

OVERVIEW ON CHEMICAL OXIDATION TECHNOLOGY IN WASTEWATER TREATMENT

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ABSTRACT

Many industrial activities utilize organic compounds as a key chemical in organic synthesis of special chemicals such as, synthetic resins, paper products, medicinal products, drugs, dyeing and others.

Different chemical processes, most of them based in oxidation-reduction reactions, are being applied. Processes such as chlorination, ozonation, UV irradiation, electrochemical treatments and processes based in OH. radical attack have been investigated looking for the the best effectiveness to eliminate these toxic soluble substances. Most of these treatments have proved worthy in this field, achieving good results in the destruction pollutants. Also most of these researches in this field have been focused in the mineralization of pollutants.

Due to the increasing interest in developing alternative methods for improving the treatment of wastewater containing organic pollutants, advanced chemical oxidation technologies (AOTs), was applied for destruction of some organic compounds from their aqueous solutions and from industrial wastewater containing them.

This review focuses on different Oxidation technologies which can be used for destruction of organic pollutants. Advanced chemical oxidation technology applications help in the elimination of environmentally hazardous waste.

This article is concerned especially with advanced chemical oxidation technologies and the application of "Fenton oxidation" as a practical example for this technology (AOTs) for removal of organic pollutants from wastewater.

Key words: Advanced chemical oxidation technologies (AOTs), Fenton reaction, Destruction of organic compounds, Hydrogen peroxide and hydroxyl radical.

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INTRODUCTION

The appearance of compounds that are difficult to degrade by conventional chemical and/or biological methods (toxic, mutagenic, carcinogenic pollutants) in natural waters recently created a pressing need for the development of efficient water-treatment processes. The search for a solution to this problem has involved extensive examinations in the field of advanced oxidation processes (AOPs). In chemical oxidation processes, reaction mechanisms change structure, and chemical properties of the organic substances. Molecules break in smaller fragments; higher percent of oxygen appears in these molecules in form of alcohol's, carboxylic acids etc. oxidation of organic compounds with oxidation such as ozone or OH. radicals usually yields more oxidized ones which are in most cases more easily biodegradable than the former ones. This is the general idea that yields to the combination of a chemical oxidation processes. Oxidation with ozone or hydrogen peroxide has been found to be an important alternative to chlorination, because the oxidation does not result in toxic chlorinated organic compounds [1, 2]. Advanced Oxidation Technologies (AOTs), including Advanced Oxidation Process (AOPs) and other physicochemical conversion methods which are [1]:

- (1) Advanced Oxidation Process (AOPs),
- (2) Non-Thermal Plasmas (NTP) for air and wastewater treatment,
- (3) Electrohydraulic cavitation and sonolysis for wastewater treatment,
- (4) Electron beam and gamma-ray irradiation,
- (5) Catalytic oxidation for air treatment,
- (6) Wet air oxidation for wastewater treatment,
- (7) Supercritical water oxidation treatment,
- (8) Electrochemical redox reactions for wastewater treatment and
- (9) Photocatalysis for wastewater and air treatment.

(1) Advanced Oxidation Process (AOPs):

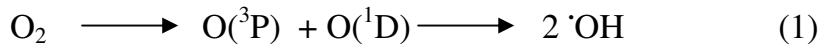
The concept of advanced oxidation process (AOPs), was defined by Glaze et al. [13] In 1987 as processes that “*involve the generation of hydroxyl radicals in sufficient quantity to affect water purification*”. In this context, advanced oxidation processes generally mean the application of either oxidation technologies using UV/O₃, O₃/H₂O₂, UV/ H₂O₂ or the photo Fenton reaction (UV/ H₂O₂/ Fe⁺⁺ or Fe⁺⁺⁺) [1]. Peyton [3] gave a detailed overview and description of AOPs in 1990. The advanced oxidation process (AOPs) will discussed in details after mention of the rest advanced oxidation technologies (AOTs).

(2) Non-Thermal Plasmas (NTP) for Air and Wastewater Treatment

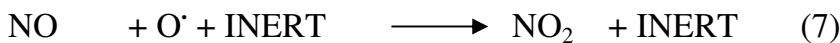
Non-thermal plasma technology (NPT) [4] is a new advanced oxidation technology, which is applied to treat air pollutant [5] and may also be applied to treat wastewater [6]. the plasma produced by an electron beam, a pulsed corona discharge or a dielectric-barrier discharge employed to create a large quantities of high reactive free radicals (mainly atomic oxygen in the ground energy state (O³P) and oxygen in the

first excited energy state (O^1D) [7], and hydroxyl radicals) in a gaseous medium at near ambient temperature. These radicals subsequently react with entrained hazardous organic chemicals, converting them to either nonhazardous substances (CO_2 , H_2O and acids, i.e., mineralized compounds) or other easily manageable compounds. Because NTP processes can simultaneously remove or convert different types of pollutant, e.g., volatile organic compounds and oxides of sulfur and nitrogen frequently found in flue gases, it is particularly attractive for many present and future environmental applications [8].

The mechanism of oxidation of SO_2 and NO by NTP [5, 9 and 10] in a gas phase also containing H_2O is given as an example. First we have:



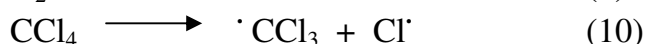
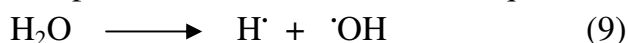
The oxygen atoms ($O\cdot$) produced in different energy states shown in Equation 1) and hydroxyl radicals can react with SO_2 to form H_2SO_4 , and can react with nitrogen oxides to form HNO_3 :



where INERT is any available third compound (usually N_2 or O_2), which is a chemically inert molecule in the reaction meant to stabilize the reaction product [11]. the final product H_2SO_4 (Equations 4 and 6) forms liquid droplets, while the gaseous reaction product HNO_3 (Eq. 8) can be removed by the injection of NH_3 or $Ca(OH)_2$ resulting in NH_4NO_3 and $Ca(NO_3)_2$, respectively. H_2SO_4 droplets and particles of NH_4NO_3 can be removed from the gas stream by using scrubber or an electrostatic precipitator.

(3) Electrohydraulic Cavitation and Sonolysis for Wastewater Treatment

Electrohydraulic cavitation involves the formation and behavior of bubbles in liquids [12, 13]. It is induced by applying electrical power is provided by a pulse-powered plasma discharge producing pulsed and/or continuous ultrasonic irradiation (i.e., sonolysis) in water. Kinetic and sonoluminescence measurements indicate that an extremely high temperature (>500 °K) and pressure (>100 atm) are generated during the adiabatic and short-time (<1 μs) implosions occurring at the cavitation sites. When a bubble fills with gas and vapor pulses and collapses, molecules inside the bubble or close to the bubble surface is fragmented, escape into the bulk of the solution and react in various ways outside (or inside) the bubble [14, 15]. In this situation, water or pollutants split into radicals as shown in Equations 9-11.





After the production of these radicals, pollutants such as tetrachloromethane and hydrogen sulphide in the water can be oxidized to final products such as CO_2 , Cl^- and SO_4^{2-} [16-18].

(4) Electron Beam and Gamma-Ray Irradiation

High-energy electron beams are gamma rays (i.e., ionizing radiation) are very effective tools for water pollutant degradation. The development of new powerful electron accelerators (e.g., an energy level of 1.0 MeV and a power level of 50 KW, or an energy level of 4.5 MeV and a power level of 400 KW) enables very effective radiation processing of wastewater streams [19]. When a high energy electron beam of gamma ray irradiates water, the water (as well as organic compounds contained in it) split into a number of primary species of e_{aq}^- (electrons in aqueous solutions), H^\cdot , $^\cdot\text{OH}$, H_2 , H_2O_2 , H^+ and OH^- . Some of these primary species then collide with other substrates in water to form more radical species that are oxidants and therefore able to oxidize organic pollutants [20, 21]. As has been observed when using this technology, many organic compounds can be promptly oxidized such as polychlorinated biphenyls (PCBs) [22-24], tetrachloromethane [25], trichloroethylene (TCE) [26], tetrachloroethylene (PCE) [27] and benzene [28].

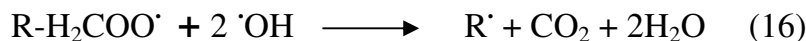
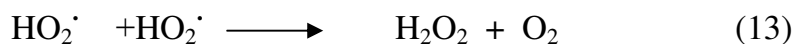
(5) Catalytic Oxidation for Air Treatment

Catalytic oxidation for the treatment of air pollution is an important environmental technology, which has been employed for environmental protection for twenty years. Catalytic oxidation, also known as catalytic incineration, is the complete chemical conversion of a gaseous organic compound with oxygen at a certain temperature (below or above 100 °C) and pressure (one or more than one atm) while both substances are in contact with a solid material (catalyst) that increases the rate of oxidation reaction. This technology is used for the treatment of organic pollutants in a gas phase, such as automotive emission control [29, 30] and control of industrial gas emissions [31, 32].

(6) Wet Air Oxidation for Wastewater Treatment

Wet air oxidation (WAO) is a well established technology for wastewater treatment, particularly for the treatment of toxic and highly concentrated wastewaters [33-34]. It is a chemical oxidation process involving organics or oxidizable inorganic components in an aqueous liquid phase at high temperatures (125-320°C) and pressures (0.5-20 Mpa), using a gaseous source of oxygen (normally air). WAO has been demonstrated to mineralize various organic compounds to carbon dioxide, water and other inorganic end products such as ammonia, nitrate, nitrogen, chloride, sulphate and phosphate. The oxidation capability of WAO is greatly enhanced if catalysts and oxidants such as ozone and hydrogen peroxide are present [34-36].

Normally, the mechanisms of WAO reactions are radical ones [37, 38]. When WAO is applied at elevated temperatures and pressures without a catalyst, the following reactions may occur in the presence of an organic pollutant R-CH₃:



Equation (16) shows that a long alkyl (R) carboxylic acid molecule will be degraded to a molecule with fewer carbon atoms. Except for carboxylic acids of low molecular weight (especially acetic and propionic acid) and polychlorinated biphenyls (PCBs), most compounds are easily degradable by WAO. At a feed COD higher than 20.000 mg/L, WAO becomes energetically self-sustaining (i.e., no additional fuel is required) and may in fact produce energy in the form of high-pressure steam. One of the most important applications of WAO is the treatment of sewage sludge from municipal wastewater treatment plants [39].

(7) Supercritical Water Oxidation Treatment

Supercritical water oxidation (SCWO) is an intensive version of the WAO process. In recent years, SCWO has become a rapidly developing innovative waste treatment technology for the oxidation of organic wastes and hazardous materials in water [40]. The SCWO process involving the mixing of wastes with an oxidant (oxygen, air, or hydrogen peroxide). The reaction with organic pollutants is carried out at a pressures and temperatures above the water critical point (374°C and 22.13 Mpa). The general SCWO reaction temperature range is between 400 and 650 °C [41]. Under these conditions, oxidation occurs rapidly (within a few seconds or minutes) and simple products (such as CO₂ and H₂O, and N₂ in the case of nitro-organics) are produced [42].

SCWO has great advantages as regards the treatment of some refractory organic compounds, including a rapid chemical reaction and no production of nitrogen oxides. The pressure and temperature required can be attained using readily available high pressure and high temperature equipment. SCWO has proven to be successful for the disposal of phenol [43], halogenated organics [44], biopharmaceutical wastes [45], chemical warfare agents, hydrolysed solid rocket propellant, and biological sledges [46].

(8) Electrochemical Redox Reactions for Wastewater Treatment

Electrochemical methods oxidize and reduce pollutants in wastewater by means of electrode reactions (electrolysis). The electrodes needed are available in various shapes (bar, plate, porous and fiber) and are made of various materials. In wastewater, such oxidizable pollutants as organic compounds are oxidized at the anode surface, and such reducible pollutants as most inorganic metal cations are reduced and

deposited (in most cases) at cathode surfaces. To bring about the required reaction, a certain electropotential is applied to the anode and cathode [1]. Electrochemical methods are employed mainly for metal ion elimination such as the recovery of copper and lead [47], mercury(II) and zinc(II) [48], cobalt(II) [49], and cadmium, etc. Another interesting application of electrochemical method is cyanide oxidation in wastewater. In most metal finishing and hydrometallurgical industrial wastewaters containing metal ions (such as gold, silver, chromium) and cyanides, the electrochemical method has an advantage in that simultaneously cyanide is decomposed (oxidized) at the anode and heavy metals are deposited (reduced) at the cathode without causing a sludge problem [50].

(9) Photocatalysis for Wastewater and Air Treatment

Photocatalysis is the combination of using a photocatalyst and UV or visible light for the treatment of wastewaters and gaseous pollutants. When illuminating a photocatalyst using UV or visible light, various organic compounds (e.g., aromatic, organochloride and organophosphorous compounds) can be oxidized and mineralized at the photocatalyst surface or oxidized in solution ambient and atmospheric conditions. This is because strong oxidation and reduction sites are produced at the photocatalyst surface when this surface is illuminated with light of the appropriate wavelength. Radicals formed at the surface dissolve in solution and then react with pollutants. It has often been demonstrated that various organic pollutants can be oxidized photochemically under the influence of large amounts of free solar energy [1].

Photocatalysis is one of the most important advanced oxidation technologies. It can be used not only for oxidative treatment of wastewater containing various organic and inorganic compounds, but also for reductive treatment such as reductive deposition of metals from wastewater.

Because the advanced oxidation process (AOPs) is the main subject of this dissertation, it is discussed in details in the paragraphs below.

Advanced Oxidation Processes (AOPs)

In this context, advanced oxidation processes generally mean the application of either advanced oxidation technologies which include the following three types:

(a) Ozonation for Organic Compound Oxidation

The most important contributions to understanding the chemistry of ozonation during water and wastewater treatment published by Hoigne and coworkers [51-53], Glaze et al. [54-56] and Peyton et al. [3, 57 and 58].

Mechanisms of the ozonation of organic soluble substrate (M) in aqueous solutions were diagrammed and clearly explained by Staehelin and Hoigne [53] (see Fig 1). The main processes of this diagram involving radical reactions are:

Initiation steps (steps 17, and 18), which generate radicals via reactions with OH⁻ and substrate (M) in an aqueous solutions:

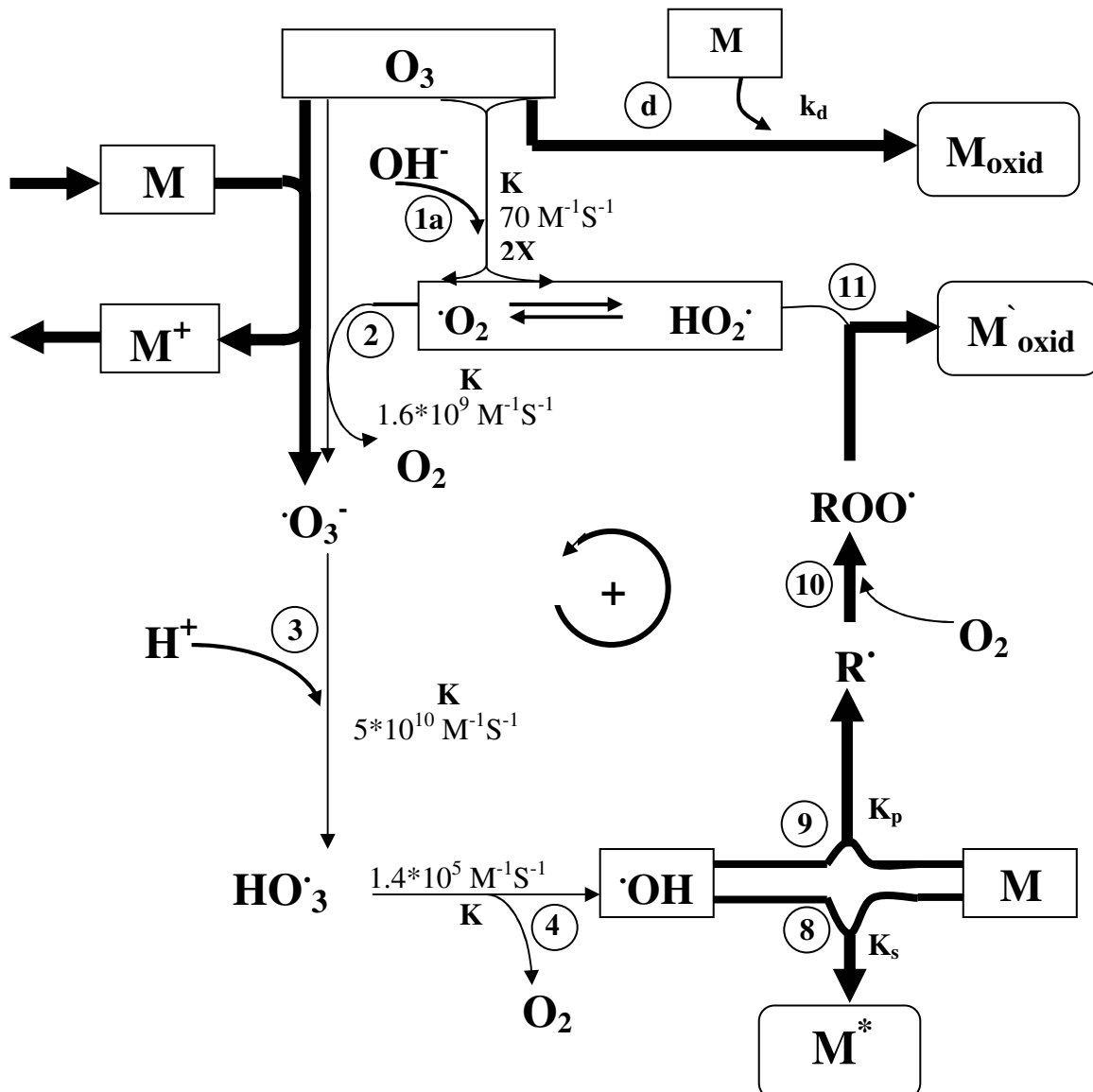
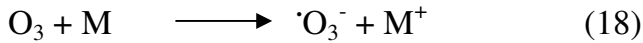
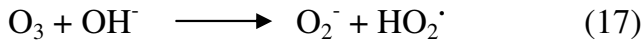
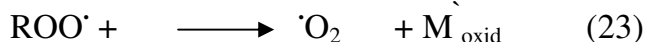
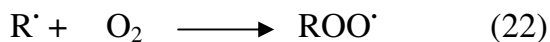
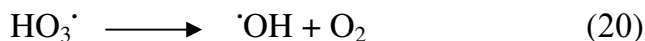


Fig. 1 Reactions of aqueous ozone in the presence of an organic compound M which react with O₃ or interacts with ·OH by scavenging it and/or converting it into HO₂· [53] is an oxidizable substrate in solution;
 k, k₁, k_d, k_p, k_s are reaction constants

Propagation steps (steps 19, 20, 21, 22, 23), which maintain the radical reaction chain:



In these steps, radical groups are propagated and maintained through reactions with H^+ and an organic substrate (M) that has alkyl groups (R). The radical propagation results in the oxidation of the alkyl groups of the substrate (step 23).

Termination step (step 24):



in step 24, M (e.g., organic substrate or bicarbonate) acts as a radical scavenger, and the radical chain reaction is ended by the formation of product $\text{M}\cdot$.

(b) Application of UV/ozone for Organic Compound Oxidation

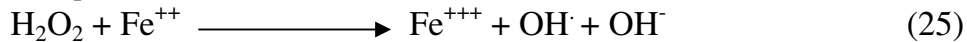
During UV/ozone processes, ozone adsorbs UV light (wavelength shorter than 310 nm) and photolyzes to produce hydrogen peroxide and hydroxyl radicals [54], which are able to oxidize organic compounds [57, 59]. For efficient ozone photolysis, UV light must have a wavelength at or shorter than 254 nm. Fronk [60] reported that a concentration of 50-384 $\mu\text{g/L}$ of halogenated alkenes and aromatic hydrocarbons could be reduced to 87% and 82%, respectively, by applying an ozone dose of 6 mg/L. Glaze [56] et al. and Peyton et al., [58] found that halogenated micropollutants such as chloroform, bromodichloromethane and tetrachloroethylene were destroyed four to fifty times faster by UV/ozone than by ozone alone. During these experiments, ozone dose rates of 0.1-1.3 mg/L min and UV intensities of 0.09-0.38 watt/L were used. Since the effect of UV on ozone in an aqueous solution is the production of hydrogen peroxide, an alternative method is to add hydrogen peroxide to the ozone solution (ozone/hydrogen peroxide system) instead of producing it in situ by ozone photolysis.

(c) Application of UV/hydrogen Peroxide and Fenton Reactions for Organic Compound Oxidation

The processes involved in the destruction of organic compounds with UV/hydrogen peroxide are shown in Fig.2. Hydrogen peroxide can be photolyzed to produce two hydroxyl radicals if the wavelength of the photon is shorter than 370 nm; these radicals can oxidize organic compounds containing an alkyl group R. Compared with the photolysis of ozone, the photodecomposition efficiency of ozone at 254 nm [61, 62]. In this respect, a very promising development of the UV/hydrogen peroxide process is the development of lamps that emit efficiently at shorter wavelength (185 nm), such as the antimony halide lamp [63].

Since the AOPs using hydrogen peroxide are based on hydroxyl radicals attacking organic compounds in wastewaters, the key to enhancing the oxidation efficiency of hydrogen peroxide is to accelerate its decomposition, producing as many hydroxyl radicals as possible. In addition to employing UV to decompose hydrogen, a catalyst can be used. An appropriate ferrous ion catalyst was discovered by Fenton in 1894 [64].

The Fenton's reagent was discovered by Fenton in 1894 [64]. Fenton's reagent is a mixture of H₂O₂ and ferrous iron, which generates hydroxyl radicals according to the reaction [65-67]:



The ferrous iron (Fe⁺⁺) initiates and catalyzes the decomposition of H₂O₂, resulting in the generation of hydroxyl radicals. The generation of these radicals involves a complex reaction sequence in an aqueous solution [68].

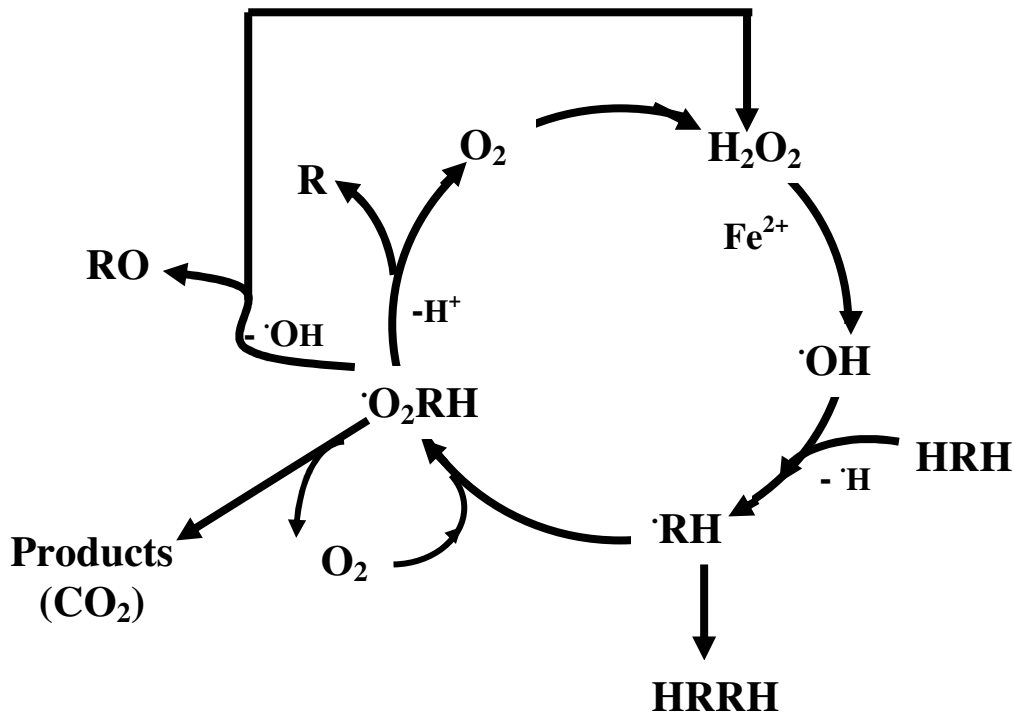


Fig. 2 Reactions processes in hydrogen peroxide/UV systems and photo Fenton/UV systems [54]

As seen in equation 32, H_2O_2 can act as an OH Scavenger as well as an initiator [67]. Due to the formation of Fe^{+++} during the reaction, the Fenton reaction is normally accompanied by the precipitation of $Fe(OH)_3$. The primary purpose of this research was to examine the feasibility and the efficiency of using Fenton's reagent for the removal of organic compounds, which found in the resultant wastewater of some industries [68].

Hydrogen peroxide and ferrous iron are used for the oxidation of organic substances. It acts as a reductant when reacting with a strong oxidizing agent such as potassium dichromate, and generates the free oxygen with decomposition by itself. Consequently, the mechanism of these reactions with respect to hydrogen peroxide is very complex and may change with conditions of the reaction and the type of catalyst [69]. Generally Fenton's oxidation process was composed of four stages, which are: pH adjustment, oxidation reaction, neutralization and coagulation, and precipitation. So, the organic substances are removed at two stages of the oxidation and the coagulation [70].

M. Kitis et al. [65] study the effectiveness of Fenton's reagent pretreatment on the biodegradability of selected nonylphenol ethoxylates (NPEs). The results showed that Fenton's reagent pretreatment was effective at enhancing the biodegradability of EO/PO block copolymers, nonylphenol, ethoxylates (NPEs) and polypropylene glycols (PPGs). Increasing oxidant dosages increased both the rate and extent of biodegradation for each compound, except for an initial decrease in biodegradability of (NPEs) at low oxidant dosages. Economic analysis indicated that chemical costs represented at least 90% of the total treatment costs in all cases.

Bum Gun Kwon [69] studied the characteristics of the Fenton oxidation of p-chlorophenol to develop a mechanistic model that appropriately represented the mechanism. Batch experiments were carried out to investigate the effects of pH, Fe^{++} and hydrogen peroxide levels, p-chlorophenol concentration and chloride level. The decomposition proceeded rapidly only within a limited pH range of 2-4. It was typical of the decomposition that an initially fast decomposition rate was significantly reduced within a few minutes, The fast initial rate was first order with p-chlorophenol and its rate constant was proportional to the initial level of Fe^{++} and hydrogen peroxide. The occurrence of the slow phase of the decomposition was primarily attributed to the Fe^{++} depletion caused by Fe-organic complex formation. The final extent of oxidation was limited by hydrogen peroxide.

Kang Y. W. [70] investigated the efficiently operate Fenton's oxidation process with quantitative analysis of the amount of the organic substances removed by oxidation and coagulation in treatment of the non-biodegradable landfill leachate by Fenton's reagents. They concluded that COD removal efficiency by oxidation was greatly affected by the pH reaction. The most effective reaction was observed below pH 4.0, but the optimal coagulation pH range to maximize the COD removal efficiency is between 3 and 6; the dosage of ferrous sulfate over 500 mg/l does not increase the overall COD removal efficiency.

Amy L. T. et. al., [71] contaminant degradation stoichiometry, and role of hydroxyl radicals (OH.) in four Fenton's systems were Investigated using trichloroethylene (TCE) as a model contaminant. A standard Fenton's system, a modified soluble iron system with a pulse input of hydrogen peroxide, and two modified mineral catalyzed systems (pH 3 and 7) were studied. In the standard fenton's system, which had the most efficient reaction stoichiometry 78% of the TCE was degraded,

Walter Z. T. et. al., [72] studied the oxidation kinetics and mechanism's of four trihalomethanes (THMs) commonly found in chlorinated drinking water by Fenton's reagent. They indicated that Fenton's reagent could oxidize the brominated THMs, e.g. bromodichloromethane, dibromochloromethane and bromoform. The oxidation kinetics increased with the increase of the number of bromine atoms present in a THM molecule and its concentration.

Sheng H. L. and Cho C. Lo [73] studied the treatment of simulated desizing wastewater by the Fenton process along with chemical coagulation. The simulated wastewater contained less than 0.2% polyvinyl alcohol (PVA) and Blue C (a direct dye) or Black B (a reactive dye). Chemical coagulation using polyaluminum chloride and polymer was found to complement the Fenton treatment process in reducing the flock settling time, enhancing color removal and reducing Fe ion concentration. The Experimental results show that there exists an optimal pH at 3 and an optimal temperature at 30°C for the Fenton treatment process.

Keiichi Tanaka et al. [74] studied Seven azo dyes were photocatalytically degraded in TiO₂ suspension. Their degradation rates were compared with disappearance and TOC elimination rates. It was demonstrated that diazo dye is less degradable than monoazo and the order of photocatalytic degradation rates was in approximate agreement with that of ozonation rates cited from literature, Major intermediates identified are aromatic amine, phenolic compounds and several organic acids. It was indicated from this study that in the photocatalytic degradation of azo dye the disappearance proceeds through both oxidation and reduction, whereas TOC is eliminated predominantly by oxidation. The following conclusions can be drawn: (1) In photocatalytic degradation of azo dye, monoazo is more degradable than diazo; (2) The order of photocatalytic degradation rates is in approximate agreement with tat of ozonation; (3) Adsorption of dye to TiO₂; is one of the important factors determining the degradation rate and (4) Photocatalytic degradation of azo dye proceeds predominantly through oxidation by positive hole (or ·OH) and reduction by conduction band electron and to some extent by electron injection from dye to conduction band.

Weshe K. D. et al, [75] studied the biokinetic parameters of phenol removal from wastewater via Biochemical Oxygen Demand (BOD) test, they concluded and proved the applicability of the plateau concept on phenol containing wastewater.

Many wastewater treatments are characterized by the presence of phenol and its derivatives. These substances are present in large quantities in wastewaters from phenolic resin, oil refining, pharmacy, electroplating, paper, cooking and iron smelting

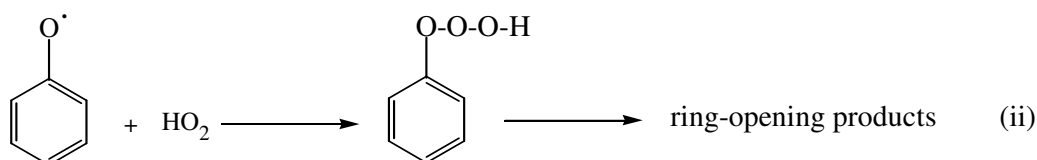
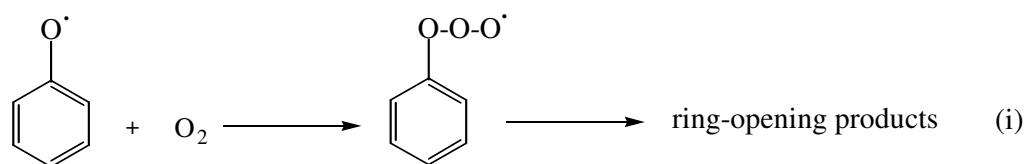
industry, etc. The treatment of phenol containing wastewaters to harmless level of 0.5 ppm phenol is a difficult process for many chemical and biological methods because of the high solubility and stability of phenols [1, 76].

Ilisz and Dombi [77] investigated the photo decomposition of phenol. They concluded that in the presence of H_2O_2 , the oxidation process leads to the degradation of phenol; besides the identified compounds, the formation of presumed ring opening products occurs simultaneously. In contrast with the general view, they pointed out that the appearance of aliphatic products takes place in the early stage of the oxidation.

There are many reports on photolysis [3, 4] and photocatalysis [5-7] for the treatment of phenol containing wastewaters. Most experiments of the photocatalysis treatment of phenol containing wastewaters use slurry TiO_2 as a photocatalyst, because until now it has proven to be the most efficient photocatalyst and it is also nontoxic. In practice, however, the problem of how to separate suspended particles from wastewater still has to be solved. There are some reports on investigations carried out into the photoactivity of other materials such as ZnO , WO_3 , CdS and Fe_2O_3 , which also proved to affect pollutants [8-10].

Rashed et. al., studied the using of Fenton reaction in the decomposition of phenol [78] and formaldehyde [79] from their aqueous solutions and from industrial wastewater containing them. They achieve a very good efficiency of removal over 90%.

The mechanism of photo Fenton oxidation of phenol the phenoxy radical can be formed from phenol via H-abstraction, or via direct electron transfer followed by deprotonation [77]. The phenoxy radical formed can react with either dissolved oxygen or HO_2^{\cdot} to give compounds with an ozonide-like structure, which favors the formation of ring-opening products [77] as shown in equations (i-ii).



They found that, the organic intermediates of Fenton oxidation of phenols included benzenediols and benzoquinones [80, 81]. It was noted that the benzenediols and benzoquinones could expedite the redox cycle of iron [82 and 83]. As the reaction proceeded, the aromatic ring ruptured and organic acids such as muconic, valeric, propionic butyric and acetic acids were produced [84] and then a possible contrasting

role of these acids might potentially deactivate iron by forming stable complexes [85-87].

CONCLUSIONS

The advanced chemical oxidation processes (Fenton's reagent) used successfully in the removal of organic pollutants from its aqueous solution which is helpful to determine the optimum conditions for their removal from industrial wastewater containing organic pollutants with high removal efficiency.

pH is the most important factor to be taken into account since at acidic pH the direct attack by free radical (OH^\cdot) is predominant and improves the efficiency of Fenton reaction, while at neutral and basic pH there was a major contribution of the free radical pathway and the addition of hydrogen peroxide can promote or inhibit the reaction of free radical.

Considering the Fenton method can be used as a preliminary step prior to a biological wastewater treatment, one has to adjust pH twice, first to an acidic pH (~3) to perform the Fenton's method and then back to a neutral pH. The biodegradability of the treated waste increased with increasing in hydrogen peroxide this revealed that destruction of organic pollutants by Fenton's reagent to give biodegradable substances.

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