



Energy, Resources and Environmental Technology

Integrated ozone–photo–Fenton process for the removal of pollutant from industrial wastewater☆



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ABSTRACT

The use of hybrid advanced oxidation processes (AOPs) for the removal of pollutants from industrial effluents has been extensively studied in recent literature. The aim of this study is to compare the performance of the photo, Fenton, photo-Fenton and ozone–photo–Fenton processes in terms of color removal and chemical oxygen demand (COD) removal of distillery industrial effluent together with the associated electrical energy per order. It was observed from the experimental results that the $O_3/UV/Fe^{2+}/H_2O_2$ process yielded a 100% color and 95.50% COD removals with electrical energy per order of $0.015 \text{ kW} \cdot \text{h} \cdot \text{m}^{-3}$ compared to all other combinations of the AOPs. The effects of various operating parameters such as H_2O_2 and Fe^{2+} concentration, effluent pH, COD concentration and UV power on the removal of color, COD and electrical energy per order for the ozone–photo–Fenton process was critically studied and reported. The color and COD removals were analyzed using a UV/Vis spectrometer and closed reflux method.

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1. Introduction

Organic, inorganic and biorefractory organic pollutants are main water pollutants. Different types of organic effluents that are known to cause serious environmental problems are produced by the pulp and paper industry [1,2], leather industry [3,4], sugar industry [5], dairy industry [6], rubber processing industry [7], agricultural industry [8], distillery industry [9–12], food industry [13], textile industry [14–16], olive processing industry [17], wood based industry [18], etc. Amongst these industries, the distillery industry [12] generates a large amount of wastewater, which has a considerable impact on water bodies. The effluent from the distillery industry is colored and has high chemical oxygen demand (COD), biological oxygen demand (BOD), total solids (TS), total dissolved solids (TDS), total suspended solids (TSS), total volatile solids (TVS) and other organic, inorganic matters such as chlorides, sulfates, total nitrogen, potassium, phosphorous, sodium and calcium which causes pollution when discharged into water bodies without proper treatment [19]. Much research has been carried out on different treatment methods of the distillery industrial effluent, including biological flocculation [20], biotreatment [21], biological treatment using thermotolerant *Pediococcus acidilactici* [22], ozone-based advanced oxidation [23], microfiltration [24], reverse osmosis [25], activated carbon [26], ozonation [27], electrochemical

degradation [28], electrocoagulation [29], UV photocatalytic [30], cavitationally induced process [31], ultrasound and ozone assisted biological processes [32]. These methods are associated with some disadvantages such as high operating cost, lower pollutant removal efficiency, transfer of pollutants from one phase to another.

Some effective and environmental friendly alternatives to conventional oxidative methods have been developed for water treatment. They are generally referred as advanced oxidation processes (AOPs) and they mainly involve UV light in the presence of hydrogen peroxide (H_2O_2) or ozone (O_3), UV-near visible light in the presence of Fenton reagent, ultrasound, etc. These methods degrade and decolorize pollutants by using highly oxidizing hydroxyl radicals ($\bullet OH$) radicals that are formed at ambient temperature and atmospheric pressure within the treatment systems. The principal mechanism of AOPs includes generation of very powerful and non-selective oxidizing agents and free hydroxyl radicals ($\bullet OH$) to destroy hazardous organic and inorganic pollutants. A single AOP usually does not completely remove pollutants. Consequently, combining two or more AOPs enhances hydroxyl radical generation, which leads to higher oxidation rates [33]. For example, a combination of the photo-Fenton with ozonation process maximizes the removal efficiency of pollutants with minimal operational cost.

To the best of our knowledge, there is limited research on the use of hybrid AOPs for industrial effluent treatment. Kusic *et al.* did a comparative investigation of the efficiency of several ozone- and/or UV-based processes for the mineralization of phenol. The highest mineralization efficiency was achieved by the $UV/H_2O_2/O_3$ process [34]. Catalkaya and Kargi employed different AOPs to treat pulp mill effluent. They found that TiO_2 -assisted photo-catalysis yielded higher total organic carbon (TOC) and toxicity removals compared to the other AOPs [35].

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Wu *et al.* studied isopropyl alcohol degradation and its major degradation intermediate-acetone. The results showed that the UV/H₂O₂/O₃ process was the most efficient compared to the other AOPs such as the O₃, O₃/UV, H₂O₂/UV, H₂O₂/O₃ processes [36]. Wu and Ng investigated decolorization of C.I. Reactive Red 2 using ozone- and photo-based AOPs. They observed that the UV/O₃/H₂O₂/Fe³⁺ system were the most suitable for high pollutant removal with minimum power consumption [37]. Lucas *et al.* used a Fenton reagent (H₂O₂/Fe²⁺) for the removal of COD from olive mill wastewater in a batch reactor [23]. Chandrasekara Pillai *et al.* treated terephthalic acid wastewater by ozonation catalyzed process with Fe²⁺, H₂O₂ and UV irradiation. The combined O₃/H₂O₂/Fe²⁺/UV process yielded high pollutant removal percentage of around 90% at 240 min compared to other AOPs [38]. Hadavifar *et al.* demonstrated the Fenton and photo-Fenton processes for the treatment of alcohol distillery industries. They concluded that higher removal efficiency was achieved in the photo-Fenton (18% to 97%) process compared to the Fenton (5% to 47%) process alone [39]. Most of the previous research focused on pollutant removal efficiency from industrial effluent and wastewater. In the photo- and ozone-based AOPs, electrical energy per order is an important parameter from the economical point of view. Besides, most of the previous research work focused on removal of pollutants from industrial effluent and wastewater using single AOP. It is not economical to use a single AOP for industrial wastewater treatment due to its high operating cost and lower pollutant removal efficiency. Therefore, it is suggested to integrate these technologies with other methods such as the photo, ozonation and Fenton processes. However, to the best of our knowledge, the removal of color and COD and determination of electrical energy per order of distillery industrial effluent by different AOPs such as the UV/H₂O₂, Fe²⁺/H₂O₂, UV/Fe²⁺/H₂O₂ and O₃/UV/Fe²⁺/H₂O₂ processes have not been reported yet.

The present work focused on combinations of AOPs such as the UV/H₂O₂, Fe²⁺/H₂O₂, UV/Fe²⁺/H₂O₂ and O₃/UV/Fe²⁺/H₂O₂ processes for the removal of color, COD and electrical energy per order from distillery industrial effluent. According to our experimental results, the O₃/UV/Fe²⁺/H₂O₂ process achieved complete pollutant removal with minimum electrical energy per order. Therefore, this process was used in the study for the treatment of industrial effluent. Effects of various operating parameters such as H₂O₂ concentration (30 to 180 mmol·L⁻¹), Fe²⁺ concentration (0.05 to 0.80 mmol·L⁻¹), effluent pH (2 to 11), COD concentration (1500 to 6000 mg·L⁻¹) and effect of UV power (8 and 16 W) on color removal, COD removal and electrical energy per order were studied.

2. Material and Methods

2.1. Characterization of distillery industrial effluent

The effluent was collected from nearby distillery premises at Kuala Lumpur, Malaysia. The main characteristics of the effluent were pH: 4.1–4.3; COD: 8000–9000 mg·L⁻¹; BOD: 7000–8000 mg·L⁻¹; TSS: 15.44 g·L⁻¹; TDS: 5550–5750 mg·L⁻¹; color – dark brown; odor – burnt sugar. The chemicals used in the experiments to adjust the pH value were H₂O₂ (50 wt%), FeSO₄·7H₂O, H₂SO₄ and NaOH. All the chemicals were of analytical grade and purchased from Merck Specialist Private Limited. Only double distilled water was used for preparing the needed solutions.

2.2. Methods

The experimental setup for the present investigation is schematically shown in Fig. 1. The experimental setup consisted of an ozone reactor and a photo-chemical reactor. The photo-chemical reactor was made of borosilicate glass with a net capacity of 600 ml. The reactor was surrounded with a water jacket to remove the heat produced by the lamp and to maintain a constant temperature. The reactor was covered with an aluminum foil to prevent light leakage from the reactor. The

reactor was placed on a magnetic stirrer in order to maintain a uniform concentration. The reactor had inlet ports for feeding reactants and for withdrawing sample with measuring temperature at the top. The source of UV irradiation was 16 W low-pressure mercury vapor lamp with the maximum emission of 254 nm, placed in a quartz tube. The lamp tube was immersed in the solution for treatment.

O₃ was generated using a lab-scale O₃ generator and O₃ was bubbled into the photo reactor through a ceramic diffuser for the O₃ based AOPs. The flow rate and concentration of O₃ were controlled at 10 L·min⁻¹ and 2 g·h⁻¹. The O₃ concentration was determined using an iodimetric method. All the experiments lasted around 4 h and 10 ml of samples was collected from the sampling port at different time intervals. The samples were then quenched with Na₂SO₃ and filtered using a filter paper to determine the color removal (UV–visible absorbance at the wavelength of λ = 290 nm) and COD removal (closed reflux method).

2.3. Analysis

2.3.1. Color removal

The color removal was calculated using Eq. (1).

$$\text{Color removal} = \frac{Abs_0 - Abs_t}{Abs_0} \times 100\% \quad (1)$$

where, Abs_0 and Abs_t are the absorbance at initial time and any time t for corresponding wavelength, $\lambda_{\max}$.

2.3.2. COD removal

The COD removal was calculated using Eq. (2).

$$\text{COD removal} = \frac{COD_0 - COD_t}{COD_0} \times 100\% \quad (2)$$

where, COD_0 and COD_t (in mg·L⁻¹) are the chemical oxygen demand (COD) at time $t = 0$ (initial) and t (reaction time) respectively.

2.3.3. Electrical energy per order evaluation

The main operating cost of the ozone-photo-Fenton process is associated with electrical energy per order during the process. The equations to identify electrical energy per order (EE/O) are discussed below.

Electrical energy per order represents a major fraction of the operating costs. Simple figures-of-merit based on electric energy consumption can be very useful and informative. A thorough understanding of the overall kinetic behavior of organic and inorganic industrial effluents is necessary for describing meaningful electrical efficiencies. Electrical energy per order can be defined as kW·h (kilo watt hour) of electrical energy required to reduce the concentration of a pollutant by 1 order of magnitude in 1 m³ of contaminated water. The electrical energy per order EE/O (kW·h·m⁻³) can be calculated by using the following Eq. (3).

$$\frac{EE}{O} = \frac{P_{el} \times t \times 1000}{V \times 60 \times \lg\left(\frac{COD_0}{COD_t}\right)} \quad (3)$$

where, EE/O is the electrical energy per order (kW·h·m⁻³), P_{el} is the electrical power input (kW), t is the irradiation time (min), V is the volume of effluent used (L), C_0 and C_t are the initial and final effluent COD concentrations (mg·L⁻¹), respectively.

The color and COD removals of industrial effluents were investigated using the pseudo first-order kinetic model, as shown in Eq. (4)

$$\lg\left(\frac{COD_0}{COD_t}\right) = kt \quad (4)$$

k is the pseudo first-order rate constant for the decay of effluent concentration (min⁻¹).

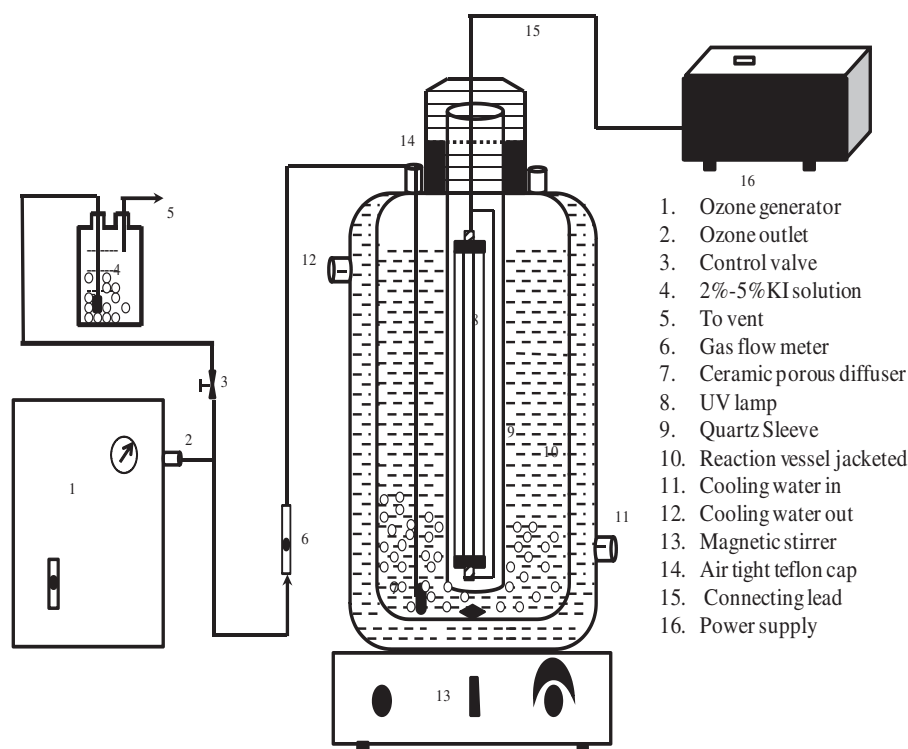


Fig. 1. Schematic diagram of ozone-photo-Fenton system.

Combining Eqs. (3) and (4) gives an equation for the electrical energy determination in the following form:

$$\frac{EE}{O} = \frac{38.4 \times P_{el}}{V \times k} \quad (5)$$

The total electrical energy per order of ozone-photo-Fenton system can be calculated by using Eq. (6).

$$EE/O = EE/O_{UV} + EE/O_{O_3} \quad (6)$$

where, EE/O_{UV} , EE/O_{O_3} – electrical energy per order for the photo and ozonation processes.

3. Results and Discussion

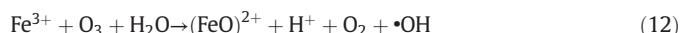
3.1. Comparisons of UV/H_2O_2 , Fe^{2+}/H_2O_2 , $UV/Fe^{2+}/H_2O_2$, $O_3/UV/Fe^{2+}/H_2O_2$

Previous research has shown that the ozonation (O_3) and photo (UV) processes are not very effective for complete removal of pollutants when used separately [40–42]. However, when they are combined with the Fenton process, they have a significant synergistic effect on pollutant removal, mainly due to considerable amount of $\bullet OH$ that is produced from the O_3 , UV and Fe^{2+}/H_2O_2 processes. The treatment process using this combination starts with the photolysis of ozone, which produces hydroxyl radicals ($\bullet OH$), as shown in the following equations.



Oxidation of H_2O_2 catalyzed by Fe^{2+} via the classical Fenton's reaction could be one of the main sources of $\bullet OH$ generation. This reaction could be further catalyzed through photo reduction of Fe^{3+} and its

reaction with O_3 , as shown in the following chemical reactions [38].



The color removal percentages, COD removal efficiency and electrical energy per order of four AOPs – UV/H_2O_2 , Fe^{2+}/H_2O_2 , $UV/Fe^{2+}/H_2O_2$ and $O_3/UV/Fe^{2+}/H_2O_2$ are compared and shown in Fig. 2(a) and (b). The figures show that the color and COD removals were about 70.75%, 52%, 100%, 100% and 62.75%, 49%, 95%, 100% for the UV/H_2O_2 , Fe^{2+}/H_2O_2 , $UV/Fe^{2+}/H_2O_2$, $O_3/UV/Fe^{2+}/H_2O_2$ processes respectively. Based on Fig. 2(a) and (b), it was evident that the color and COD removal efficiencies were significantly higher for the $UV/Fe^{2+}/H_2O_2$ and $O_3/UV/Fe^{2+}/H_2O_2$ processes compared to the UV/H_2O_2 and Fe^{2+}/H_2O_2 processes. The above results indicated that introducing H_2O_2 , Fe^{2+} and O_3 into the UV system led to a significant increase in the color and COD removals. This could be attributed to the available parallel pathways to generate abundant $\bullet OH$ radicals for efficient color and COD removals from distillery effluent within a shorter reaction time.

The economic feasibility of hybrid ozonation and photo processes is associated with electrical energy per order. The minimum electrical energy per order of $0.015 \text{ kW} \cdot \text{h} \cdot \text{m}^{-3}$ was required for the removal of color (100%) and COD (100%) in the $O_3/UV/Fe^{2+}/H_2O_2$ process. The other hybrid processes such as the UV/H_2O_2 and $UV/Fe^{2+}/H_2O_2$ processes required high power consumption for color and COD removals compared to the $O_3/UV/Fe^{2+}/H_2O_2$ process.

3.2. Effect of experimental parameters on $O_3/UV/Fe^{2+}/H_2O_2$ process

The effects of selected operating parameters of the $O_3/UV/Fe^{2+}/H_2O_2$ process, including H_2O_2 and Fe^{2+} concentration, effluent pH,

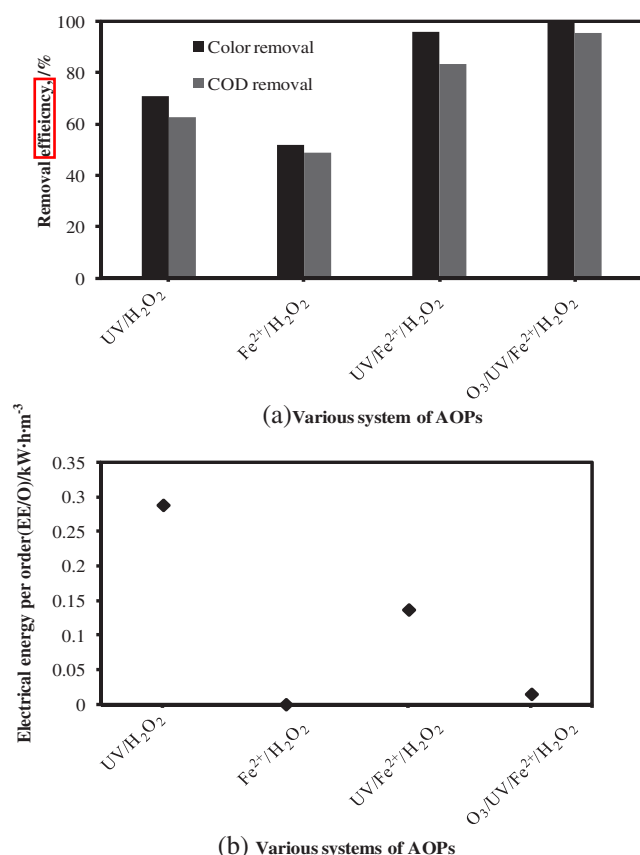


Fig. 2. Comparison of various AOPs such as UV/H₂O₂, Fe²⁺/H₂O₂, UV/Fe²⁺/H₂O₂ and O₃/UV/Fe²⁺/H₂O₂ on (a) color and COD removals and (b) electrical energy per order.

COD concentration and UV power on decolorization and degradation of distillery industrial wastewater were investigated in this study and the results are discussed below.

3.2.1. Effect of H₂O₂ concentration

The oxidation of industrial effluent by the O₃/UV/Fe²⁺/H₂O₂ process was tested with the feed amounts of oxidants (H₂O₂) chosen from the preliminary experiments. The results are shown in Fig. 3. It can be ascertained from Fig. 3 that the H₂O₂ concentration varied from 30 to 120 mmol·L⁻¹ and the color and COD removals increased from 53.06% to 100% and 40.26% to 91.65%, respectively within 3 h. The COD removal slightly decreased from 91.65% to 90.43% by further increasing the concentration of H₂O₂ from 120 to 180 mmol·L⁻¹. This phenomenon, which is known as •OH scavenging by H₂O₂, has been widely reported in the literature [43,44]. The reactions are shown in Eqs. (13)–(15).



The reduction potential of HO₂• is much lower (1.0 V; (Mohan et al.)) than that of •OH (2.8 V) and this was most probably the reason for the observed decrease in color and COD removals. H₂O₂ of the optimum dosage should be added to achieve higher pollutant removal rate.

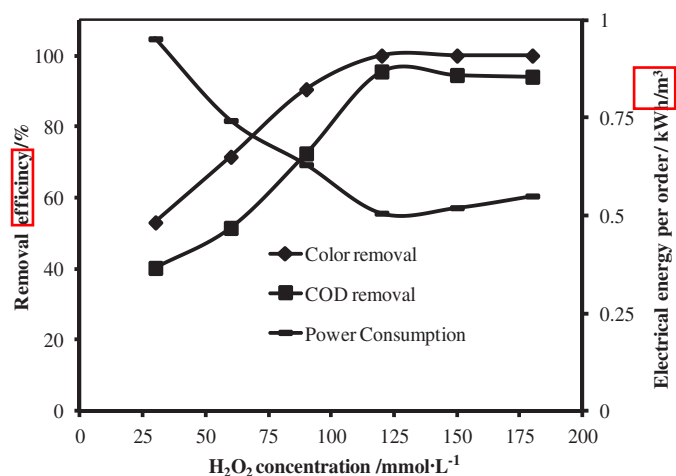


Fig. 3. Effect of H₂O₂ concentration on color and COD removals and electric energy per order in O₃/UV/Fe²⁺/H₂O₂ process (conditions: COD concentration: 3000 mg·L⁻¹; Fe²⁺ concentration: 0.40 mmol·L⁻¹; effluent pH: 7; UV lamp: 16 W and 254 nm; O₃ flow rate: 10 L·min⁻¹ and reaction time: 3 h).

The electrical energy per order was calculated based on different concentrations of H₂O₂ shown in Fig. 3. The electrical energy per order decreased from 0.95 to 0.51 kW·h·m⁻³ with increasing H₂O₂ concentration from 30 to 120 mmol·L⁻¹. It was due to generation of more •OH radicals. However, the electrical energy per order tend to increase slightly from 0.51 to 0.55 kW·h·m⁻³ with increasing concentration of H₂O₂ from 120 to 180 mmol·L⁻¹, which may be attributed to coincident •OH consumption at high H₂O₂ concentrations [45].

3.2.2. Effect of Fe²⁺ concentration

The amount of Fe²⁺ concentration in the O₃/UV/Fe²⁺/H₂O₂ process is an important parameter affecting the oxidation processes. Fe²⁺ acts as a catalyst, does not precipitate in the reaction and enhances the O₃/UV/Fe²⁺/H₂O₂ process. Therefore, with increasing Fe²⁺ iron, the surface of iron and simultaneous production of free radicals increased, which eventually increased the color and COD removal efficiencies. The results are shown in Fig. 4. The figure shows that when Fe²⁺ concentration increased from 0.05 to 0.40 mmol·L⁻¹, the color and COD removals increased from 88.52% to 100% and from 82.30% to 95.53%, respectively. Further increase in Fe²⁺ concentration from 0.40 to 0.80 mmol·L⁻¹ slightly decreased the color and COD removals from 100% to 98% and

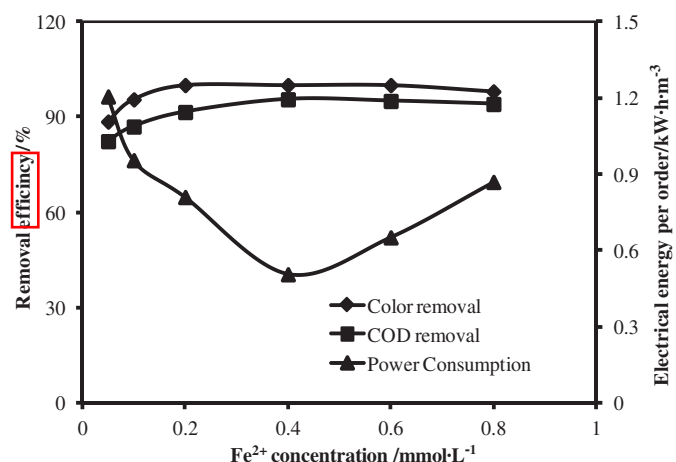


Fig. 4. Effect of Fe²⁺ concentration on color and COD removals and electric energy per order in O₃/UV/Fe²⁺/H₂O₂ process (conditions: COD concentration: 3000 mg·L⁻¹; H₂O₂ concentration: 120 mmol·L⁻¹; effluent pH: 7; UV lamp: 16 W and 254 nm; O₃ flow rate: 10 L·min⁻¹ and reaction time: 3 h).

95.53% to 94.05%, respectively. It could be explained by redox reaction that $\bullet\text{OH}$ is either scavenged by hydroxyl radicals or Fe^{2+} , as shown in the following equations [46].



The effect of Fe^{2+} concentration on electrical energy per order is shown in Fig. 4. Experiments with varying Fe^{2+} concentrations from 0.05 to 0.80 $\text{mmol}\cdot\text{L}^{-1}$ were conducted. When the concentration of Fe^{2+} increased from 0.05 to 0.40 $\text{mmol}\cdot\text{L}^{-1}$, the electrical energy per order decreased from 1.21 to 0.51 $\text{kW}\cdot\text{h}\cdot\text{m}^{-3}$. Further increasing the initial concentration of Fe^{2+} from 0.40 to 0.80 $\text{mmol}\cdot\text{L}^{-1}$ increased the electrical energy per order from 0.51 to 0.87 $\text{kW}\cdot\text{h}\cdot\text{m}^{-3}$. The above results indicated that more hydroxyl radicals could be produced with optimum Fe^{2+} and H_2O_2 concentrations in the UV and O_3 processes.

3.2.3. Effect of pH

The optimum pH for removal of pollutants by using the Fenton and photo-Fenton processes is between 2 and 4.5 [47–49]. However, the ozonation process is more efficient at high pH values compared to under an acidic condition due to the presence of hydroxyl radicals [50]. Fig. 5. shows the effect of the effluent pH value during the use of $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process. It can be ascertained from the figure that the color and COD removals increased from 88.90% to 100% and from 80.76% to 95.45% with increasing effluent pH from 2 to 7. Further increasing effluent pH from 7 to 11 slightly decreased the color and COD removals.

Electrical energy per order of the $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process at different effluent pH was studied and the results are shown in Fig. 5. It was observed that the electrical energy per order decreased from 1.19 to 0.51 $\text{kW}\cdot\text{h}\cdot\text{m}^{-3}$ with increasing effluent pH from 2 to 7, hence the electrical energy per order also increased from 0.51 to 0.96 $\text{kW}\cdot\text{h}\cdot\text{m}^{-3}$ with further increase of the initial effluent pH from 7 to 11. The above results indicated that more hydroxyl radicals were produced at neutral condition than at acidic and alkali conditions.

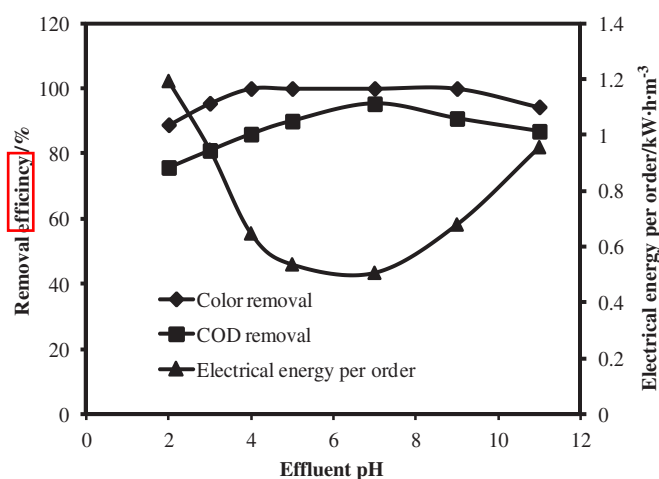


Fig. 5. Effect of pH on color and COD removals and electric energy per order in $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process (conditions: COD concentration: 3000 $\text{mg}\cdot\text{L}^{-1}$; H_2O_2 concentration: 120 $\text{mmol}\cdot\text{L}^{-1}$; Fe^{2+} concentration: 0.4 $\text{mmol}\cdot\text{L}^{-1}$; UV lamp: 16 W and 254 nm; O_3 flow rate: 10 $\text{L}\cdot\text{min}^{-1}$ and reaction time: 3 h).

3.2.4. Effect of COD concentration

The effect of COD concentration on color and COD removals of the distillery industrial effluent by the $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process and the associated electrical energy per order were investigated. Pollutant concentration is an important parameter in any effluent treatment

techniques. The influence of COD concentration is shown in Fig. 6. The figure showed that the color and COD removals decreased from 100% to 75% and from 100% to 63% with increasing COD concentration from 1500 to 6000 $\text{mg}\cdot\text{L}^{-1}$ within 3 h. It was also observed that the electrical energy per order increased with increasing COD concentration. It was attributed to the fact that an increase in COD concentration increases the number of organic molecules but the adding of H_2O_2 and Fe^{2+} was constant, consequently, the generation of $\bullet\text{OH}$ radicals is constant. The results showed that the $\bullet\text{OH}$ radicals produced at high COD concentration were inefficient to absorb all the COD concentrations in the solution which decrease the color and COD removals. Increasing the number of organic molecules also obstructs the penetration of photons into the solution, therefore producing less $\bullet\text{OH}$ radicals [51]. It was suggested that the optimal COD concentration for the $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process in the experiment was 3000 $\text{mg}\cdot\text{L}^{-1}$ and the color and COD removal percentages reached 100% and 95.50%.

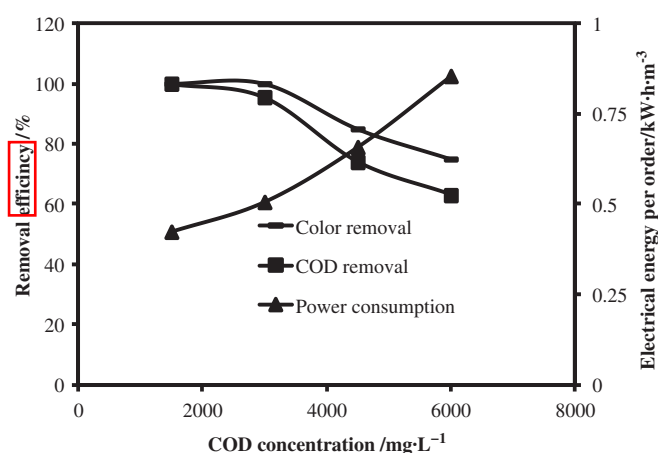


Fig. 6. Effect of COD concentration on color and COD removals in $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process (conditions: H_2O_2 concentration: 120 $\text{mmol}\cdot\text{L}^{-1}$; Fe^{2+} concentration: 0.4 $\text{mmol}\cdot\text{L}^{-1}$; effluent pH: 7; UV lamp: 16 W and 254 nm; O_3 flow rate: 10 $\text{L}\cdot\text{min}^{-1}$ and reaction time: 3 h).

3.2.5. Effect of UV power

The effects of UV power have important parameters to check performance of $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process. UV is mainly used for photolysis of H_2O_2 and photo reduction of ferric ion to ferrous ion. The influence of UV on color and COD removals of distillery industrial effluent was investigated by using two different UV powers — 8 and 16 W. The results are shown in Fig. 7. The color and COD removals increased from 95% to 100% and from 90% to 100% within 3 h when the UV powers were 8 and 16 W, respectively. This could be attributed to increased number of photons that reacted with Fe^{3+} ions, which increased the number of active species and formed hydroxyl radicals. The photolysis rate of H_2O_2 and photo reduction of Fe^{3+} reduced at low UV power.

3.3. Instrumental analysis

Treatment (color and COD removals) of distillery industrial effluent by the $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ process was performed in this study. After a predetermined time interval, the samples were evaluated using UV/Vis spectra and the results are shown in Fig. 8. The absorbance of UV/Vis peak decreased by increasing the reaction time of the $\text{O}_3/\text{UV}/\text{Fe}^{2+}/\text{H}_2\text{O}_2$ system. The position of the peak in the UV/Vis region also changed from 301 nm to around 260 nm, which indicated formation of new smaller organic byproducts. According to the UV/Vis data, it

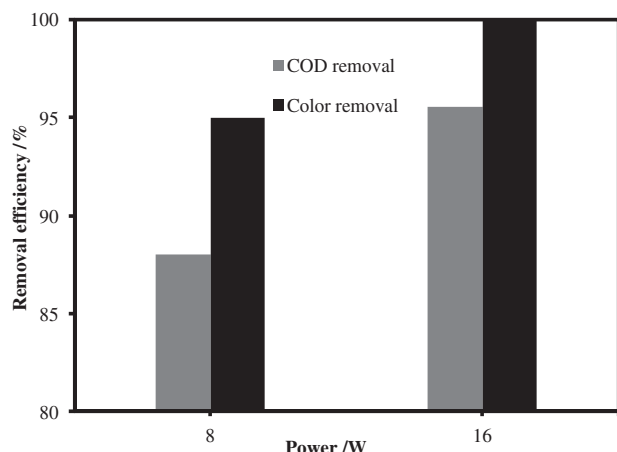


Fig. 7. Effect of UV power on color and COD removals in $O_3/UV/Fe^{2+}/H_2O_2$ process (conditions: COD concentration: $3000\text{ mg}\cdot\text{L}^{-1}$; H_2O_2 concentration: $120\text{ mmol}\cdot\text{L}^{-1}$; Fe^{2+} concentration: $0.4\text{ mmol}\cdot\text{L}^{-1}$; effluent pH: 7; UV lamp: 16 W and 254 nm; O_3 flow rate: $10\text{ L}\cdot\text{min}^{-1}$ and reaction time: 3 h).

might be attributed to the color and COD removals of the distillery effluent.

4. Conclusions

In this study, the color and COD removals of distillery industrial effluent using the UV/H_2O_2 , H_2O_2/Fe^{2+} , $UV/H_2O_2/Fe^{2+}$ and $O_3/UV/Fe^{2+}/H_2O_2$ processes, together with the associated electrical energy per order were investigated successfully. The results showed that the hybrid system of $O_3/UV/Fe^{2+}/H_2O_2$ completely removed color and COD from the effluent within 3 h with minimum electrical energy per order. Various operating parameters of the hybrid AOPs ($O_3/UV/Fe^{2+}/H_2O_2$) were studied. It was concluded that the $O_3/UV/Fe^{2+}/H_2O_2$ process was effective compared to other processes reported in the present investigation. The results of the $O_3/UV/Fe^{2+}/H_2O_2$ process for removal of pollutants from industrial effluent

showed that this hybrid process could be used as an efficient, effective and environmental friendly technique for complete removal of organic and inorganic pollutants, which increases the reusability of wastewater.

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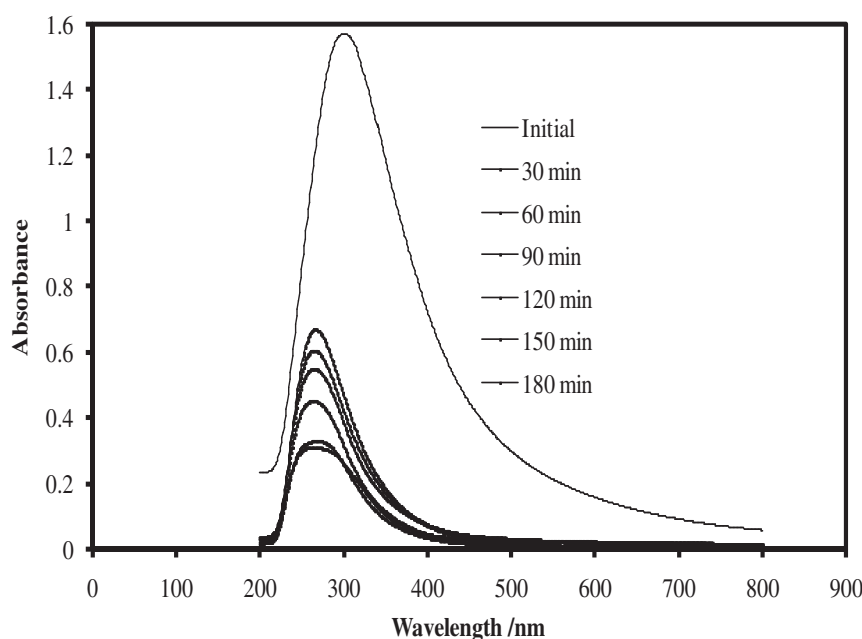


Fig. 8. Instrumental analysis (UV/Vis characteristics).

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