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Selecting the optimal process for the removal of reactive red 198 dye from textile wastewater using analytical hierarchy process (AHP)

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ABSTRACT

In this study, the application of adsorption processes on the surface of TiO_2 nanoparticles and oxidation by O_3, UV, O_3/TiO_2, and the UV/TiO_2 in the removal of reactive red 198 dye form textile wastewater was examined. Then, Analytical Hierarchy Process (AHP) was used to choose the best removal method. The studied criteria for decision-making in selecting the best choice included the rate of dye removal in different situations, with the sub-criteria of studied variables, cost, with the sub-criteria of initial operation and maintenance cost, and the required expertise to use each method. Grading and preference of each method were calculated based on the efficiency of removal in different conditions, the price of each tool in the market, and the consumed energy of each method. The UV/TiO_2 process was considered as the best-known method based on AHP model. Results indicated that this model can be a useful and suitable tool for policy-makers and decision-makers to choose the best treatment process in different conditions.

Keywords: Reactive red 198 dye; Oxidation process; AHP

1. Introduction

In recent years, industrial development has caused many problems, especially environmental pollution [1]. The pollutants include dyes, heavy metals, and organic and non-organic pollutants [2,3]. One important category of pollutants is dyes [4]. Dyes are generally used in textile, paper, cosmetics, food, pharmaceutical, and leather industries [5–7]. Studies show that approximately 40 million tons of textiles are produced in the world yearly and the produced waste by this industry is about 4–8 million cubic meters [8]. The most striking feature of textile industry wastewater is the dyes in it [9]. Discharged wastewater has low BOD and high COD [10]. The dyes cause many problems, such as skin

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sensitivity, skin irritation, cancer, mutation, etc. Workers' continuous exposure in textile industry is associated with a high risk of bladder cancer [11]. For example, several epidemiological studies have shown that the use of benzidine-based dyes can result in bladder cancer [12]. In general, because of the complex molecular structures of dye molecules, they are highly resistant to biodegradation [2]. Due to low biodegradable feature of the dye, conventional biological wastewater treatment methods are not effective. Therefore, the dye wastewater is usually treated by physical or chemical methods [13]. The methods used for removing dyes from wastewater include physicochemical, biological, and chemical methods such as coagulation, flocculation, precipitation, adsorption, membrane filtration, electrochemical techniques, ozonation, and photocatalytic oxidation [14–16]. Compared to other methods, chemical oxidation is more effective in removing dye and ozone is the most efficient material used in this method because of its power to break down. In wastewater treatment and dye removal, ozone molecules rapidly react with unsaturated bonds of chromospheres and quickly remove the dye [17]. Another advanced oxidation method is using photocatalytic processes. Among these processes, the use of nanoparticles along with catalytic processes is a new wastewater treatment method in textile industry that has been used in many studies. The basis of advanced oxidation processes is releasing the hydroxyl radicals that have high oxidation capabilities [18–21]. In a study on the ozonation of nitrobenzene, Yang et al. stated that ozone in alkaline conditions produces hydroxyl radicals and, compared to acidic conditions, it has more power to remove nitrobenzene [22]. The study of Beltran et al. showed that due to the acidic conditions in the removal of oxalic acid, the efficiency of ozonation process is not sufficient and the use of catalyst makes this efficiency significant [23].

Analytical Hierarchy Process (AHP) was introduced first by Sa'ati [24]. This method involves different options in decision-making and makes it possible to analyze the sensitivity on the criteria and sub-criteria. This method is also based on paired comparison that facilitates the judgments and calculations and shows compatibility or incompatibility of the decision [25]. In the analytic hierarchy process, the elements of each level are compared with their associated elements in the higher level as the pair. In addition, relative weights of the elements are compared and then combined to determine the final weight of each option. The final weight is obtained from the total product of the importance of the criteria by the weight of the options [26]. One of the major benefits of AHP is measuring and monitoring the compliance of each matrix and decision. Incompatibility of the system depends on the ability of decision-makers but in general, Sa'ati suggests that if the decision incompatibility is more than 0.1, the decision-maker should revise his judgments [25]. AHP method is a good method for multicriteria decisions in wastewater treatment. This method is able to consider various aspects in selecting the best option [27,28]. Dabaghian et al. used AHP to select the optimal method of wastewater treatment in electroplating industries. In this research, four treatment processes were studied and the most appropriate method was selected at the end [29]. This study dealt with different methods of dye removal from textile synthetic wastewater and finally the most optimal process was selected using AHP method.

2. Materials and methods

This experimental study aimed to perform a comparative study on removing the reactive dye 198 from textile synthetic wastewater using advanced oxidation processes in different situations and finally selecting the best choice using AHP model. At first, removal of RR198 from textile synthetic wastewater was separately examined through the adsorption on TiO_2 nanoparticles, oxidation by O_3, and UV irradiation. Then, processes of UV/TiO_2 and O_3/TiO_2 were combined, in the same conditions for all five methods. Reactive red 198 dye of the Dye Star Company and the other materials of the Merck Company in Germany were used to make synthetic wastewater. In order to measure the concentration of reactive red 198 dye, the spectrophotometer device (UV/vis, Optima SP-3000 Plus model, made in Japan) was used.

Ozonation process was in a laboratory cylindrical reactor of Plexiglas with a height of 1 m and useful volume of one liter (Fig. 1). Ozone was produced by the ozone generator (Ned Gas MK940) using pure oxygen as input gas and the amount of produced ozone and the amount of output ozone were assessed by KI method.

The ultraviolet irradiation was used in a process with the useful volume of 1.7 L in a Plexiglas photocatalytic reactor that included two 15 Watt lamps producing UV-C, the diameter of 30 mm, the length of 490 mm, and a cooler to avoid increasing temperature (Fig. 2).

The studied variables in all processes were measured in three different value levels of initial dye concentrations including 100, 150, and 200 mg/l of reactive red 198 dye, in the pH of 4, 7–10 and at the time of 30, 60, 90, 120, 150, and 180 min. Concentration

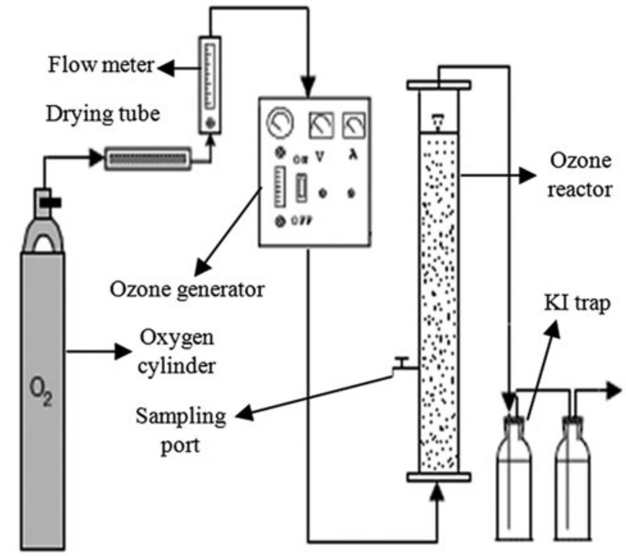

Fig. 1. Diagram of the reactor used in ozonation process.

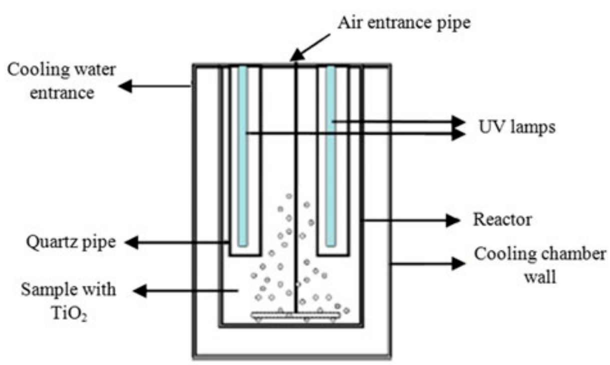

Fig. 2. Diagram of the reactor used in photocatalytic process.

of TiO_2 nanoparticles was 0.4 g/l at all times. Collecting the data and drawing the diagrams were done using EXCEL.

2.1. Application of AHP model

In this study, AHP model was used through the software of Expert choice v.4. To use the model, application of UV/TiO_2, O_3/TiO_2, UV, O_3, and adsorption on TiO_2 were studied as decision-making choices of the best method for removal of reactive dye 198 from textile synthetic wastewater.

The studied criteria for decision-making in selecting the best choice included the rate of dye removal in different situations, with the sub-criteria of studied variables, cost, with the sub-criteria of initial operation and maintenance cost, and the required expertise to use each method. Grading and preferring each method were calculated based on the removal efficiency in different conditions, the price of each tool in the market, and the consumed energy of each method.

3. Results

3.1. The effect of contact time on dye removal

The flow intensity of oxygen entered into the generator and the amount of input ozone into the reactor in all stages were constant and respectively 0.1 l/min and 0.11 g/hr. The effect of time at 100 mg/l concentration of RR198 dye, 0.4 g/l of TiO_2 and contact times of 30, 60, 90, 120, 150, and 180 min were studied. The results are shown in Fig. 3. The relative removal of UV/TiO_2, O_3/TiO_2, and O_3 at 180 min is 100%, but at the time of 120 min UV/TiO_2 has the most removal efficiency. So this time was used for the tests in the next stages.

3.2. The effect of pH on dye removal

The effect of pH was studied in RR198 with initial concentration of 100 mg/l, 0.4 g/l of TiO_2, 0.1 l/min of flow intensity of oxygen into the generator, 0.11 g/hr of entrance ozone into the reactor, contact time of 120 min, and the pH of 4, 7–10. The effect of pH on the amount of dye removal is shown in Fig. 4. According to the diagram, UV/TiO_2 has the highest removal rate in acidic condition.

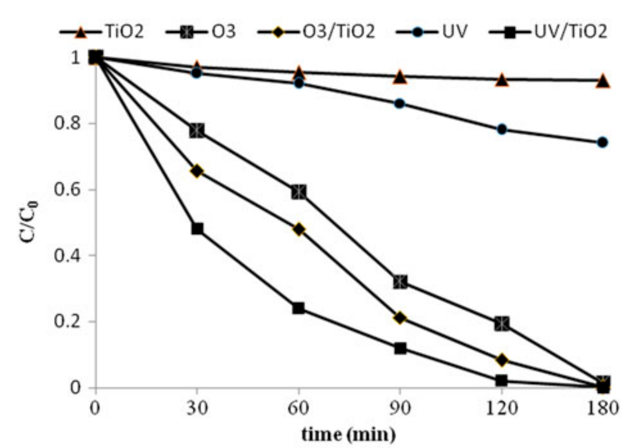

Fig. 3. The effect of contact time on removal of reactive red 198 dye in different studied processes.

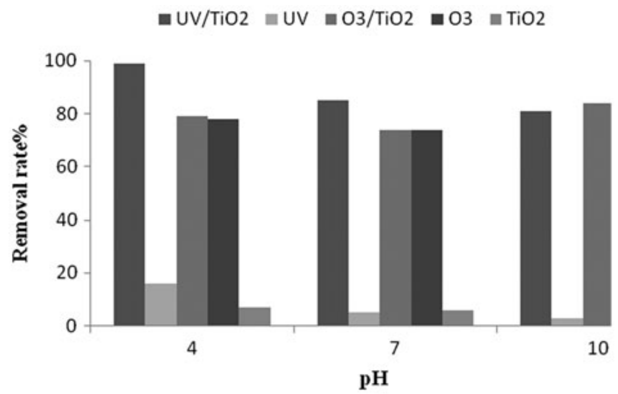

Fig. 4. The effect of pH on the removal of reactive red 198 dye in various studied processes.

3.3. The effect of initial dye concentration

The effect of initial concentration is measured at the same pH 0.4 g/l of TiO_2, the 0.1 1/min of flow intensity of oxygen into the generator, 0.11 g/hr of entrance ozone into the reactor, contact time of 120 min, and the dye initial concentrations of 100, 150, and 200 mg/l. Fig. 5 shows the effect of initial dye concentration on its removal in various processes. According to the diagram, the removal rate of UV/TiO_2 process is more than other processes; although O_3 and O_3/TiO_2 have significant removal rate.

3.4. The model results

Fig. 6 shows the results of using AHP model in the removal of reactive red 198 dye from textile synthetic wastewater. According to the output, UV/TiO_2 with 0.353 has the highest score among the choices and has been chosen as the best option for the removal of reactive dye 198. The incompatibility of system is 0.07, so the judgments suggest an acceptable compatibility with respect to this that it is less than 0.1. Regarding the cost and the problems of ozonation process, this is a logical and good choice. Based on Table 1, the most important criteria to choose the best removal method is removal efficiency that has the highest weight among all criteria and according to Figs. 4 and 5, UV/TiO_2 process has the most removal efficiency.

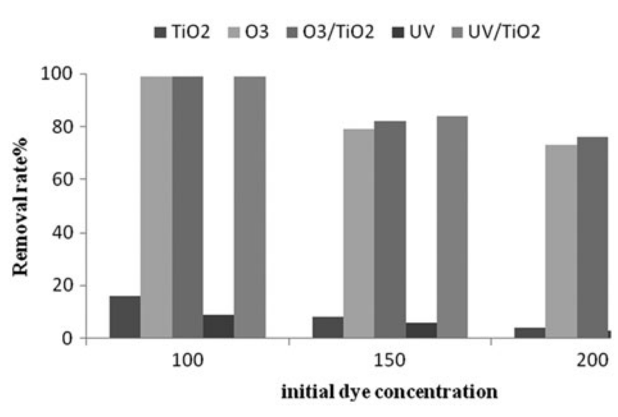

Fig. 5. Effect of initial concentration on the removal rate of reactive dye 198 in various studied processes.

4. Discussion and conclusion

The results indicate a relatively rapid rate of dye removal during photocatalytic process. It can be due to the dye structure and chemical bonds available in its structure and show that energy of links available in dye has a relatively low stability and the oxidation conditions caused by the energy of the photons emitted from ultraviolet light on the surface of titanium dioxide has a good potential to fail these links and decompose the dye.

The results indicated that pH has a significant effect on dye removal. These effects on decomposition of dye can be related to the pH of the environment on the surface characteristics of titanium dioxide nanoparticles and ionization conditions of the pollutant.

Increasing pH within 4–10 reduces dye removal in photocatalytic processes. This phenomenon could be due to the effect of these factors on the electrical charge change dominant on the surface of titanium dioxide. Since pH_{ZPC} of the titanium dioxide of this study was in the range of 6.3, we can conclude that in pH values such as 4, the available electrical charge on TiO_2 surface is positive and thus the absorption of this pollutant at TiO_2 surface is higher. Since the hydroxyl free radical is produced by stimulating the titanium dioxide surface, more absorption of pollutant on its surface causes the radicals produced on TiO_2 surface to affect the dye molecules faster and remove them.

Such results have also been reported by other researchers [17]. Other researchers who studied the effect of pH on removal of reactive red 198 dye concluded that increasing pH from 4 to 10 reduces the efficiency of dye removal from 98 to 35% that it is corresponded with the results of this study. The researchers attributed the high efficiency under acidic conditions to the effect of pH on the situation of surface charge of particles of titanium dioxide.

Ozone eliminates organic materials in water through a direct reaction mechanism (molecular ozone effects on specific functional groups from pollutants) and indirect reaction mechanism (decomposition of ozone and hydroxyl radical production) [23]. Molecular ozone reactions with organic materials

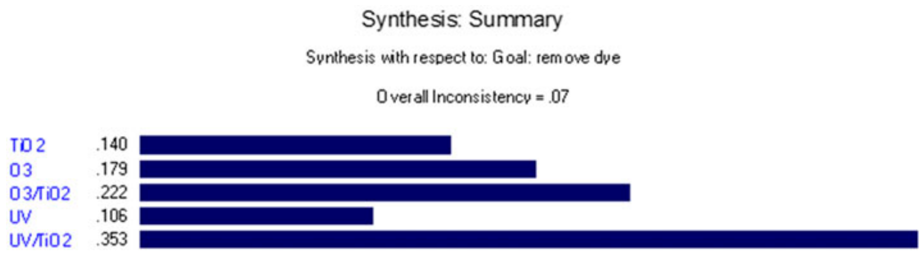

Fig. 6. Prioritizing the choices for dye removal.

Table 1
Weight of indicators and the criteria to select the best process for the removal of RR198 dye

Criteria	Weight of criteria	Indicators	Weight of indicators
Removal rate	0.722	Contact time	0.297
		PH	0.163
		Initial concentration of dye	0.540
Cost	0.184	Initial cost	0.20
		Operation and maintenance cost	0.80
Required expertise	0.094	–	–

often lead to the formation of aldehydes and carboxylic acids which do not react with ozone any more. One of the major limitations in the use of ozone is that it is not able to mineralize the organic materials perfectly. Ozone decomposition in water completely depends on pH and is accelerated by increasing it. Ozone in alkaline conditions were converted into hydroxyl radicals more easily than in acidic conditions because hydroxide ions trigger a chain reaction of ozone decomposition and produce hydroxyl radicals [30,31]. The efficiency of organic matter decomposition in alkaline pH ($pH > 10$) is relatively like the elimination rate in the catalytic ozonation. However, according to the results of current study, it seems that O_3 does not stimulate TiO_2 significantly and does not produce hydroxyl radicals. That's why the results of dye decomposition in the ozonation process and integration process of O_3/TiO_2 are close to each other.

The general results of this study using the model of AHP mention that the advanced oxidation process (TiO_2/UV-C) is more appropriate than other studied processes because of creating synergistic effect in decomposing reactive red 198 dye. This effect is due to the production of hydroxyl free radicals ($OH^{\bullet}$) that degrades and oxidizes a wide range of pollutants quickly and in a nonselective manner. Given the favorable results of photocatalytic decomposition process of TiO_2/UV-C in the removal of reactive red 198 dye, it can be stated that the efficiency of the process for removing other dyes and pollutants should be examined to determine its potential use for the treatment of wastewaters containing different dye pollutants.

Results indicated that this model can be a useful and suitable tool for policy-makers and decision-makers to choose the best treatment process in different conditions.

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