mainly used in industry, such as fossil fuel extraction, wood processing industry, pesticide manufacturing plants, pharmaceutical industry, petrochemicals, petroleum refinery, preservatives, tanneries and so on. The annual production of phenolic pollutant is quite high for example the annual output of biphenyl is up to 4.69 million tons [S. Y. Li, et al 2015]. Phenolic compounds, the most archetypal contaminant, have serious effects on living organisms inhabiting the growth rate of microorganisms in water and disturbing the ecological balance. Even at low concentration, phenol-containing wastewater directly leads to crop death [Ertani, M. Schiavon, et at 2011]. The harmful effects of phenolic pollutants on the environment are massive, and the need to effectively degrade the phenol pollutants in water has become a big problem in the world.

Objective of the Study

Literature study reveals that extensive work has been done on biodegradation of phenolic waste by indigenous. The idea behind this study was to explore the microbial community existing in these areas. It is a well-known fact that phenols are the major component of most of the disinfectant used in recent time. The present work primarily involves the study on biological degradation of phenol using different microbial strains.

Chemical and Physical Identity of Phenol

Phenol, C_6H_5OH (also known as hydroxybenzene or carbolic acid phenic acid, phenylic acid, phenyl hydroxide or oxybenzene [Nair et al., 2008], is an aromatic molecule containing hydroxyl group attached to the benzene ring structure. Phenol with characteristic acrid smell and a sharp burning taste, forms white to colorless crystals, colorless to pink solid or thick liquid [Gardner et al. 1978], has a Molecular Weight of 94.11gm/mol, Melting point 43ºC, Boiling point (ºC) 181.8 and Auto-ignition temperature 715 ºC [Lide, 1993]. It is relatively highly water-soluble and is soluble in most organic solvents such as aromatic hydrocarbons, alcohols, ketones, ethers, acids, halogenated hydrocarbons, etc. [Lide, 1993; ATSDR, 2008]. However, the solubility of phenol is quite limited in aliphatic solvents. The odor threshold of phenol in the air is 0.04 ppm (v/v) and in water between 1 ppm and 7.9 ppm (w/v) [Amoore and Hautala, 1983]. Phenol is a weak acid and in its ionized form, it is highly sensitive for electrophilic substitution reactions and oxidations.

Toxicity of Phenol

Phenol and its derivatives are classified as a priority pollutant owing to their high toxicity and widespread environmental occurrence and are included in the list of EPA 1979 [Agarry et al., 2008]. These compounds are highly toxic even at low concentrations and the toxicity of phenols for microbial organisms has been investigated [Keweloh et al., 1990; 1998; Kahru et al., 2002]. and the adverse effects of phenol on health were documented [Calabrase and Kenyon, 1991; Sax, 1984]. Fatal blood concentration for phenol is around 4.8 to 130 mg/100 ml. Acute exposure of phenolic compounds to human beings for a prolonged period of time causes disorders of central nervous system may lead to damage in blood, and vital body organs like liver, kidney, cardiac toxicity causing weak pulse, cardiac depression and reduced blood pressure at concentrations levels ranging between 10 and 240 mg/L [Barker et al. 1978]. Hypothermia, gastrointestinal disturbance, burning sensation on the skin and of eyes, diarrhea, and excretion of dark urine were also reported by the researchers [Olujimi et. al., 2010; Khare, 2011; Tziotzios et al., 2005; Chakraborty et al., 2010]. Due to these disagreeable damaging health effects of phenols, the World Health Organization has set a maximum permissible limit for phenol in wastewater i.e. is 0.1 mg/l [Kumaran and Paruchuri, 1996; Nuhoglu and Yalcin, 2005; Saravanan et al., 2008]. Therefore, it can be seen that the disposal of phenol has become a major global concern.

The harmful impact of pollution on the environment have led to intense scientific analysis and investigation for removal of phenol from industrial effluents by the researchers from different fields and has initiated the quest for possible solutions for treating phenol. Different treatment methods are available for removal of phenolics in wastewater. Depending upon the concentration, cost, and effectiveness of the method, the volume of the effluent, many physical, chemical, physicochemical and biological treatment methods are being used for the treatment of phenolic wastewater. [Santiago et al. 2002;, Arutchelvan et al. 2005; Klein and Lee 1978; Anselmo and Novais 1992; Koyama et al., 1994; Mokrini et al., 1997; Chan and Fu, 1998; Danis et al., 1998; Reardon et al., 2000; Backhaus et al., 2001; Ajay et al., 2004].

Treatment methods & Chemical Oxidative Treatment Methods

Chemical treatment involves the use of chemicals for complete ting them into simpler compounds that are less harmful and toxic which can be further degraded by microorganisms [Hamby D. M., 1996]. Chemical oxidative degradation of organic pollutants is a potentially beneficial alternative when the effluent contains non-biodegradable and/or noxious contaminants in high concentration. These oxidizing agents are strong oxidants out of which hydrogen peroxide which is widely used for this purpose [Dias-Machado et al., 2006; Ksibi, 2006]. However, Hydrogen peroxide when used alone is very less reactive causing incomplete oxidation of contaminants [Kamenev et al., 1995; Ikehata and Gamal El-Din, 2006]. There are many disadvantages linked with the chemical oxidation process viz. high cost of the chemicals, emission of harmful gases as by-products, and production of secondary hazardous chemicals. [Jena et al., 2005].

Physico-Chemical Methods

A wide variety of treatment methods have been used for removal of phenols from industrial effluent. Many other treatment methods for removal of the phenolic waste include granular activated carbon processes, reverse osmosis, anaerobic processes, the electrolytic oxidation, coagulation processes, stripping, etc are available.

Advanced Oxidation Processes (AOPs)

Advanced Oxidation Processes, impregnating ozone is gaining acceptance worldwide nowadays. AOPs use ozone, Ultraviolet radiation, or ozone in combination with UV radiations. Combination of ozone with hydrogen peroxide and UV is gaining attention as it ensures complete oxidation of organic phenols and its derivatives. However, the high treatment cost of AOPs is still the biggest disadvantage and prime concern for the researchers.

Electrolytic Oxidation

Researchers are studying for the use of electrochemical cell which is capable of removing phenols from industrial effluent as an alternative tool in pollution abatement programs. However, the main disadvantage of this treatment process is high capital cost, incomplete phenol removal, soaring reagent and energy requirements, generation of toxic sludge and difficulty in its careful disposal.

Ion Exchange Method

Natural and synthetic ionic resins, which are specifically designed to enable ion exchange with high adsorption properties are used in this process for removal of organic and other inorganic pollutants form Purification and decontamination of industrial effluent. The main properties of the ionic resins include adsorption capacity, porosity, density, etc [Zorpas et al., 2010]. Caetano et al., [2009] have reported two different types ion exchange resins, Dowex XZ (strong anion exchange resin) and AuRIX 100 (weak anion exchange) for efficient phenol removal under alkaline conditions. However, it is reported that the phenol is removed by the ion exchange resins only in the alkaline medium while the maximum phenol removal was obtained by the non-functionalized resin in the acidic medium [Caetano et al.,2009]. The main disadvantage with this method is the high cost of the ion exchange resins and one resin selectively removes one type of pollutant only [Talley and Sleeper, 1997]. Another drawback is the pH sensitivity of the ion exchange process [Saparia et al., 1996; Liotta et al., 2009].

Adsorption

Adsorption method has been widely used for removal and recovery of heavy metals and organic phenolic pollutants present in the industrial effluents [Al- Rekabi et al., 2007; Patel and Vashi, 2010; Basso et al., 2002; Park et al., 2006]. Adsorption by activated carbon for the removal of phenolic contaminates is a widely studied treatment method [Garcia-Araya et al., 2003]. Selection of the proper adsorbent material, particle size, surface area, porosity and pore size distribution of the activated carbon are the most important factors that affect the adsorption of phenol [Gardea-Torresdey et al., 2004; Kyuya et al., 2004]. However, these processes are high energy-consuming, noneconomic and not cost-effective as this is associated with recovery of activated carbon particles from the effluent, wastewater also requires further treatment and most importantly, it produces a large amount of solid waste, which further requires safe disposal. [Banat et al., 2000]. Apart from these extensively used methods, other methods such as photo-catalysis, solvent extraction, coagulation, flocculation, Reverse osmosis is also used in the removal of phenol from wastewater.

Biological Treatment Method/ Bioremediation of Organic Pollutant

Development of treatment methods that emphasize the degradation of phenolic waste without the above-mentioned drawbacks of chemical and physicochemical methods had been the biggest focus of the research in the last many years. Treatment of industrial effluent with pure and mixed microbial strains is measured to be an efficient and cost-effective biological tool for the treatment of contaminated wastewaters containing phenolic compounds [Monteiro et al., 2000; Banerjee et al., 2001; Abuhamed et al., 2004; Kumar et al., 2005; Rodriguez et al., 2006]. This new technology has been loosely grouped under the term "Bioremediation", which involves the treatment process that uses microorganisms to breakdown, or degrades hazardous substances into less toxic or non-toxic substances. Utilizing the perspective of microbes to degrade phenol has always been a green option to develop Bioremediation approaches, for treatment of contaminants present in wastewater.

Biodegradation process is an entrenched and powerful technique for treating industrial effluents. The efficiency of biodegradation depends on the type of the organic pollutant, the nature of the microorganisms, the enzyme involved, the method of degradation (aerobic or anaerobic) and the nature of other influencing factors such as temperature, concentration, etc. Biodegradation of Phenol and its derivatives by microbes under aerobic and anaerobic conditions is been widely adopted and there is an increased interest in the use of these organisms for effluent treatment during the past three decades.

Advantages of Biodegradation

Biodegradation process is being chosen over the other treatment methods of phenol due to its potential to degrade phenol completely with no dangerous end products, is economic and most importantly maintains phenol concentration below the toxic limit. The microorganisms digest phenolic compounds completely and employ it in the TCA (tricarboxylic acid cycle) cycle for their energy requirements.

Microorganisms Involved in Biodegradation

Microbial biodegradation of phenols in the effluent is a complex series of biochemical reactions and is different when diverse microorganisms are involved including bacteria, fungi, algae, yeast, and actinomycetes. Bacterial species include Bacillus sp, Pseudomonas sp, Acinetobacter sp, and Achromobacter sp, etc. Fungal groups like Fusarium sp, Phanerocheate chrysosporium, Corious versicolor, Ralstonia sp, Streptomyces sp, etc are also proved to be efficient in biodegradation of phenol. decomposition of phenols by yeast strains like Saccharomyces, Candida, Debaryomyces and Trichosporon cutaneum is also reported by the researchers [Harris and Rickettes, 1962; Henderson, 1961; Neujahr and Varga, 1970; Neujahr et al. 1974; Hashimoto, 1973]. Among the yeast strains, Candida tropicalis has been the most studied and able to degrade phenol, phenol derivatives and aliphatic compounds at a relatively high phenol concentration [Krug et al. 1985; Chang et al. 1995; Ruiz-Ordaz et al. 2000)]. Mutant strains Comamonas teststeroni E23 has been reported as the best phenol degrader of all strains reported up to date [Yap et al. 1999]. The physiological and genetic basis of phenol degradation has been explained by many researchers [Kotturi et al. 1991; Nurk et al. 1991; Kiyohara et al. 1992; Motzkus et al. 1993; Arquiaga et al. 1995; Puhakka et al.1995; Buitron and Gonzalez, 1996]. However, this bacterial or fungal microorganism growth is inhibited at higher concentration of phenol, by which the growth is inhibited [Prieto et al., 2002].

Bacteria

Depending on the type of bacteria that are accountable for the biodegradation bioremediation is categorized as aerobic or anaerobic. The bacterial species that degrade phenols can be divided into two types: the first type can use phenols as the sole source of carbon including arthrobacter, acinetobacter, alcaligenes, corynebacterium micrococcus and staphylococcus. The second type of bacteria depends on other carbon sources to degrade phenols. This type of bacteria mainly decomposes phenols through co-metabolism pattern, which usually needs two or more bacteria working together [Ali et al. 1998]. The genus Pseudomonas is widely applied for the degradation of phenolic compounds for their immense ability to grow on various organic compounds [Annadurai et al., 2000a, b]. Phenol and other phenolic compounds which are the major constituents of many industrial effluents can be safely treated and disposed of degradation using batch and fed-batch fermentation under aerobic condition [Mohd Tuah, 2006; Borghei and Hosseini, 2004]. Degradation of phenol and some of its alkyl derivatives (p-cresol, 4-n-propyl phenol, 4-i –propyl phenol, 4-n-butyl phenol, 4-sec-butyl phenol, 4-t-butyl phenol, and 4-t-octyl phenol) were examined under both aerobic and anaerobic conditions in seven Japanese paddy soil samples by using Klebsiella oxytoca strain and It was found that K.lebsiella oxytoca degraded phenol at elevated concentration where 75% of initial phenol concentration at 100 ppm was degraded within 72 h [Atsushi et al., 2006; Shawabkeh et al., 2007]. The immobilized stain of Alcaligenes sp d2 was effectively used for the treatment of phenolic effluent where succinic acid and glycine were found to as respective carbon and nitrogen source and the most efficient co-substrates for the removal of phenol [Nair and Shashidhar, 2008. The list of a bacterial strain that was used in the degradation of phenol and its derivatives is shown in Table no 1.

Table 1. Bacterial Strains in Biodegradation of Phenolic Compounds

S/N	Bacteria	Reference
1	Achromobacter sp	Xiangchun et al. (2003)
2	Acinetobacter calcoaceticus	Nakamura and Sawada (2000)
3	Acinetobacter Calcoaceticus PHEA-2.	Zhan et al. (2009)
4	Acinetobacter johnsonii	Hoyle et al. (1995)
5	Acinetobacter sp	Hao et al. (2002)
6	Acinetobacter sp W-17	Beshay et al. (2002)
7	Alcaligenes sp	Baek et al. (2001)
8	Alcaligenes sp	Nair and Shashidhar (2004)
9	Bacillus brevis	Arutchelvan et al. (2006)
10	Bacillus sp	Ali et al. (1998)
11	Bacillus stearothermophilus	Gurujeyalakshmi and Oriel (1988)
12	Micrococcus sp.	Tibbles and Baecker, 1989b
13	Nocardia sp.	Vijaygopal and Viruthagiri, 2005
14	Nocardioides	Cho et al. (2000)
15	Pleurotus ostreatus	Hublik and Schinner (2000)
16	Pseudomanas putida	Oliver 2002)
17	Pseudomonas flurorescens	Torres et al. (1998)
18	Pseudomonas pictorium	Annadurai et al. (2000)
19	Pseudomonas putida	Allsop et al. (1993)
20	Pseudomonas putida	Loh and Wang (1998)
21	Pseudomonas putida	Mordocco et al. (1999)
22	Pseudomonas putida	Wang and Loh (1999
23	Pseudomonas putida	Zumriye and Gultac (1999)
24	Pseudomonas putida	Loh and Tar (2000)
25	Pseudomonas putida	Loh and Liu (2001)
26	Pseudomonas putida	Petruschka et al. (2001)
27	Pseudomonas putida	Farighian (2003)
28	Pseudomonas putida	Hamed et al. (2004)
29	Pseudomonas putida	Kargi and Eker (2005)
30	Pseudomonas putida MU 174	Chitra et al. (1995)
31	Pseudomonas putida (MTCC 1194).	Bandhyopadhyay et al. (1998)
32	Pseudomonas putida 548.	Monterio et al. (2000)
33	Pseudomonas putida F1	Reardon et al. (2000)
34	Pseudomonas putida F1 ATCC 700007	Abuhamed et al. (2003)
35	Pseudomonas putida p8	Morsen and Rehm (1990)
36	Pseudomonas sp	Bodzek et al. (1996)
37	Pseudomonas sp	Gotz and Reuss(1997)
38	Pseudomonas sp	Gonzalez et al. (2001)

39	Pseudomonas sp	Prpich and Douglis (2005)
40	Pseudomonas sp. strain CF600	Shingler et al. (1992)
41	Ralstonia eutropha	Leonard et al. (1999 a,b)
42	Rhodococcus erythropolis	Prieto et al. (2002)
43	Sphingomonas chlorophenolica	Bielefeldt and Cort (2005)
44	Streptomyces setonii	An et al. (2001)

Fungi

The main fungi of phenolic pollutants degradation are filamentous fungi, including white-rot fungi, fusarium, penicillium, Agaricus, coprinus and so on. They degrade phenol contaminants through a series of enzymatic reactions. Yeast mainly includes Candida albicans, Candida maltosa, Trichosporon cutaneum, and Oidium, etc. The research shows that the yeasts have a strong ability to degrade phenols and tolerate phenols with high initial concentration [Ariana Fialova et al., 2004]. A list of fungi is shown in Table no 2.

Table 2. Fungi in Biodegradation of Phenolic Compounds

S/N	Fungi	Reference
1	Agaricus bisporus	Burton et al. (1993)
2	Aspergillus niger	Garcia et al., 2000
3	Aspergillus terreus	Garcia Garcia et al., 1997
4	C. cinereus	Guiraud et al., 1999
5	Chalara paradoxa	Robles et al. (2000)
6	Clavariopsis aquatica	Moeder et al. (2006)
7	Coprinus cinereus	Masuda et al., 2001
8	Coprinus cinereus	Schneider et al. (1999)
9	Coprinus cinereus	Sakurai et al. (2001)
10	Coprinus sp.	Guiraud et al., 1999 \
11	Fung trogii	Garzillo et al. (1998)
12	Fusarium flocciferum	Anselmo et al. (1992)
13	Fusarium sp	Santos and Linardi (2004)
14	Lentinula edodes	Okeke et al. (1997)
15	Lentinus bisporous	Okeke et al. (1993)
16	Phanerocheate chrysosporium	Garcia et al. (2000)
17	Rhizoctonia praticola	Bollag et al. (1988
18	Termitomyces albuminosus	Johjima et al. (2003)
19	Trichosporon cutaneum	Ghioureliotis et al. (1999)

Algae

Algae are also reported in the degradation of phenolic contaminants. It is reported that they can degrade alkyl-phenol and the rate of bio-degradation is determined by the growth rate of algae and the initial concentration of Phenolic substances [9]. list of algae reported in researches is shown in Table no 3.

Table 3. Algae in Phenol Biodegradation

S/N	Algae	Reference
1	Ankistrodesmus braunii	Gabriele pinto et al., 2002
2	Coriolus versicolor	Kadhim et al. (1999)
3	Ochromonas danica	Semple and Cain(1997)
4	Phormidium valderianum	Shashirekha et al. (1998)
5	Scenedesmus quadricauda	Gabriele pinto et al., 2002

Moreover, some yeast is also capable of degrading phenol. The list is given in Table -4

Table 4. Yeast in Phenol Biodegradation

S/N	Yeast	Reference
1	Candida tropicalis CHP4	Kumaran, 1980
2	Candida maltosa	Ariana Fialova et al., 2004
3	Candida tropicalis	Ehrhardt and Rehm, 1985),
4	Candida tropicalis	Salmeron- Alcocer et al., 2007
5	Candida tropicalis Ct2	Komarkova et al., 2003
6	Candida tropicalis H15	Krug et al., 1985, Krug and Straube, 1986
7	Cryptococcus elinovii H1	Morsen and Rehm (1990)
8	Fusarium flocciferium	Anselmo et al., 1985; Mendoca et al., 2004)
9	Trichosporon cutaneum	(Gaal and Neujahr, 1980; Yang and Humphrey, 1975)

Normally organic pollutants are degraded by natural bacteria. However, aromatic compounds various substituents are more recalcitrant. Scientists have been working on these microbes which are capable of degrading phenolic compounds through the action of a variety of enzymes. These enzymes may include oxygenase, horseshoe peroxidase, hydroxylase, tyrosinases, and oxidases, etc.

Table 5. Enzymes Involved in Biodegradation of Phenolic Compounds

S. No.	Enzyme	References
1	Bis phenol Peroxidase	Sakurai et al. (2001)
2	Catechol 1,2oxygenase	An et al. (2001)
3	Catechol 2,3 dioxygenase	Ali et al. (1998)
4	Horseradish peroxidase	Wu et al. (1998)
5	Horseradish peroxidase	Zahida et al. (1998)
6	Laccase	Bollag et al. (1998)
7	Laccase	Hublik and Schinner (2000)
8	Laccase	Kadhim et al. (1999)
9	Laccase	Robles et al. (2000)
10	Laccase	Schneider et al. (1999)
11	Lignophenols Peroxidase	Xia et al. (2003)
12	Methoxyphenol Laccase	Setti et al. (1999)
13	Peroxidase	Ghioureliotis and Nicell (1999)
14	Phenol hydroxylase	Gurujeyalakshmi and Oriel (1988)
15	Phenol oxidase	Johjima et al. (2003)
16	Phenol Oxidase	Okeke et al. (1997)
17	Polyphenol Oxidase	Burton et al. (1993)
18	Polyphenol Oxidase	Cano et al. (1997)
19	Polyphenol oxidase	Edwards et al. (1999)
20	Polyphenol oxidase	Garzillo et al. (1998)
21	Polyphenol oxidase	Luke and Burton (2001)
22	Polyphenol oxidase	Shashirekha et al. (1997)
23	Polyphenol oxidase	Steffens (2002)
24	Tyrosinase	Xiangchun (2003)

Method of Biodegradation of Phenol

Selection of sewage treatment method before sending the phenolic effluent for bio-degradation of phenolic effluent is very important. The main biodegradation methods include activated Sludge, fixed and floating bed biofilm reactor, biological contact oxidation, biological fluidized bed, and immobilization technology.

Principle and the Properties of The Biological Treatment Methods of Industrial Effluents

Activated Sludge

Principal

This process involves adsorption a biological degradation by the microorganism present in the activated sludge. This takes place aerobically.

Properties

In this treatment method, simple equipment is used. Although the treatment effect is good, it has high preprocessing requirements and is not suitable for large-scale treatment plants.

Fixed Bed Biofilm Reactor

Principle

In this method, the microorganisms are attached to the surface of the fixed or floating bio-film which is in contact with the sewage.

Properties

It's a combination of biofilm and activated sludge which requires stable water quality and fixed volume for the treatment. The treatment plant is a way to operate. However, uncontrollable microbial development and biomass is the most important issue to be handled.

Biological Fluidized Bed

Principle

Fluidization state of the carrier for attaching microorganism

Properties

Combination of membrane separation technology and bioreactor

Immobilization

Principle

To locate Microorganisms or enzymes in the limited-space area by chemical or physical means

Properties

High microbial density, Fast reaction speed, Low microbial loss, Easy separation of products, Miniaturization of processing equipment

Conclusions and Perspectives

Due to the developmental pressure and increasing public concern, over the past few decades, researchers and investigators had a great opportunity to explore and discover new applications and technologies for biodegradation of industrial effluent. As discussed above in the paper, use of such technologies in industrial effluent treatment has been extensive and has also achieved extraordinary outcome in the facet of phenol and other phenolic derivatives degradation. However, because of the massive yearly release of phenolic contaminants, and itself being anti microbial in nature many microorganisms have not been able to spread out the extent of wastewater treatment. Therefore, much attention for the development of more effective treatment methods and application is needed.

References:

Abuhamed, T.A., Bayraktar, E., Mehmetoglu, T. and Mehmetoglu, U. (2003). Substrate interactions during the biodegradation of benzene, toluene and phenol mixtures. Process Biochemistry. 39: 27-35.

Abuhamed, T., Bayraktar, E., Mehmeto_lu, T., Mehmeto_lu, U., 2004. Kinetics model for the growth of Pseudomonas putidaF1 during benzene, toluene and phenol biodegradation. Process Biochemistry 39(8), 983-988.

Agarry, S. E., Solomon, B. O., Audu, T. O. K., 2010. Substrate utilization and inhibition kinetics: Batch degradation of phenol by an indigenous monoculture of Pseudomonas aeruginosa. International Journal for Biotechnology and Molecular Biology Research 1(2),22-30.

Agarry, S. E., Solomon, B. O., 2008. Kinetics of batch microbial degradation of phenols by indigenous Pseudomonas fluorescence. International Journal of Environmental Science an Technology 5 (2), 223-232.

Agarry, S.E., Durojaiye, A.O., Solomon, B.O., 2008. Microbial degradation of phenols solutions by adsorption on alumina pillared clays and mesoporous alumina aluminum phosphates. Water Resource 32, 295–302.

Agency for Toxic Substances and Disease Registry (ATSDR),. Toxicological Profile for Phenol. US Department of Health and Human Services, ATSDR, US, 2008.

Ajay, K.J., Vinod, K.G., Shubhi, J., Suhas, 2004. Removal of chlorophenols using industrial wastes. Environmental Science and Technology 38, 1195–1200.

Ali, S., Roberto, F., La Fuente. and Dona, A.C.(1998). Meta pathway degradation of phenolics by thermophilic Bacilli. Enzyme and Microbial Technology. 23:462-468.

Ali S, Roberto F, La Fuente, Dona AC (1998). Meta pathway degradation of phenolics by thermophilic Bacilli. Enzyme Microbial Technol. 23: 462-468.

Allsop PJ, Chisti Y, Moo-Young M, Sullivan GR (1993). Dynamics of phenol degradation by Pseudomonas putida. Biotechnol. Bioeng. 41: 572-580.

Al-Rekabi, W.S., Qiang, H., Qiang, W.W., 2007. Improvements in Wastewater Treatment Technology. Pakistan Journal of Nutrition 6(2), 104-110.

Amoore, J.E. and Hautala, E.. Odors as an aid to chemical safety: odor threshold limit values and volatilities for 214 industrial chemicals in the air and water dilution. Appl. Toxicol. 3: 272-290, 1983.

Annadurai G, Balan MS, Murugesan T (2000a). Design of experiments in the biodegradation of phenol using immobilized Pseudomonas pictorium (NICM – 2077) on activated carbon. Bioproc. Eng. 22: 101-107.

Annadurai G, Rajesh Babu S, Mahesh KPO, Murugesan T (2000b). Absorption and biodegradation of phenol by Chitosan immobilized Pseudomonas putida (Mcm.2174). Bioproc. Eng. 22: 493-501.

Annadurai, G., Rajeshbabu, S., Mahesh, K.P.O. and Murugen, T. (2000). Adsorption and biodegradation of phenol by chitosan-immobilized Pseudomonas putida (NCIM 2174). Bioprocess Engineering. 22: 493-501.

Anselmo, A.M., Mateus, M., Cabral, J.M.S., Novias, J.M., 1985. Degradation of phenol by immobilized cells of Fusarium flocciferum. Biotechnology Letters 7(12), 889–894

Anselmo, A.M., Novais, J.M., 1992. Biological treatment of phenolic wastes: Comparison between free and immobilized cell systems. Biotechnology Letters 14(3), 239-244.

Ariana Fialova., Elke Boschke. and Thomas Bley. (2004). Rapid monitoring of the biodegradation of phenol-like compounds by the yeast Candida maltosa using BOD measurements. International Biodeterioration and Biodegradation. 54(1): 69-76.

Arquiaga, M.C., Canter, L.W. and Robinson, J.M. 1995. Microbiological characterization of the biological treatment of aircraft paint stripping wastewater. Environ. Pollut. 89: 189-195.

Arutchelvan, V., Kanakasabai, V., Nagarajan, S., and Murali Krishnan, V. (2005). Isolation and identification of novel high strength phenol degrading bacterial strains from phenol-formaldehyde resin manufacturing industrial wastewater. J.of hazardous materials. 238-243.

Arutchelvan, V., Kanakasabai, V., Nagarajan, S. and Muralikrishnan, V. 2006.Kinetics of high strength phenol degradation using Bacillus brevis. Journal of Hazardous Materials. B129: 216-222.

Atsushi S, Yasushi I, Arata K (2006). Aerobic and anaerobic biodegradation of phenol derivatives in various paddy soils. Sci. total Environ. 367: 979-987.

Backhaus, W.K., Klumpp, E., Narres, H-D., Schwuger, M.J., 2001. Adsorption of 2,4-Dichlorophenol on Montmorillonite and Silica: Influence of Nonionic Surfactants. Journal of Colloid and Interface Science 242, 6–13.

Baek, S.H., Yin, C.R. and Lee, S.T. 2001. Aerobic nitrate respiration by newly isolated phenol degrading bacterium, Alcaligenes strain P5. Biotechnol. Lett. 23: 627-630.

Banat F. A., Al-Bashir, B., Al-Asheh, S., Hayajneh, O., 2000. Adsorption of phenol by bentonite. Environmental Pollution 107, 391-398.

Bandhyopadhyaya, K., Das, D. and Maiti, B.R. 1998. Kinetics of phenol degradation using Pseudomonas putida MTCC 1194. Bioprocess Engineering. 18(5) : 373-377.

Banerjee, I., Modak, J.M., Bandhyopadhyay, K., Das, D., Maiti, B.R., 2001. The mathematical model for evaluation of mass transfer limitations in phenol biodegradation by immobilized Pseudomonas putida. Journal of Biotechnology 87(3), 211-223.

Barker, E.L., Peter, E.B., Petrecia, H.F. and Grant, S.K. 1978. Phenol poisoning due to contaminated drinking water. Arch. Environ. Health. 33: 89-94.

Basso, M. C., Cerrella, E. G., Cukierman, A. L., 2002. Lignocellulosic Materials as Potential Biosorbents of Trace Toxic Metals from Wastewater. Industrial and Engineering chemistry research 41, 3580-3585.

Beshay, U., Abd-El-Haleem, D., Moawad, H., Zaki, S., 2002. Phenol biodegradation by free and immobilized Acinetobacter. Biotechnology Letters 24, 1295–1297.

Bodzek M, Jolanta B, Malgorzata K (1996). Immobilized enzyme membranes for phenol and cyanide decomposition. J. Membrane Sci.113: 373-384.

Bollag JM, Shuttle WKN, Anderson DH (1988). Laccase mediated detoxification of phenolic contaminants. Appl. Environ. Microbiol. 54(12): 3086-3091

Bollag, J.M., Shuttle, W.K.N.N. and Anderson, D.H. (1998). Laccase mediated detoxification of phenolic contaminants. Appl. Environ. Microbiol. 54(12): 3086-3091.

Borghei SM, Hosseini SH (2004). The treatment of phenolic wastewater using a moving bed biofilm reactor. Proc. Biochem. 39; 1177-1181.

Buitron, G. and Gonzalez, A. 1996. Characterization of the microorganisms from an acclimated activated sludge degrading phenolic compounds. Wat. Sci. Technol. 34: 289-294.

Burton S.G., John, R.D., Perry, T.K. and Peter, D.R. (1993). The activity of mushroom polyphenol oxidase in an organic medium. Biotechnology and Bioengineering. 42: 938-944.

Burton SG, John RD, Perry TK, Peter DR (1993). The activity of mushroom polyphenol oxidase in an organic medium. Biotechnol. Bioeng. 42: 938-944.

Caetano, M., Valderrama, C., Farran, A., & Cortina, J., 2009. Phenol removal from aqueous solution by adsorption and ion exchange mechanisms onto polymeric resins. Journal of Colloid and Interface Science 338(2), 402-9.

Calabrase, E.J., Kenyon, E.M., 1991. Air Toxics and Risk Assessment. Lewis Publishers,

Cano, P.M., Begona de Ancos., Gloria, L.M. and Mariana, S. (1997). Improvement of Frozen nanana (Musa cavendisher, C. Ventana) color by branching relationship between browign, phenols, and polyphenol oxidase and peroxides activities. Z lebnsm unters Forsch A. 60-65.

Chakraborty, S., Bhattacharya, T., Patel, T.N., Tiwari, K.K., 2010. Biodegradation of phenol by native microorganisms isolated from coke processing wastewater. Journal of Environmental Biology 31, 293-296.

Chang, S.Y., Li, C.T., Chang, M.C. and Shieh, W.K. 1998. Batch phenol degradation by candida tropicalis and its fusion. Biotechnol. Bioeng. 60: 391-395.

Chang, S.Y., Li, C.T., Hiang. S.Y. and Chang, M.C. 1995. Intraspecific protoplast fusion of Candida tropicalis for enhancing phenol degradation. Appl. Microbiol. Biotechnol. 43: 534-538.

Chitra, S., Sekaran, G., Padamavathi, S., Chandrakaran, G., 1995. Removal of phenol from wastewater using a biocatalyst. Applied and Environmental Microbiology 13, 1-4.

Cho Y, Rhee S, Lee S (2000). Influence of phenol on biodegradation of p-nitrophenol by freely suspended and immobilized Nocardioides sp. NSP.41. Biodegradation, 11: 21-28.

Danis, T.G., Albanis, T.A., Petrakis, D.E., Pomonis, P.I., 1998. Removal of chlorinated chemicals (phenol and phthalates) in the South African environment: a need for more, Chelsea, Michigan

Dias-Machado, M., Madeira, L.M., Nogales B., Nunes O.C., Celia, M., 2006. Treatment of cork boiling wastewater using chemical oxidation and biodegradation. Chemosphere 64, 455–461.

Edwards W, Bowness R, Leukes WD, Jacobs EP, Sanderson R, Rose PD, Burton SG (1999a). A capillary membrane reactor using immobilized polyphenol oxidase for the removal of phenols from industrial effluents. Enzyme Microbial Technol. 24: 209-217.

Ehrhardt, H.M., Rehm, H. J., 1985. Phenol degradation by microorganisms adsorbed on activated carbon. Applied Microbiology and Biotechnology 21, 32-36.

Ertani, M. Schiavon, A. Altissimo, C. Franceschi and S. Nardi, "Phenol-containing organic substances stimulate phenylpropanoid metabolism in Zea mays," Journal of Plant Nutrition & Soil Science, vol. 174 (3), pp. 496-503, May 2011.

Farighian A, Hill G, Headlen J, Pedias S (2003). Enhancement of 4- Chlorophenol biodegradation using glucose. Clean Technol. Environ. Policy, 51-65.

Gaal, A., Neujahr, H.A., (1980). cis,cis-Muconate cyclase from Trichosporon cutaneum. Biochemical Journal 191, 37-43.

Gabriele Pinto., Antonino Pollio., Lucio Previtera. and Fabio Temussi. (2002). Biodegradation of phenols by microalgae. Biotechnology letters. 24(24): 2047-2051.

Garcia Garcia I., Bonilla Venceslada, J.L., Jimenez Pena, P.R. and Ramos Gomez, E. (1997). Biodegradation of phenol compounds in Vinasse using Aspergillus terreus and Geotrichum candidum. Water Research. 31 (8): 2005-2011.

Garcia I.G., Pena, P.R.J., Veneceslada, J.K.B., Santoz, A.A.M., and Gomez, E.R. (2000). Removal of phenol compound from olive mill wastewater using Phanerochaete chryososporium, Aspergillus niger,

Garcia, I.G., Pena, P.R.J., Veneceslada, J.K.B., Santoz, A.A.M. and Gomez, E.R. 2000. Removal of phenol compound from olive mill wastewater using Phanerochaetechryososporium, Aspergillusniger, Aspergillusterreus, and Geotrichumcandidum. Process Biochemistry. 35: 751-758.

Garcia-Araya, J. F., Beltran, F.J., Alvarez, P., Masa, F.J., 2003. Activated Carbon Adsorption of Some Phenolic Compounds Present in Agroindustrial Wastewater. Adsorption 9,107–115.

Gardea-Torresdey, J.L., de la Rosa, G., Peralta-Videa, J.R., 2004. Use of phyto filtration Fenton oxidation and methanogenic digester sludge. Water Resource 28, 895–899.

Gardener, W., Cooke, E.I. and Cooke, R.W.I. Handbook of Chemical Synonyms and Trade Names. Boca Raton, FL: CRC Press, 1978.

Garzillo AMV, Colao MC, Caruso C, Caporate C, Celletti D, Buonocore V (1998). Laccase from the white rot fungus Trametes trogii. Appl. Microbiol. Biotechnol. 49: 545-551.

Garzillo AMV, Colao MC, Caruso C, Caporate C, Celletti D, Buonocore V (1998). Laccase from the white rot fungus Trametes trogii. Appl. Microbiol. Biotechnol. 49: 545-551.

Ghioureliotis M, Nicell J (1999). Assessment of soluble products of peroxidase catalyzed the polymerization of aqueous phenol. Enzyme Microbial Technol. 25: 185-193

Ghioureliotis M. and Nicell, J. (1999). Assessment of soluble products of peroxidase catalyzed the polymerization of aqueous phenol. Enzyme Microbial Technol. 25: 185-193.

Ghisalba, O., Chemical wastes and their biodegradation: An overview. Experientia398, 1247-1263. 1983.

Gonzalez, G., Herrera, G., Ma, T. and Garcia Pena, M. (2001). Biodegradation of industrial phenolic wastewater in fluidized bed reactor with immobilized cells of Pseudomonas putida. Bioresource technology. 80: 137-142.

Gotz P, Reuss M (1997). Dynamics of microbial growth: modeling time delays by introducing polymerization reaction. J. Biotechnol. 58: 101-114.

Guiraud P., Steiman, R., Ait-Laydi, L. and Seigle-Muranid, F. (1999). Degradation of phenolic and chloroaromatic compounds by Corprinus sp. Chemosphere. 38(12): 2775-2789

Gurujeyalakshmi G. and Oriel, P. (1988). Isolation of phenol degrading Bacillus sterothermophilus and partial characterization of the phenol hydroxylase. Appl. Environ. Microbiol. 55(2): 500-502.

Hamby D. M., 1996. Site remediation techniques supporting restoration activities - A review. Science of the Total Environment 191, 203-224.

Hamed TA Emine B, Ulku M, Tanju M (2004). The biodegradation of benzene, toluene, and phenol in a two-phase system. Biochem. Eng. 32: 68-79.

Hao OJ, Kim MH, Seagren EA, Kim H (2002). Kinetics of phenol and chlorophenol utilization by Acinetobacter sp. Chemosphere, 46: 797-807.

Harris, G., And Ricketts R.W. 1962. Metabolism of phenolic compounds by yeasts. Nat. 195: 473-474. Hashimoto, K. 1973. Oxidation of phenols by yeast. II. Oxidation of cresol by Candida tropicalis. Gen. Appl. Microbiol. 19: 171-187.

Hashimoto, K. 1973. Oxidation of phenols by yeast. II. Oxidation of cresol by Candida tropicalis. Gen. Appl. Microbiol. 19: 171-187.

Henderson, M.E.K. 1961. The metabolism of aromatic compounds related to lignin by some Hyphomycetes and yeast-like fungi of soil. Gen. Microbiol. 26: 155-165.

Hoyle BL, Scow KM, Fogg GE, Darby JL (1995). Effect of carbon/nitrogen ratio on the kinetics of phenol biodegradation by Acinetobacter johnsonii in saturated sand. Biodegradation, 6(4): 283-293.

Hublik G, Schinner F (2000). Characterization and immobilization of the laccase from Pleurotus ostreatus and its use for the continuous elimination of phenolic pollutants. Enzyme Microbial Technol. 27: 330- 336.

Hublik G, Schinner F (2000). Characterization and immobilization of the laccase from Pleurotus ostreatus and its use for the continuous elimination of phenolic pollutants. Enzyme Microbial Technol. 27: 330-336.

Ikehata, K., El-Din, M.G., 2006. Aqueous pesticide degradation by hydrogen peroxide/ultraviolet irradiation and Fenton-type advanced oxidation processes: a review. Journal of Environmental Science and Engineering 5, 81-135.

Jena, H. M., Roy, G. K., Meikap, B. C., 2005. Development and comparative study of a semi-fluidized bed bioreactor for the treatment of wastewater from process industries. Process and Plant Engineering 23(1), 70-75.

Johjima T, Ohkuma M, Kudo T (2003). Isolation and cDNA cloning of novel hydrogen peroxide dependent phenol oxidase from the basidiomycete Termitomyces albuminosus. Appl. Microbiol. Biotechnol. 64: 220-225.

Johjima T, Ohkuma M, Kudo T (2003). Isolation and cDNA cloning of novel hydrogen peroxide dependent phenol oxidase from the basidiomycete Termitomyces albuminosus. Appl. Microbiol. Biotechnol. 64: 220-225.

Kadhim H, Graham C, Baratt P, Evane CS, Rastall RA (1999). Removal of Phenolic compounds by Coriolus versicolor has grown on wheat bran. Enzyme Microbial Technol. 24: 303-307.

Kadhim H, Graham C, Baratt P, Evane CS, Rastall RA (1999). Removal of Phenolic compounds by Coriolus versicolor grew on wheat bran. Enzyme Microbial Technol. 24: 303-307.

Kahru, A., Maloverjan, A., Sillak, H., Pollumaa, L., 2002. The Toxicity and Fate of Phenolic Pollutants in the Contaminated Soils Associated with the Oil Shale Industry. Environmental Science and Pollution Research 1, 27-33.

Kamenev, S., Kallas, J., Trapido, M., Munter, R., 1995. Chemical Oxidation of Biologically Treated Phenolic Effluent. Waste Management 15, 203-208.

Kargi F, Eker S (2005). Removal of 2,4 dichlorophenol and toxicity from synthetic wastewater in a rotating perforated tube film reactor. Proc. 4958 Afr. J. Biotechnol.Biochem. 40: 205-211.

Keweloh, H., Heipieper, H.J., Rehm, H.J., 1998. Tolerance of bacteria against phenol after immobilization in Ca-Alginate. Dechema-Biotechnol Conferences 3, 797–800.

Keweloh, H., Wehrauch, G., Rehm, H.J., 1990. Phenol induced membrane changes in free and immobilized Escherichia coli. Applied and Environmental Microbiology 61, 1252–1256.

Khare, P., 2011. Treatment of phenolic water using adsorption. Thesis, National Institute of Technology, Department of Chemical Engineering, Rourkela.

Kiyohara, H., Hatta, T., Ogawa, Y., Kakuda, T., Tokoyama, H. and Takizawa, N. 1992. Isolation of Pseudomonas picketti strains that degrade 2,4,6- trichloro-phenol and their dechlorination of chlorophenols. Appl. Environ. Microbiol. 58: 1276-1283.

Klein, J.A., Lee, D.D., 1978. Biological treatment of aqueous wastes from usual conversion processes. Biotechnology and Bioengineering 8, 379–390.

Komarkova, E., Paca, J., Klapkova, E., Stiborova, M., Soccol, C.R. and Sobotka, M. (2003). Physiological changes of Candida tropicalis population degrading phenol in a fed-batch reactor. Braz. Arch. Biol. Technology. 46(4): 537-543.

Kotturi, G., Robinson, C.W., and Inniss, W.E. (1991). Phenol degradation by the psychrotrophic strain of Pseudomonas putida. Applied Microbiology Biotechnology. 34: 539-543.

Koyama, O., Kamayat, Y., Nakamura, K., 1994. Degradation of chlorinated aromatics by the microbial consortium during phenol degradation in a batch reactor. Bioresource Technology, 99, 205–209.

Krug, M. and Straube, G. (1986). Degradation of phenolic compounds by the yeast Candida tropicalis HP-15. II. Some properties of the first two enzymes of the degradation pathway. Basic Microbiology. 26 (5): 271-281.

Krug, M., Ziegler, H., and Straube, G. (1985). Degradation of phenolic compounds by the yeast Candida tropicalis HP-15. I. Physiology and growth

Ksibi, M., 2006. Chemical oxidation with hydrogen peroxide for domestic wastewater treatment. Chemical Engineering Journal 119, 161–165.

Kumar, A., Kumar, S., Kumar, S., 2005. Biodegradation kinetics of phenol and catechol using Pseudomonas putida MTCC 1194. Biochemical Engineering Journal 22, 151–159.

Kumaran, P. (1980). Microbial degradation of phenol in phenol-bearing industrial wastes. Ph.D. thesis, Nagpur.

Kumaran, P., Paruchuri, Y. L., 1996. Kinetics of phenol biotransformation. Water Resource 31(1), 11-22.

Kyuya, N., Akio, N., Shin, R.M., Hajime, T., Pisit, A., Wiwut, T., 2004. Adsorption of phenol and reactive dye from aqueous solution on activated carbons derived from solid wastes. Water Resource 38, 1791–1798.

Leonard D, Ben CY, Destnehaut C, Lindley ND, Queinnec I (1999b). Phenol degradation by Ralstonia eutropha, calorimetric determination of 2- hydroxymuconic semialdehyde accumulation by fed-batch fermentation. Biotechnol. Bioeng. 65(4): 407-414.

Leonard D, Lindly NA (1999a). Growth of Ralstonia eutropha on the inhibitory concentration of phenol: Diminished Growth can be attributed to hydrophilic perturbation of Phenol hydroxylase activity. Enzyme Microbial Technol. 25: 271-277.

Lide, D.R. 1993. CRC Handbook of Chemistry and Physics. Boca Raton, FL: CRC Press.

Liotta, L.F., Gruttadauria, M., Carlo, G.D., Perrini, G., Librando, V., 2009. Heterogeneous catalytic degradation of phenolic substrates: Catalysts activity. Journal of Hazardous Materials 162, 588–606.

Loh, K.C. and Liu, J. (2001). External loop inversed fluidized bed airlift bioreactor (EIFBAB) for treating high strength phenolic wastewater. Chemical Engineering Science. 56: 6171-6176.

Loh K, Wang S (1998). Enhancement of phenol and a nongrowth substrate 4-chlorophenol by medium augmentation with conventional carbon sources. Biodegradation. 8: 329-338.

Loh KC, Tar PP (2000). Effect of additional carbon sources on Biodegradation of phenol. Bull. Environ. Contam. Toxicol. 64: 756-763.

Luke AK, Burton SG (2001). A novel application for Pseudomonas putida progress from batch culture to a membrane bioreactor for the bioremediation of phenols. Enzyme Microbial Technol. 29: 348-356.

Masuda, M., Sakurai, A., and Sakakibara, M. (2001). Effect of enzyme impurities on phenol removal by the method of polymerization and precipitation catalyzed by Coprinus cinereus peroxidase. Applied Microbiology Biotechnology.57: 494-499.

Moeder M, Martin C, Schlosser D, Harynad J, Gorreeki T (2006). Separation of technical 4-nonylphenols and their biodegradation products by comprehensive two-dimensional gas chromatography coupled to time of flame mass spectrometry. J. Chromatograph. A, 1107, 1(2): 223-239.

Mohd. Tuah. 2006. The response of phenol biodegradation by Candida tropicalis RETL-Cr1 using Batch and Fed-batch fermentation techniques. Ph.D. thesis. Universiti Teknologi Malaysia. Pieper, D.H. and Reineke, W. 2000. Engineering bacteria for bioremediation. Curr. Opin. Biotechnol. 11 (3): 262-270.

Mokrini, A., Ousse, D., Esplugas, S., 1997. Oxidation of aromatic compounds with UV monitoring. Water SA 36(5).

Monteiro, Á.A.M.G., Boaventura, R.A.R., Rodrigues, A.E., 2000. Phenol biodegradation by Pseudomonas putida DSM 548 in a batch reactor. Biochemical Engineering Journal 6, 45–49.

Monterio, A.A.M., Boaventura, R.A.R. and Rodriguez, A.E. (2000). Phenol degradation by Pseudomonas putida DSM 548 in a batch reactor. Biochemical Engineering. 6: 45-49.

Mordocco A, Clern K, Roger J (1999). Continuous degradation of phenol at low concentration using immobilized Pseudomonas putida. Enzyme Microbial Technol. 25: 530-536.

Morsen, A., Rehm, H. J., 1990. Degradation of phenol by a defined mixed culture immobilized by adsorption on activated carbon and sintered glass. Applied Microbiology and Biotechnology, 33, 209-212.

Motzkus, C., Welge, G. and Lamprecht, I. 1993. Calorimetric investigations of phenol degradation by Pseudomonas putida. Thermochem. Acta. 229: 181-192.

Nair IC, Shashidhar S (2004). Microbial degradation of phenol by a species of Alcaligenes isolated from a tropical soil. Soil sci. T.5, 3-(4): 47- 51.

Nair, A. Rathinam, A. Giridhar and N. Nagiah, “Synergistic effect of pseudomonas aeruginosa and escherichia coli in the biodegradation of phenolic compounds,” Journal- American Leather Chemists Association, vol. 103 (7), pp. 222-226, July 2008.

Nair, C. I., Jayachandran, K., Shashidhar, S., 2008. Biodegradation of phenol. African Journal of Biotechnology. 7 (25), 4951-4958.

Nakamura, Y. and Sawada, T. 2000. Biodegradation of phenol in the presence of heavy metals. Chemical Technology Biotechnology. 75: 135-142.

Neujahr H.Y., Lindsjo, S., and Varga, J.M. 1974. Oxidation of phenol by cells and cell-free enzymes from Candida tropicalis. Antonie van Leeuwenhoek. 40: 209-216

Neujahr, H.Y. and varga, J.M. 1970. Degradation of phenols by intake cells and cell-free preparations of Trichosporoncutaneum. Eur. Biochem. 13: 37-44.

Nuhoglu A, Yakin B (2005). Modeling of phenol removal in a batch reactor. Proc. Biochem. 40: 233-239.

Nurk, A., Kasak, I., and Kivissar, M. 1991. The sequence of the gene (PhEA) encoding phenol monooxygenase from Pseudomonas sp. Est 1001-expression in Escherichia coli and Pseudomonas putida. Gene. 102: 13-18.

Okeke BC, Paterson A, Smith JE, Watson CIA (1997). Comparative biotransformation of pentachlorophenol in soils by solid substrate cultures of Lentinula edodes. Appl. Microbial. Biotechnol. 48: 563-569.

Okeke BC, Paterson A, Smith JE, Watson CIA (1997). Comparative biotransformation of pentachlorophenol in soils by solid substrate cultures of Lentinula edodes. Appl. Microbial. Biotechnol. 48: 563-569.

Okeke BC, Smith JE, Paterson, Watson, Cruicle IA (1993). Aerobic metabolism of pentachlorophenol by spent sawdust of shitake mushroom (Lentinus edodes) in Soil. Biotechnol. Lett. 15(10): 1077- 1080.

Oliver J Hao., Michael H Kim., Eric A Seagren. and Hyunook Kim. (2002). Kinetics of phenol and chlorophenol utilization by Acinetobacter species. Chemosphere. 46: 797-807.

Olujimi, O.O., Fatoki, O.S.., Odendaal, J.P., Okonkwo, J.O., 2010. Endocrine-disrupting radiation/ozone/hydrogen peroxide. Water Science Technology 35, 95–102.

Park, J.H., Cho, I. H., Chang, S.W., 2006. Comparison of Fenton and photo-Fenton processes for livestock wastewater treatment. Journal of Environmental Science and Health 41, 109- 120.

Patel, H., Vashi, R.T., 2010. Treatment of Textile Wastewater by Adsorption and Coagulation. E-Journal of Chemistry 7(4), 1468-1476.

Petruschka L, Burchardf G, Muller C, Weihe. C and Herrmann. H (2001). The CYO operon of Pseudomonas putida is involved in carbon catabolite repression of phenol degradation. Mole. Genet. Genom. 266: 199-206.

Prieto MB, Hidalgo A, Rodriguez FC, Serra JL, Llama MJ (2002). Biodegradation of phenol in synthetic and industrial wastewater by Rhodococcus erythropitics. UPV-1 immobilized in the air-stirred reactor with clarifier. Appl. Microbiol. Biotechnol. 58: 583-859.

Prieto, M.B., Hidalgo, A. Serra, J.L. and Llama, M.J. 2002. Degradation of phenol by Rodococcuserythropolis UPV-1 immobilized on bio light in a packed –bed reactor. Biotechnology. 97: 1-11.

Prpich GP, Daugulis AJ (2005). Enhanced biodegradation of phenol by a microbial consortium in a solid-liquid two-phase *partitioning bioreactor. Biodegradation. 16: 329-339.*

Puhakka, J.A., Herwig, R.P., Koro, P.M., Wolfe, G.V. and Ferguson, J.F. 1995. Biodegradation of chlorophenols Eco-1 Eco-1 26.

Reardon, K.F., Mosteller, D.C. and Rogers, J.D. 2000. Biodegradation kinetics of benzene, toluene, and phenol in a single and mixed substrate for Pseudomonas putida F1. Biotechnology Bioengineering. 69: 385-400.

Reardon, K.F., Mosteller, D.C., Rogers, J.D.B., 2000. Biodegradation Kinetics of Benzene, Toluene, and Phenol as Single and Mixed Substrates for Pseudomonas putida F1. Biotechnology and Bioengineering 69(4), 385-400..

Robles A, Lucas R, Cienfueges AD, Galvez A (2000). Phenol oxidase activity in strains of the hyphomycete Chalara paradoxa isolated from Olivemill wastewater disposal ponds. Enzyme Microbial Technol. 26: 484- 490.

Robles A, Lucas R, Cienfueges AD, Galvez A (2000). Phenol oxidase activity in strains of the hyphomycete Chalara paradoxa isolated from Olivemill wastewater disposal ponds. Enzyme Microbial Technol. 26: 484- 490.

Rodriguez, G.V., Youssef, C.B., Vilanova, J.W., 2006. Two-step modeling of the biodegradation of phenol by an acclimated activated sludge. Chemical Engineering Journal 117(3), 245-252.

Ruiz-Ordaz, N., Juarez Ramirez, J.C., Castonon-Gonzalez, H., Lara-Rodriguez, A.R., Christiani-Urbina, E. nadGalindez-Mayer, J. 2000. Aerobic bioprocesses and bioreactors used for phenol degradation by free and immobilized cells. In: Pandalai, S.G. (ed.) Recent Research Developments in Biotechnol. and Bioeng. Res. Signpost. Triv. India. 83-94.

S. Y. Li, Q. P. Wei, S. B. Xie, T. T. Zeng, and L. S. Rong, "Phenolic wastewater treatment via catalytic gasification," Polish Journal of Environmental Studies, vol. 24 (3), pp. 1147-1151, January 2015.

Sakurai, A. and Sakakibara, M. 2001. Effect of enzyme impurities on phenol removal by the method of polymerization and precipitation catalyzed by Coprinuscinereus peroxidase. Applied Microbiology Biotechnology. 57: 494-499.

Sakurai, A., Toyoda, S., and Sakakibar. (2001). Removal of bisphenol A by polymerization and precipitation method using Corpinus cinereus peroxidase. Biotechnol. Lett. 23: 995-978.

Salmeron – Alcocer, A., Ruiz-Ordaz, N., Juarez-Ramirez, C. and Galindez-Mayer, J. (2007). Continuous biodegradation of single and mixed chlorophenols by a mixed microbial culture constituted by Burkholderia sp., Microbacterium phyllosphaerae, and Candida tropicalis. Biochemical Engineering Journal.1-11.

Santiago Esplugas, Jaime Gimenez, Sandra Contreras, Esther Pascual, and Miguel Rodriguez. 2002. Comparison of different advanced oxidation processes for phenol degradation. Water Research. 36: 1034-1042.

Santos V.L., and Valter R. Linardi. 2004. Biodegradation of phenol by a filamentous fungus isolated from industrial effluents-identification and degradation potential. Process Biochemistry. 39 (8) : 1001-1006.

Saparia, N., Idrisb, A., Hamid, N.H.A., 1996. Total removal of heavy metal from mixed plating rinse wastewater. Desalination 106, 419-422.

Saravanan, P., Pakshirajan, K., Saha, P., 2008. Growth kinetics of indigenous mixed phenol removal using suspended growth and packed bed reactors. Biochemical Engineering Journal 26, 65–71.

Sax, N.I., 1984. Dangerous properties of industrial materials. New York, Van Nostrand Reinhold Company

Schneider P, Michael BC, Kristine M, Torben, Lars KS, Peter RO, Kiberly MB, Stephen HB, Feng X (1999). Characterization of a Coprinus cinereus laccase. Enzyme microbial Technol. 25: 502-508.

Schneider P, Michael BC, Kristine M, Torben, Lars KS, Peter RO, Kiberly MB, Stephen HB, Feng X (1999). Characterization of a Coprinus cinereus laccase. Enzyme microbial Technol. 25: 502-508.

Semple K.T. and Cain, R.B. (1995). Metabolism of phenols by Ochromonas danica. FEMS Microbiology Letters. 133(3): 253-257.

Setti L, Silvia g, Giovanni S, Pier GP (1999). Laccase catalyzed oxidative coupling of 3-methyl 2 benzothiazolenone hydrazones and methoxy phenol. Enzyme Microbial Technol. 25: 285-289.

Shashirekha S, Uma L, Subramanian G (1997). Phenol Degradation by the marine cyanobacterium Phormidium valderianum BDU 30501. J. Ind. Microbiol. Biotechnol. 19: 130-133.

Shawabkeh R, Khaled M, Khleifat (2007). Rate of biodegradation of phenol by Klebsiella oxytoca in minimal medium and nutrient broth conditions. Bioremediation J. 11: 13-19.

Shingler, V., Powlowski, J., Marklund, U., 1992. Nucleotide Sequence and Functional Analysis of the CompletePhenol/3,4-Dimethylphenol Catabolic Pathway of Pseudomonas sp. Strain CF600. Journal of Bacteriology 174(3), 711-724.

Steffens LJC (2002). Overexpression of polyphenol oxidase in transgenic tomato plants results in enhanced bacterial disease resistance. Planta, 215: 239-247.

Talley, J.W., Sleeper, P.M., 1997. Roadblock to the implementation of biotreatment strategies. Bajpai, R.K. and Zappi, M.E. (Eds.): Annuals *of New York Academic of Sciences 829, 17–29.*

Tibbles, B.J. and Baecker, A.A.W. 1989b. Effect of pH and inoculum size on phenol degradation by bacteria isolated from landfill waste. Environmental Pollution. 59 (3) : 227-239.

Torres LG, Alicia Sanchez de-la-vega Norma A, Beltran KB, Jimmenz (1998). Production and characterization of calcium alginate biocatalyst for removal of phenol and chlorophenols from wastewaters. Proc. Biochem. 33(6): 625-634.

Tziotzios, G., Teliou, M., Kaltsouni, V., Lyberatos, G., Vayenas, D.V., 2005. Biological technologies in the removal of heavy metals: A review. Pure and Applied Chemistry 764,

Vijaygopal, V. and Viruthagiri, T. 2005. Batch kinetic studies in phenol biodegradation and comparison. Indian Journal of Biotechnology. 4: 565-567.

Wang, S.J. and Loh, K.C. (1999). Modeling the role of metabolic intermediates in the kinetics of phenol biodegradation. Enzyme. Microbiology Technology. 25: 177-184

Wu, Y., Keith, F.Y., Nihar, B. and Jatinder, K.B. (1998). A model for the protective effect of additives on the activity of horseradish peroxides in the removal of phenol. Enzyme Microbial Technol. 22: 315-322.

Xiangchun Q, Zhang YM (2003). Biodegradation of 2, 4 dichlorophenol in an airlift honeycomb-like ceramic reactor. Proc. Biochem. 38: 1545-1551.

Xiangchun, Q. and Zhang, Y.M. (2003). Biodegradation of 2, 4 dichlorophenol in an airlift honeycomb-like ceramic reactor. Proc. Biochem. 38: 1545-1551.

Xiangchun, Q. and Zhang, Y.M. (2003). Biodegradation of 2, 4 dichlorophenol in an airlift honeycomb-like ceramic reactor. Proc. Biochem. 38: 1545-1551.

Y. Q. Huang, C. K. Wong, J. S. Zheng, et al, "Bisphenol a (BPA) in China: a review of sources, environment levels, and potential human health impacts," Environment International, vol. 42, pp. 91-99, July 2012.

Yang, R.D., Humphrey, A.E., 1975. Dynamic and steady-state studies of phenol biodegradation in pure and mixed cultures. Biotechnology and Bioengineering, 17(8), 1211-1235

Yap, L.F., Lee, Y.K. and Poh, C.L. 1999. The mechanism for phenol tolerance in phenol degrading Comamonastestosteroni strain. Applied Microbiology Biotechnology. 5 (6): 833-840.

Zahida Deva W, Gulam M, Peerzuda MD, Diagambar VB (1998). Oxidation of phenols by horseradish peroxidase and lactoperoxidase compound II. Kinetic consideration, 35: 353-357.

Zhan, Y., Yu, H., Yan, Y., Ping, S., Lu, W., Zhang, W., Chen, M., Lin, M., 2009. Benzoate Catabolite Repression of the Phenol Degradation in Acinetobacter calcoaceticus PHEA-2. Current Microbiology 59, 368–373.

Zorpas Antonis, A., Inglezakis, V. J., Stylianou, M., Irene, V., 2010. Sustainable Treatment Method of a High Concentrated NH3 Wastewater by Using Natural Zeolite in Closed-Loop Fixed Bed Systems. Open Environmental Sciences 4, 1-7.

Zumriye A, Gultac B (1999). Determination of the effective diffusion coefficient of phenol in calcium alginate immobilized Pseudomonas putida. Enzyme Microbial Technol. 25: 344-348.