Review on Removal Techniques for Phenolic Compounds

Kritika Mathur

Abstract

Realising the growing demand of energy and resources conservation, it has become indispensable to devise a treatment technology which is both economical and environment friendly. The United States Environmental Protection Agency recommends level of Phenol in surface water limited to 0.5 mg/L. The permissible limit for discharge of Phenol in drinking water defined by US-EPA (Ohio EPA 2002), European Union (Busca et al., 2008) and MINAS of CPCB, India is 0.5 mg/L.

Conventionally, phenols are treated using chemical oxidation (C.O), bio-oxidation (B.O) or adsorption (Siemens Water Technologies Corp., 2009) where all the methods have their own advantages and disadvantages.

Introduction

The exposure to Phenol causes skin irritation and necrosis. It damages kidney, liver, muscles and eyes. The main reason behind the skin damage is the coagulation due to reaction of Phenol with amino acids present in the keratin of the epidermis and collagen in inner skin. Its harmful effects are characterised by dryness in throat and mouth, dark coloured urine and strong irritation in mucous membranes (Michalowicz and Duda, 2007). Their presence even in low concentration can cause hindrance in use and/or reuse of water. This results in unpleasant taste and odour of water and imparts negative effects on different biological processes (Dąbrowski et al., 2005).

1. Phenol removal

2.1 Techniques for phenol removal

The removal techniques can be broadly classified into *Batch* and *Continuous* processes. The technologies used for its removal are adsorption on activated carbon (Ahmaruzzaman & Sharma., 2005), using a disinfectant like Chlorine Dioxide (ClO2) (Siemens Water Technologies Corp, 2009). Phenols may be treated by chemical oxidation or bio-oxidation.

Wastewater with Phenol concentration 500-2000 mg/l or higher is considered good for Phenol recovery in solvent extraction and adsorption on granular activated carbon (National Recommended Water Quality Criteria., 1999). Table 1 provides criteria for selecting removal technique based on phenol concentration in wastewater (National Recommended Water Quality Criteria., 1999).

Table 1 Criteria for selecting removal technique for phenol from wastewater

Criteria	Remarks
Intermediate or low Phenol concentration	Solvent extraction not good option
Economics not major issue	Adsorption on activated carbon or biological removal better choice
Phenol < 5 mg/L or less	Biological treatment and adsorption not fruitful
Toxin free water	Biological treatment reduces 200-300 mg/L phenol to 0.5-1.0 mg/L

A. **Batch Processes**: The list of batch processes for their treatment is described as under.

1. *<u>Separation by Steam Distillation</u>*: The streams containing organics are generally treated for Phenol removal by steam distillation based on steam volatility of Phenol. In Phenol rich phenol-water mixture, drying of Phenol takes place in distillation process. This is applicable for dewatering columns in Phenol synthesis plants. Azeotropic distillation followed by steam stripping is a good process for purification of water from Phenol impurities. The azeotrope is split into Phenol rich phase which is recovered and water rich phase is refluxed into the system. The stripping/distillation column which works on this principle is shown in Figure 1. However, this process has huge energy requirement and high process cost.

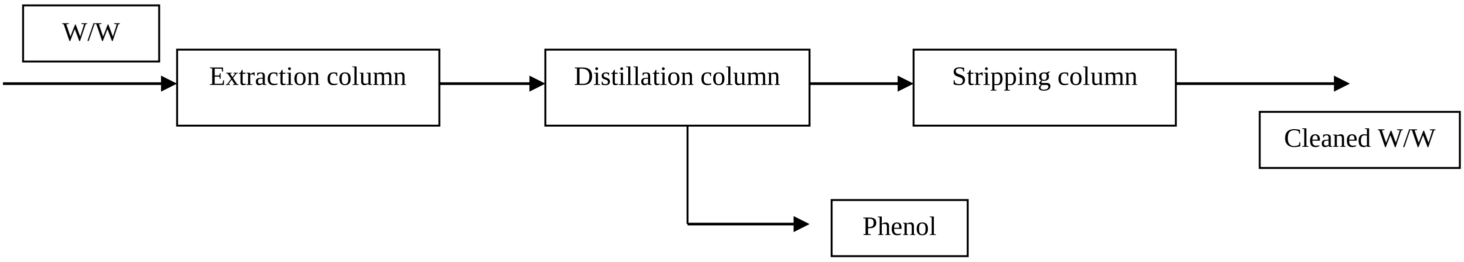

Figure 1 Schematic diagram of Phenol removal from wastewater using MIBK (Busca et al., 2008)

2. *Separation by Extraction*: Hydrocarbon and oxygenated organic solvents have the potential to extract Phenol from wastewater. Solvents used include benzene, toluene, n-hexane, acetate esters, di-isopropyl ethers, methyl iso-butyl ketone etc (Pinto et al., 2005). Wastewater from distillation unit of Acetone crude in production of Phenol using cumene process containing Phenol in the range 1-3% are treated by extraction method. Cumene solvent is scrubbed of Phenol in a counter current caustic scrubber unit and the resulting sodium phenate solution is passed into a settling tank where cumene is recovered and recycled. The bottom of this tank is net result of all Phenol and its residual concentration goes up to 20-500 mg/L. The remaining Phenol is cleaned using biological processing. This process is combined with distillation for its efficient use. Phenol removal process was developed for coal gasification wastewater (Yang et al., 2005). For this extraction process, an appropriate solvent was prepared considering Phenol removal, solvent recovery and COD removal. It is one of the most important techniques when Phenol concentration in wastewater is high. Micro-organisms cannot survive when Phenol concentration is high hence biological treatment becomes difficult. Moreover, the presence of non-volatile dihydric and trihydric phenols is resistant to biological treatment. Therefore, a pre-treatment of coal gasification wastewater is particularly crucial. Extraction using four alternative solvents namely diisoprpyl ether (DIPE), butyl acetate, methyl isobutene ketone (MIBK), and 30% tributyl phosphate was investigated.
3. *Separation by adsorption*: Adsorption is a widely used technique for removal of Phenol from water. Various adsorbents used for adsorption are activated carbon, activated alumina, bentonite clays etc. Advantages of adsorption are simple column design and low installation which are cost effective. . In recent years, low cost adsorbents (locally available) having high binding towards the pollutant has been developed. Activated carbon is easily available and is commonly used as an adsorbent. Other conventional adsorbents used are bentonites (Banat et al., 2000), synthetic resins (Lin and Juang, 2011), polymer and polymeric based hybrid adsorbents (Pan et al., 2009) and alumina pillared clays (for removal of chlorinated phenols) etc. (Petrakis et al., 1998).

a. *Adsorption on activated carbon using agricultural waste*: Activated carbon prepared from rubber seed coat (RSCC) which is an agricultural by product used as an adsorbent for Phenol removal from wastewater (Rengaraj et al., 2001). RSCC is used as a fuel and manure in Southern India. The studies show that it is a potential source for preparation of activated carbon since its Phenol removing capacity from aqueous solutions is 96% at prevailing conditions (Rengaraj et al., 2001). It can be used commercially for tertiary treatment of potable water and industrial effluents. Since commercial activated carbon is expensive, adsorbents are prepared from disposed wastes that are cheap and easily available. This serves two purposes; it is economical for the treatment plants to use recycled products and secondly it helps to dispose of the solid waste, which otherwise is a major cause of increased landfills. Substitute materials include straw, automobile tyres, fly ash, coal reject, sewage sludge, bagasse, fertilizer waste and saw dust. Due to high cost and variable performance of carbon regeneration, single use materials are desirable. Pine bark and apricot are used for making activated carbon and have also been used for Phenol removal from aqueous solutions.

b. *Adsorption using algae*: Sargassum Muticum is commonly known as Japanese Wireweed. It is large brown seaweed of the genus called Sargassum (Rubín et al., 2006). Phenol, 2-chlorophenol and 4-chlorophenol bio-sorption on Sargassum Muticum has been investigated.

c. *Pervaporation and Adsorption*: Pervaporation, is a membrane process that separates a pure liquid or a liquid mixture when in contact with membrane on the feed or upstream side at atmospheric pressure and permeate is removed as vapour because of a low pressure existing on downstream side (Kujawski et al., 2004). This is an energy saving method in comparison to conventional methods. This enables to remove large quantity of Phenol from wastewater thereby purifying it to a greater extent. Using suitable organophilic membranes, pervaporation process can remove phenol effectively.

d. *Cross linked Cyclodextrin particles*: Cyclodextrin particles are used as sorbents when wastewater contains 8.9% phenol, m- and p- cresols 0.33% and xylenes 0.44% (by weight). A series of sorbents are prepared by varying the composition of cyclodextrin, the cross-linker hexamethyl diisocyanate (HDI) or toluene 2, 6- diisocyanate and changing their molar ratio in the reaction batch. This process is instantaneous and is completed within 5 minutes. The best removal efficiency was obtained by the crosslinked -CyD with HDI in a 1:8 molar ratio or the crosslinked Mix-CyD with HDI in a 1:8 molar ratio. The prepared sorbents were efficiently regenerated by elution of the adsorbed phenols from the crosslinked polymers with methanol (Yamasaki et al., 2006).

4. *Electrochemical Treatment*: Electrochemical method for water treatment is a versatile technique making purification of gases, liquids and solids possible and environmentally compatible. These are employed in removing naphthalene and anthraquinone sulphonic acids present in wastewater. However, use of suitable electrode is a matter of concern. The removal of these compounds has been done using Ti/Pt, Ti-Ru-Sn-SbO_2 and carbon felt (Panizza et al., 2000).

a. *Electro-coagulation by iron electrodes*: It serves as an alternate technology for water treatment. The advantages are its in-situ delivery of reactive agents, secondary pollutants are not generated and compact equipment is used (Kobya et al., 2003).

B. Continuous process

1. *Adsorptive Parameter pumping*: A cyclic process based on the fact that adsorption equilibrium isotherms of solutes onto adsorbents are dependent on thermodynamic variables like temperature, pressure and pH etc. The two approaches for this process are: direct method, where in temperature change is imposed through the wall of the column and secondly when the temperature change is carried by the liquid stream. The advantage of this technique is its continuous mode of operation at low potential thermal energy as a regenerant thereby achieving a zero-pollutant plant (Ramalho et al, 1991).

3. Reactive Adsorption: Brief introduction

The coupling of a chemical reaction along with physical means of separation in a single unit operation is called Reactive Adsorption. Reactive adsorption can be carried out in two kinds of reactors namely: adsorptive reactors (AR) and chromatographic reactors (CR).

Realising the growing demand of energy and resource conservation, it is necessary to devise a treatment technology that is both economical and environment friendly. In the era of “more production with less energy” conventional unit operations have some disadvantages. Simple adsorption can be enhanced by coupling chemical reaction along with it and referred to as reactive adsorption. A reaction can be introduced into physical adsorption by two ways:

1. Crossing energy barrier of species to make them reactive by increasing either temperature or pressure.
2. Modifying adsorbent surface to provide a platform for reaction to occur.

Reactive adsorption (and its reverse, reactive desorption) resembles dissociative adsorption (and its reverse, associative desorption) but one fragment adds to an adsorbate rather than to a surface site (Compendium of Chemical Technology., 1997). Reactive adsorption is a process when adsorbate reacts with chemical specie (reactant) coated on the surface of an adsorbent and forms a product. Thus, in this case the product of adsorption interaction process is separated from the adsorbent. Reactive adsorption technique compared to simple physical adsorption has more potential to serve our purpose. The single unit of reactor-adsorber might reduce the design complexity and investment cost. It may also yield high purity products with reduced or eliminated downstream processing (Sharma et al., 2013). Although this technique is not new but a great deal of research has not been conducted till date.

4. Advanced Oxidation Processes (AOPs)

AOPs have become popular in recent years as an alternative for wastewater treatment. The basic principle of AOP's is degradation of pollutants by oxidation. These processes are defined broadly as aqueous phase oxidation processes based primarily on the formation of hydroxyl radical in the mechanism(s) which results in the destruction of the target pollutant or contaminant compound (Esplugas et al., 2002). The limitations associated include high cost of reagents such as ozone, hydrogen peroxide and source of light, ultraviolet radiation. However, costs can be reduced by using solar radiation as a source of energy. AOPs are best suited for pollutant degradation when biological treatments are not feasible (Esplugas et al., 2002).

4.1 Chemistry of AOPs

These processes have considerable similarities due to the presence of hydroxyl radicals participating in most mechanisms. The hydroxyl ions are extremely unstable and highly reactive. Therefore, kinetics seems to be first order with respect to OH^- ions and pollutant concentration. The reaction constant k value ranges from 10^8 to 10^{10} $M^{-1}s^{-1}$. The concentration of radicals (at steady state) varies from 10^{-10} to 10^{-12} M. Hence, the pseudo first order k is in the range of 1-10^{-4} s^{-1} (Esplugas et al., 2002). These reactions are characterized by little selectivity of attack of the substrate and reaction conditions. AOPs offer different possible ways for production of hydroxyl ions thereby allowing a better compliance with the specific treatment requirements (Andreozzi et al., 1999).

AOP systems are classified as photochemical and non-photochemical depending upon the requirement of light for the reaction. In recent years, AOPs such as photo-catalyst, ozonation, photo-fenton, oxidation, ultrasound etc have been proposed for treating wastewater containing non-biodegradable or toxic substances in high concentration.

1. *Fenton Oxidation*: (Golbaz, 2013): Fenton agent used comprises of Fe^{2+} and H_2O_2 in acidic medium. Hydroxyl and ferrous ions both play an important role in enhancing the progress of the reaction according to the conditions like type of wastewater, ratio of Fe^{2+}/H_2O_2 and presence of foreign substance.
2. *Ozonation* (Yang, 2012): The combined process of sonolysis and ozonation is one of the most effective methods in producing free radical ions. Since these processes are mass transfer limited in nature, this problem is overcome by the application of induced turbulence generated by ultrasound. In ozonation, various compounds can react with ozone via different ways. Firstly, they can react directly via molecular ozone and secondly indirectly via reactions with radical species (OH^*, HO_2^*), that are formed when ozone decomposes in water (Hoigné and Bader, 1975, 1976). On comparing it with reactive adsorption, ozonation is unselective and instant while the former is selective and may or may not be instantaneous. A transition state is achieved in RA where the product formed is detached from the surface of the adsorbent and no radical formation occurs. However, for molecular ozone reactions, selectivity and limitation towards degree of unsaturation, aromaticity, type of functional group, presence of double bonds etc are the factors affecting this process (Hoigné and Bader, 1975, 1976).

3. *Electro-catalytic Degradation* (Zhou, 2002): These processes are used because of their amenability to automation, environmental compatibility and high efficiency. The degradation of phenol on various electrodes such as on PbO_2 and glassy carbon electrodes has been studied earlier.
4. *Catalytic wet oxidation processes* (Hussain, 2009): It is one of the most economically and technologically viable solution for treatment of wastewater when phenol concentration is increased to 20 mg/L. In this process, organic pollutants dissolved in water are partially degraded by means of oxidising agent into biodegradable intermediates or mineralised inorganic compounds such as CO_2, H_2O and inorganic salts. This process is carried out under high temperature and high pressure conditions. Metal oxides mixtures of Cu, Co. Mn, Zn, and Bi are used as catalysts in CWO. Both noble and metal oxides catalysts exhibit good properties in CWO.
5. *Electro coagulation process* (Abdelwahab, 2009): Electro-coagulation is a process of utilising sacrificed anodes forming active coagulants which removes pollutants using precipitation and floatation in situ. It can remove smallest colloidal particles.

This process occurs in a series of steps sequentially in the following order:

i. Electrolytic reactions at electrode surface such as on Al surface, where Al ions are formed at anode and hydroxyl ions at cathode
ii. In situ oxidation of Al ions and subsequent precipitation of aluminium hydroxide in aqueous phase
iii. Adsorption of colloidal or soluble pollutants on coagulants that are removed by sedimentation and floatation

Table 2 Types of AOPs

Name of AOP Process	Nature of Process	Remarks	Reference
O_3	Direct and radical path	*Direct*: reaction between ozone & dissolved compounds *Radical path*: reaction between radicals (produced due to ozone decomposition) & dissolved compounds	Esplugas et al., 2002
O_3/H_2O_2	OH^- generated by radical chain mechanism; interaction between O_3 and H_2O_2 $H_2O_2 + 2O_3 \longrightarrow 2OH^* + 3O_2$	Efficiency increases by adding UV radiation	Esplugas et al., 2002
UV radiation	Supplies radiation to chemical compounds	Excited state, sufficient time to promote reactions	Esplugas et al., 2002
UV/O_3	Energy supplied by UV interacts with ozone $H_2O + 2O_3 \xrightarrow{hv} 2OH^* + 3O_2$	High synergic effect between ozone & UV radiation separately	Esplugas et al., 2002
UV/H_2O_2	Cleavage of molecule into two hydroxyl radicals formed per quantum of radiation absorbed $H_2O_2 \xrightarrow{hv} 2OH^*$	Radiation with wavelength lower than 400 nm able to photolize H_2O_2 molecule	Legrini et al., 1993

$O_3/UV/H_2O_2$	Increased fraction of ozone, enhanced rate of ozone mass transfer in bulk liquid	Fast and complete pollutant mineralisation, most effective treatment for high polluted effluents	Legrini et al., 1993; Esplagus et al., 2002
Fenton reagent	Reaction between hydrogen peroxide and iron (II) salts; iron considered a real catalyst $H_2O_2 + Fe^{2+} \longrightarrow Fe^{3+} + OH^{*} + OH^{-}$ (Acidic medium)	Incomplete mineralisation of organic compounds	Saritha et al., 2007; Esplugas et al., 2002
Photo-catalysis	In presence of artificial UV light and semi-conductor like TiO_2 or ZnO	Slow process, incomplete mineralisation of organic compounds	Saritha et al., 2007

The combination of degradation and adsorption for phenols has been studied. Co/SBA-15 catalyst has been used for simultaneous adsorption and degradation of phenols (Sharma et al., 2013). Howsoever, technology feasibility and development of reactive adsorbents surfaces needs investigation for large scale industrial applications.

Table 3 gives a comparative study of the processes used for removal of phenol and its derivatives.

Table 3 Comparative studies on the techniques for phenol removal

Treatment Technology	Principle/Reagent used	Advantages	Disadvantages	Reference
Distillation	Difference in steam volatility	High process efficiency	High energy demands, expensive technology	Franck and Stadelhofer, 1989 Busca et al., 2008
Extraction	Difference in affinities of third solvent with solution to be separated, C_6H_6, Toluene, n-Hexane	Gives good results when practised with distillation	Requires costly reagents as solvents	Pinto et al., 2005; Busca et al., 2008
Activated Carbon Adsorption	Physical adsorption, Activated carbon	Economic easy to install , easy regeneration	Expensive, pure carbon incomplete utilisation	Busca et al., 2008, Freeman, 1995
Adsorption Resin	Physical Adsorption	Simple installation, operation	Costly resin production, produces secondary pollutants during reactivation	Busca et al., 2008
Oxidation with ozone	O_3: Ozone	Effective phenol removal	TOC & COD not efficiently reduced as	Busca et al., 2008

			intermediates are formed	Gimeno et al., 2005
Oxidation with other Chemical Oxidants	TiO_2, H_2O_2, Fe^{2+}	Use of ferrate (VI) dissociates phenol in environmentally sound way	Ferrate (VI) process is slow, other oxidants not applicable as they form toxic end products	Throop, 1975 & 1977, Graham et al., 2004
Photo Catalytic Oxidation	-	Significant destruction of phenol	High band width only part of the radiation is utilized	Gimeno et al., 2005
Bio Chemical Abatement	Sargassum Muticum: Japanese wireweed, brown algae	Inexpensive, environment friendly	Requires more research, more dilution is needed since phenol is toxic to microbes	Busca et al., 2008 Lond Jang et al., 2006 Shetty et al., 2007
Electro-chemical Process	Al or Fe electrodes	In-situ delivery of reactive agents, no generation of secondary pollutant and compact equipment	Sludge formation	Kobya et al., 2003

Pervaporation and adsorption	Membrane separation	Greater extent of purification obtained, energy saving method	Membrane fouling	Kujawski et al., 2004
Parameter Pumping	Continuous process, change brought about by changing temperature, pressure, pH	-	Parameter optimisation is a problem	Mishra et al., 2007
Reactive Adsorption	Reactive surface of adsorbent	No separate step for regeneration	Selective in nature, not instantaneous	Sharma et al., 2013

For effective adsorption process, adsorbent must be regenerated without losing its adsorption capacity. Desorption is achieved either by causing variation in temperature or pressure or through displacement with another compound with higher affinity. Among different available regeneration techniques, the selection depends on economics and technical considerations of the reaction systems (Sharma et al., 2013).

5. Regeneration of spent adsorbent

Adsorbents that are widely used for adsorption of Phenol from wastewater become saturated after prolonged usage. Hence, these must be regenerated after fixed or non-fixed duration of time since it is the only solution which is economical and feasible (Castilla et al., 1995).

The most commercially used adsorbent worldwide is activated carbon. A typical diagrammatic flowchart below represents the techniques used to regenerate a spent adsorbent.

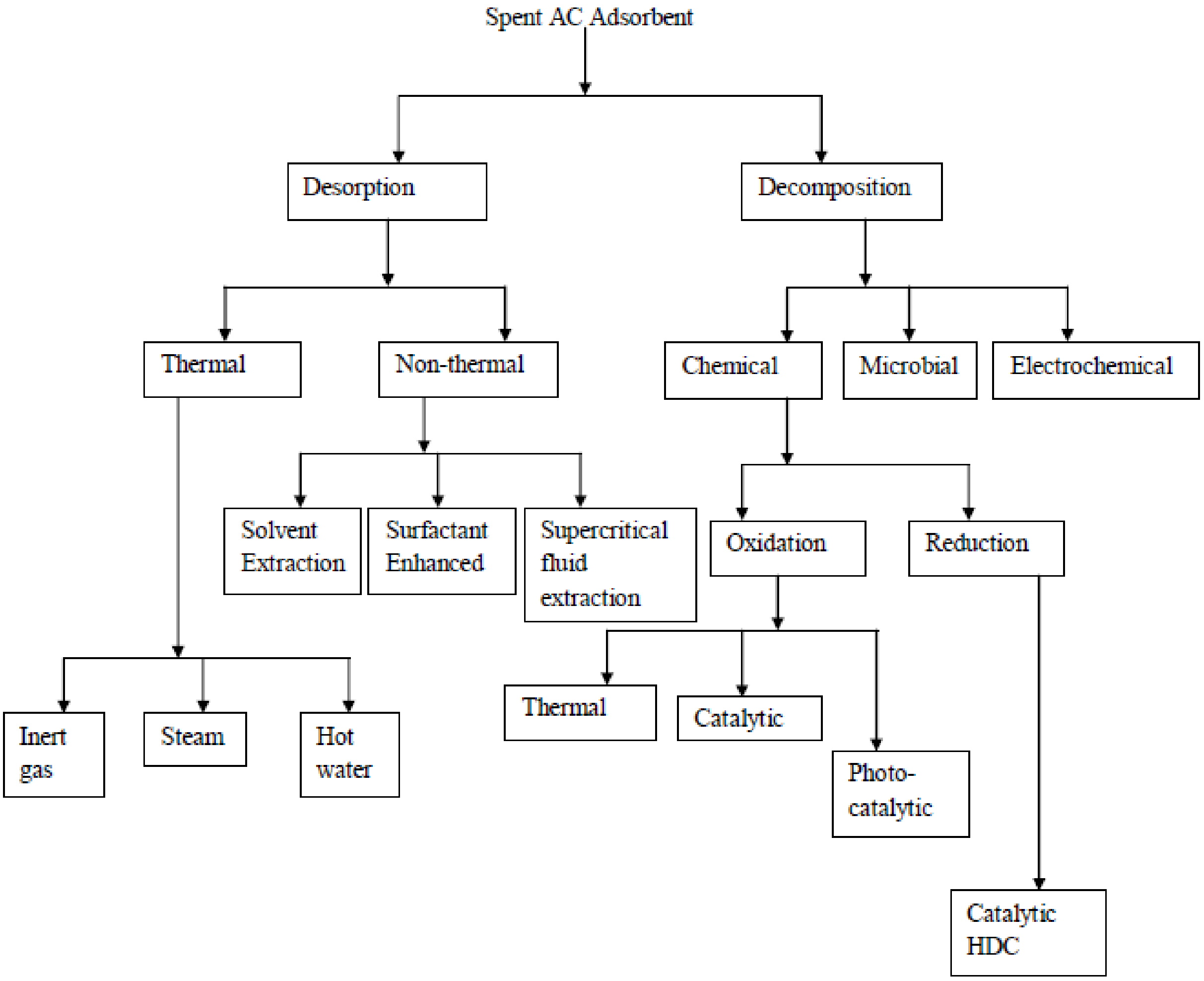

Figure 2 Overview of techniques for regeneration of Activated Carbon (Meytal and Shientuch., 1999)

There are several methods of regenerating a spent adsorbent. Some of them are discussed below”

1. *Electrochemical Regeneration*: This process is used for regeneration of activated carbon saturated with p-nitrophenol (PNP) (Zhou and Lei, 2006). A non-active electrode modified PbO_2 electrode was used which generated hydroxyl radical ion effectively and was able to maintain stable performance for organic wastewater treatment. Its service life is expected to be 10.4 years under the application of current density of magnitude 0.1 A/cm^2 and strong acidic solutions (9 M H_2SO_4) (Zhou and Lei., 2006).

   This method has also been used for regenerating activated carbon made of coconut shell exhausted with phenol (Zhang, 2000).

2. *Thermal Regeneration*: This involves following procedure: (1) drying at 150°C, (2) pyrolysis under inert atmosphere and (3) gasification of residual organics, by oxidising gas, like steam or CO_2. In the recovery of activated carbon exhausted with p-nitrophenol, thermal regeneration is done through three methods: (1) Pyrolysis (2) Pyrolysis-Gasification and (3) Direct gasification. The gasifying agents are water and CO_2 (Sabio et al., 2004).

   a. *Thermal regeneration at high pressure*: A new procedure to recover activated carbon is a combination of thermal desorption with water at high temperature and pressure (150 atm and 623K) in complete absence of oxygen (Utrilla et al., 2002).

3. *Electrochemical Regeneration*: This technique has been used to recover spent granular activated carbon because of its certain unique features such as: low temperature operation, no chemical added and in-situ cracking of organics deposited on carbon surface without damaging the structural properties and characteristics of carbon (Wang and Balasubramanian, 2009).

Table 4 A comparative study of various regeneration processes of spent activated carbon are described below

Treatment Technology	Principle / Reagent used	Operating Conditions	Advantages	Disadvantages	Reference
Thermal Regeneration	Drying, thermal desorption and high temperature reactive treatment in inert gas	700-1000°C	Simple process applicable to all regeneration processes	Continuous loss of 5-15% per cycle in adsorption capacity carbon surface area	Meytal and Shientuch., 1999
Extractive Regeneration	Use volatile solvents	-	-	-	Meytal and Shientuch., 1999
Surfactant enhanced regeneration	Flushing concentrated surfactant solution through spent AC	Miscelles formed consisting 50-100 molecules	Adsorption capacity over 50% observed on virgin AC	Expensive, environmentally unacceptable	Meytal and Shientuch, 1999
Chemical regeneration	Complete conversion of adsorbed species to harmless products/ Oxidants used Chlorine, peroxide, chlorine dioxide, ozone	-	-	Not feasible for continuous processes, not economically viable	Meytal and Shientuch, 1999; Utrilla et al., 2002

Photo-Catalytic Regeneration	TiO_2, SnO_2, ZrO_2 used in presence of UV light	-	-	Long process hence not practically possible	Meytal and Shientuch, 1999
Reductive Treatment	Catalytic HDC using reductants like H_2 and $NaBH_4$ or H_2 and N_2H_4	-	Still under development stage	-	Meytal and Shientuch, 1999
Microscope induced regeneration	Microwave regeneration	Microwave output power is 2000 W at 2450 MHz, single mode cavity where sample is exposed to microwave heating	Requires short period of time, lower consumption of gas energy, preserves the porous structure, increased adsorption capacities, carbon can be recycled and reused a large number of times	Input power of microwaves need to be increased when samples are saturated	Ania et al., 2004
Ozone regeneration	Ozone as oxidizing gas	Room temperature	Removes both physically and chemically adsorbed phenol	Restoration of surface area depends on ozonation time	Álvarez et al., 2004

			from carbon surface, restores most of its surface area	GAC itself, ozonation beyond optimum time gives rise to a slightly decreased surface area	
High pressure and temperature	Liquid water at high pressure and temperature	623 K and 150 atm in absence of oxygen	No oxidation of Carbon; no losses of carbon during treatment, consumes less energy than thermal regeneration	Slight destruction of mesopores and opening of micropores and macropores, Regenerated sample has decreased surface area and pore volume	Utrilla et al., 2002
Electrochemical Regeneration	Uses SnO_2/Ti anodes and 5 % Na_2SO_4 solution as electrolyte	Semi batch electrochemical reactor operating under wide conditions	Environmental compatibility, versatility, energy and cost efficient, amenability to automation	-	Wang and Balasubramania n, 2009
	Uses two Platinum electrodes	NaCl, Na_2CO_3, $NaHCO_3$, Na_2SO_4		-	Zhang, 2002

	as electrolytes (1%), 50 mA current density,25°C for 5 h	NaCl has high regeneration efficiency		
Anode: β-PbO_2 modified with fluorine resins	NaCl as electrolyte, 25±0.5°C for 30-120 min, fluidised electrochemical reactor	AC effectively regenerated within 1.5 h without much change in pore structure, cost effective	Slight decrease in micropore volume	Zhou and Lei, 2006

The present review covers description of removal techniques of phenols from wastewater. There has been a growing demand to devise an eco-friendly and economically feasible method for wastewater treatment owing to the hazardous and toxic nature of the phenolic compounds and their derivatives. The study compares various conventional and latest methodologies for the same.

References:

1. Álvarez, P. M., Beltran, F. J., Gomez-Serrano, V., Jaramillo, J., & Rodrıguez, E. M. (2004). Comparison between thermal and ozone regenerations of spent activated carbon exhausted with Phenol. Water research, 38(8), 2155-2165.
2. Andreozzi, R., Caprio, V., Insola, A., & Marotta, R. (1999). Advanced oxidation processes (AOP) for water purification and recovery. Catalysis today, 53(1), 51-59.
3. Ania, C. O., Menéndez, J. A., Parra, J. B., & Pis, J. J. (2004). Microwave-induced regeneration of activated carbons polluted with Phenol. A comparison with conventional thermal regeneration. Carbon, 42(7), 1383-1387.
4. Banat, F. A., Al-Bashir, B., Al-Asheh, S., & Hayajneh, O. (2000). Adsorption of Phenol by bentonite. Environmental pollution, 107(3), 391-398.
5. Bingjun Pan, Bincai Pan, Weiming Zhang, Lu Lv, Quanxing Zhang & Shourong Zheng, Development of polymeric and polymer based hybrid adsorbents for pollutants removal from water, Chemical Engineering Journal, 151 (2009), 19-29.
6. Chufen Yang, Yu Qian, Lijuan Zhang, Jianzhong Feng., Solvent extraction process development and on-site trial-plant for Phenol removal from industrial Coal-gasification wastewater, Chemical Engineering Journal, (2006), 179-185.
7. Dąbrowski, A., Podkościelny, P., Hubicki, Z., & Barczak, M. (2005). Adsorption of Phenolic compounds by activated carbon—a critical review. Chemosphere, 58(8), 1049-1070.
8. Danis, T. G., Albanis, T. A., Petrakis, D. E., & Pomonis, P. J. (1998). Removal of chlorinated Phenols from aqueous solutions by adsorption on alumina pillared clays and mesoporous alumina aluminum phosphates. Water Research, 32(2), 295-302.
9. Hoigne, J., & Bader, H. (1976). The role of hydroxyl radical reactions in ozonation processes in aqueous solutions. Water research, 10(5), 377-386.
10. Esplugas, S., Gimenez, J., Contreras, S., Pascual, E., & Rodríguez, M. (2002). Comparison of different advanced oxidation processes for phenol degradation. Water research, 36(4), 1034-1042.

11. Rubín, E., Rodríguez, P., Herrero, R., de Vicente, S., & Manuel, E. (2006). Biosorption of phenolic compounds by the brown alga Sargassum muticum. Journal of Chemical Technology and Biotechnology, 81(7), 1093-1099.
12. Freeman HM, Industrial Pollution Prevention Handbook, McGraw Hill, Inc., (1995).
13. Gimeno O., Carbajo M., Rivas F.J., Phenol and substituted Phenols AOPs remediation, J. Hazard. Mater. B 119 (2005), 99-108.
14. Graham N., Jiang C.C., Li X.Z., Jiang J.Q., Ma J., The influence of pH on the degradation of Phenol and chloroPhenol by potassium ferrate, Chemosphere 56 (2004) 949-956.
15. Guido Busca, Silvia Berardinelli, Carlo Resini, Laura Arrighi., Technologies for removal of Phenol from fluid streams: A short review on recent developments, Journal of Hazardous materials 160 (2008), 265-288.
16. H.G. Franck, J.W. Stadelhofer, Industrial Aromatic Chemistry, Springer Verlag Berlin (1989) 148-157.
17. Hirohito Yamasaki,1∗ Yousuke Makihata1 and Kimitoshi Fukunaga, Efficient Phenol removal of wastewater from Phenolic resin plants using crosslinked cyclodextrin particles, J Chem Technol Biotechnol 81:1271–1276 (2006).
18. Hoigne, J. (1985). Organic micropollutants and treatment processes: kinetics and final effects of ozone and chlorine dioxide. Science of the Total Environment, 47, 169-185.
19. IUPAC Compendium of Chemical Terminology, 2nd edition (2007).
20. Kujawski, W., Warszawski, A., Ratajczak, W., Porębski, T., Capała, W., & Ostrowska, I. (2004). Application of pervaporation and adsorption to the phenol removal from wastewater. Separation and Purification Technology, 40(2), 123-132.
21. Legrini, O., Oliveros, E., & Braun, A. M. (1993). Photochemical processes for water treatment. Chemical reviews, 93(2), 671-698.
22. L. P. Yang, W. Y. Hu, H. M. Huang & B. Yan, Degradation of high concentration Phenol by ozonation in combination with ultrasonic irradiation, Desalination and Water Treatment, (2012).
23. M.H Zhou and L.C Lei, Electrochemical regeneration of activated carbon loaded with p-nitroPhenol in a fluidized electrochemical reactor, Chemical Engineering Journal, 51, 4489-4496, (2006).

24. Marco Panizza, Cristina Bocca & Giacomo Cerisola, ELECTROCHEMICAL TREATMENT OF WASTEWATER CONTAINING POLYAROMATIC ORGANIC POLLUTANTS, Wat. Res. Vol. 34, No. 9, pp. 2601±2605, (2000).
25. Mehmet Kobya, Orhan Taner Can, Mahmut Bayramoglu, Treatment of textile wastewaters by electrocoagulation using iron and aluminum electrodes, Journal of Hazardous Materials B100 (2003) 163–178.
26. Minghua Zhou , Zucheng Wu & Dahui Wang, ELECTROCATALYTIC DEGRADATION OF PHENOL IN ACIDIC AND SALINE WASTEWATER, Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering, (2007).
27. Mishra, P. K., Nanagre, D. M., & Yadav, V. L. (2007). Treatment of chromium bearing wastewater using thermal parametric pumping. Journal of Scientific and Industrial Research, 66(1), 79.
28. Moreno-Castilla, C., Rivera-Utrilla, J., Joly, J. P., López-Ramón, M. V., Ferro-García, M. A., & Carrasco-Marín, F. (1995). Thermal regeneration of an activated carbon exhausted with different substituted phenols. Carbon, 33(10), 1417-1423.
29. National Recommended Water Quality Criteria, 1999
30. O. Abdelwahaba, N.K. Amin, E-S.Z. El-Ashtoukhy, Electrochemical removal of Phenol from oil refinery wastewater, Journal of Hazardous Materials, 163 (2009), 711-716.
31. Ohio, E. P. A. (2002). OhioEPA. Anderson Publishing Company.
32. Ramalho, E., Costa, C., Rodrigues, A., & Grevillot, G. (1991). Adsorptive parametric pumping for the purification of phenolic effluents. Separations Technology, 1(2), 99-107.
33. R.T.P Pinto, L.Lintomen, L.F.L. Luz Jr, M.R.Wolf-Maciel., Strategies for recovering Phenol from wastewater: thermodynamic evaluation and environmental concerns, Fluid Phase Equilibria 228-229 (2005), 447-457.
34. Rivera-Utrilla, J., Ferro-García, M. A., Bautista-Toledo, I., Sánchez-Jiménez, C., Salvador, F., & Merchán, M. D. (2003). Regeneration of ortho-chloroPhenol-exhausted activated carbons with liquid water at high pressure and temperature. Water research, 37(8), 1905-1911.
35. Saritha, P., Aparna, C., Himabindu, V., & Anjaneyulu, Y. (2007). Comparison of various advanced oxidation processes for the degradation of 4-chloro-2 nitrophenol. Journal of hazardous materials, 149(3), 609-614.

36. S. Rengaraj, Seung-Hyeon Moona, R. Sivabalan, Banumathi Arabindoo, V. Murugesan, Removal of Phenol from aqueous solution and resin manufacturing industry wastewater using an agricultural waste: rubber seed coat, Journal of Hazardous Materials B89 (2002) 185–196.
37. S. Tajammul Hussain, Sadaf Jamil & Muhammad Mazhar, Catalytic wet oxidation of Phenol: The role of promoter and ceramic support, Environmental Technoology, (2009).
38. Sabio, E., Gonzalez, E., Gonzalez, J. F., González-Garcıa, C. M., Ramiro, A., & Ganan, J. (2004). Thermal regeneration of activated carbon saturated with p-nitroPhenol. Carbon, 42(11), 2285-2293.
39. Sharma, M., Vyas, R. K., & Singh, K. (2013). A review on reactive adsorption for potential environmental applications. Adsorption, 19(1), 161-188.
40. analysis. Analytica chimica acta, 419(1), 9-16.
41. Shientuch, M. Meytal, Y.I. Matatov, Comparison of catalytic processes with other regeneration methods of activated carbon, Chemical Engineering Journal, 53, 73-80, (1999).
42. Siemens Water Technologies Corp, (2009).
43. Somayeh Golbaz a , Ahmad Jonidi Jafari b & Roshanak Rezaei Kalantari, The study of Fenton oxidation process efficiency in the simultaneous removal of Phenol, cyanide, and chromium (VI) from synthetic wastewater, Desalination and Water Treatment, (2013).
44. Su-Hsia Lin, Ruey-Shin Juang, Adsorption of Phenol and its derivatives from water using synthetic resins and low-cost natural adsorbents: A review, Journal of Environmental Management 90 (2009) 1336–1349.
45. Throop W.M., Alternative methods of Phenol wastewater control, J. Hazard. Mater. 1 (1975/1977) 319-329.
46. USEPA. Ambient water Quality criteria Doc: Phenol, us ePA-440/5-80-066 (Pb 81-117772), pp. 1100-1156, 1980.
47. Vidya Shetty K., Ramanjaneyulu R., Srinikethan G., Biological Phenol removal using immobilized cells in a pulsed plate bioreactor: Effect of dilution rate and influent Phenol concentration, J.Hazard. Matter. 149 (2007) 452-459.
48. Wang, L., & Balasubramanian, N. (2009). Electrochemical regeneration of granular activated carbon saturated with organic compounds. Chemical Engineering Journal, 155(3), 763-768

49. Zhang, H. Regeneration of exhausted activated carbon by electrochemical method, Chemical Engineering Journal, 85, 81-85, (2002).

50. Zhou, M., Wu, Z., & Wang, D. (2002). Electrocatalytic degradation of phenol in acidic and saline wastewater. Journal of Environmental Science and Health, Part A, 37(7), 1263-1275.