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A comparative study of photocatalytic degradation of airborne styrene using TiO2 and ZnO nanoparticles immobilized on activated carbon

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Abstract

Background: With the growth of industries and advancing civilization, controlling air pollution from both human and natural sources has become a major concern. Styrene, a volatile organic compound (VOC), is recognized as a hazardous and toxic atmospheric contaminant.

Methods: In this study, the removal of Styrene vapors using ZnO and TiO_2 nanoparticles coated on activated carbon (AC) was investigated and the styrene removal capacity of AC-ZnO and AC-TiO_2 catalysts was compared. The coated adsorbents were characterized using a field emission scanning electron microscope (FESEM), X-ray diffraction patterns (XRD), and the Brunauer–Emmett–Teller (BET) method. All laboratory-scale experiments were conducted at ambient temperatures. Styrene concentrations of 50, 100, and 300 ppm were tested at an input flow rate of 0.03, and 0.06 m^3/h.

Results: The AC-TiO_2 catalyst had a styrene removal efficiency (RE) of 81%, as compared to 74% efficiency for the AC-ZnO catalyst, this is at a flow rate of 0.06 m^3/h and a concentration of 50 ppm. The results indicated that increasing styrene concentrations reduced breakthrough time but increased adsorption capacity. Also, by increasing the inflow rate, the adsorption capacity decreased. At all concentrations and flow rates, the adsorption capacity of the AC-TiO_2 catalyst was higher than the AC-ZnO catalyst.

Conclusion: According to the results, it can be concluded that the AC-TiO_2 catalyst is more effective in the removal of Styrene vapor from the air as compared to the AC-ZnO catalyst.

Keywords: Charcoal, Titanium dioxide, Zinc oxide, Photocatalyst, Styrene

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Introduction

Over the past 50 years, industrialization and urbanization have caused serious air pollution, posing significant threats to human health and contributing to climate change (1). Air pollution from volatile organic compounds (VOCs) has recently become a significant environmental concern (2-4). The World Health Organization (WHO) categorizes VOCs as substances with a boiling point of less than 205°C. These compounds are released into the atmosphere from various anthropogenic and biogenic activities. These substances have the power to harm the neurological system and to excite the respiratory system (5). In the process of making polystyrene, which is used extensively in the manufacture of rubber and plastics, styrene monomer (C6H5CH = CH2), a volatile organic chemical is frequently released into the air at work, endangering the health of hundreds of workers (6,7). Proper control of these compounds is becoming increasingly crucial as emission standards are improved to ensure a higher quality of air.

Varieties of technologies are commonly used for the treatment of air pollution with VOCs, such as adsorption by a membrane, activated carbon (AC), separation, catalytic thermal oxidation, and photocatalytic degradation. The photocatalytic oxidation process is an advanced oxidation technology that is one of the most effective methods for removing organic contaminants in the gas and water phases. This method has great potential for environmental

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remediation. As a part of the photocatalytic degradation process, semiconductors are activated by UV or suitable visible light radiation, and hydroxyl radicals are formed and oxidized. Heterogeneous photocatalysts, such as ZnO or TiO_2, have been employed in this technique to effectively degrade organic contaminants, serving as a suitable substitute for other removal processes (8,9). This method has several advantages compared to the classical chemical oxidation process (10,11). TiO_2 and ZnO nanoparticles have received much attention in recent years due to their various applications in the photocatalytic degradation of organic pollutants (12,13). Some researchers suggest that to increase the effectiveness of the removal process, certain catalysts should be combined with adsorbent materials such as AC, zeolites, clay, metal ions, etc. Applying a combination of adsorbents and photocatalysts to design an efficient photocatalytic system is intensively studied (14-16). Stabilization of semiconductors on a proper substrate due to increasing charge separation, the increasing lifetime of charge carriers, increasing transfer of load surface in terms of the adsorbent substrates, and reducing cost may induce removal of contaminants from the atmosphere, and subsequently, improve air quality. To effectively remove diluted organic pollutants, photocatalytic degradation relies on the adsorption and enrichment of organic pollutants surrounding TiO_2 and ZnO nanoparticles from air and water (17,18).

Among different adsorbent candidates, AC is most widely used because of its high specific surface area and well-developed porous structure. This creates an attractive force toward organic molecules (19,20), raising photocatalyst adsorption capacity through the photocatalytic reaction between nanoparticles and pollutants. Many studies have used AC as a photocatalyst substrate (21-23). AC used as an adsorber is only able to transfer from the gas phase to the solid phase, and thus, cannot remove pollutants completely. This limitation can be overcome by immobilizing nanoparticles on AC in conjunction with UV irradiation (23). Kuo et al investigated the photocatalytic degradation of toluene using several adsorbent beds, and the results showed a performance improvement of 130%-137% using TiO_2 immobilized on AC as compared to using AC alone (22).

Although ZnO and TiO_2 have nearly the same band gap energy, various studies have different opinions on the photocatalytic removal efficiency (RE) of TiO_2 and ZnO nanoparticles. Most studies have shown higher photocatalytic activity of TiO_2 (13,21), and several studies have reported higher RE of ZnO compared to TiO_2 under certain operating conditions (24,25). Therefore, this study investigated the photocatalytic RE of styrene as an example of VOCs by these nanoparticles under similar conditions, which are separately immobilized on activated carbon (AC-TiO_2 and AC-ZnO). Also, the effect of different variables including gas inlet load (50, 100, and 300 ppm), UV irradiation, and gas flow rate (0.03, and 0.06 m^3/h) in the removal of styrene was investigated. Finally, this research attempted to introduce the most appropriate catalyst for removing styrene.

Materials and Methods

Materials

For this study, AC (particle diameter of 0.5-1 mm and a specific surface area of 735.6 m^2/g) and styrene (analytical grade ≥ 99% purity) were purchased from Merck Company, Germany. The nano-sized ZnO and TiO_2 components in this study were purchased from Sigma Aldrich, USA, with an average size of 20 - 40 nm and a specific surface area of 45 and 50 m^2/g, respectively.

Catalyst preparation

The wet insemination technique (WIT) was used to stabilize nanoparticles on the surface of AC at an optimal concentration of 12 wt.%. To prepare 10 g of AC-TiO_2 catalyst, 1.2 g of TiO_2 nanoparticles were added to 50 ml of distilled water and the suspension was stirred for 15 minutes in a mixer. The suspension was then placed in an ultrasonic bath (Starsonic, Italy) at 50 kHz frequency for 30 minutes until TiO_2 nanoparticles were separated from each other completely and a uniform suspension was created. Then, 8.8 g of AC was added to the suspension and placed in an incubator for 24 hours at a temperature of 37 °C and stirred at 150 rpm until the AC was covered with nano-TiO_2. The prepared catalyst was then placed in an oven for 2 hours at a temperature of 300°C to thermally fix the sample. The same process was applied to the AC-ZnO catalyst.

Samples characterization

X-ray diffraction (XRD) analysis was performed using an X-PERT PRO MPD instrument, and Cu-Kα radiation (40 kV and 40 mA) was used to identify the crystal phases of the sorption media. The XRD patterns were obtained at a variable rotation of 1.5 A° in the angular measurement range of 2 to 80° 2θ with an accuracy of 0.02° at 0.5 s/step. The specific surface area and pore distribution of the samples were measured by N_2 adsorption using a micro-metrics Brunauer–Emmett–Teller (BET) method (Quantachrome Chem BET). The morphology of the samples was characterized using a field emission scanning electron microscope (FESEM) by MIRA3 TESCAN-XMU device at 15kV (TSCAN, USA).

Experiment set-up

The experimental setup is shown in Figure 1. A dynamic photoreactor system was applied to provide a continuous gas stream containing styrene in the desired concentrations. It can be divided into three sections: (a) Input, (b) removal or adsorption, (c) sampling.

In this system, the air was pumped using a 51 W air

pump (Hitachi Ltd, Japan) at a pressure of 11.147 mm Hg and passed through a container filled with AC and silica gel to control humidity in the system. Styrene stream was produced for the system with an initial concentration of 50, 100, or 300 mg/L at flow rates of 0.03 or 0.06 m^3/h.

Photocatalytic degradation was done in a reactor containing photocatalyst beds. One of the most important parameters in the design of the reactors is the particle diameter. A cylindrical quartz glass reactor with 280, 20, and 2 mm in length, diameter, and thickness, respectively, was employed for UV irradiation (Figure 1). In this cylindrical reactor, an inlet and outlet were improvised at a distance of 2 cm from both ends of the cylinder in opposite directions. This cylinder was equipped with an 8 W UV lamp at the center and three 6 W UV lamps outside the cylinder. According to other studies, nanoparticles of TiO_2 and ZnO have the highest photocatalytic function in the presence of UVA light at a wavelength of 356 nm (26). The photocatalyst beds (5 g) (i.e., AC-ZnO, AC-TiO_2) were placed within the reactor and around the inner lamp. The reactor was covered with aluminum foil to protect our system from ambient light exposure. After flowing gas through the system, gas sampling was conducted at the inlet and outlet of the reactor with a time interval of 5 min using a portable photoionization detector (Phocheck Tiger, model 5000, Ion Science Ltd., UK). For more accuracy, the concentration of samples was also measured by a gas chromatographer (Philips PU4410) equipped with a flame ionization detector. All the experiments and sampling were conducted three times. It must be noted that flow rates, temperatures, relative humidity, and styrene concentrations were monitored and controlled by software specially designed by the author. The RE was calculated using Eq. (1):

$$RE = \left(\frac{C_i - C_o}{C_i}\right) \times 100 \quad (1)$$

Where *Ci* is inlet gas concentration (ppm) and *Co* is outlet gas concentration (ppm).

Results

AC-ZnO and AC-TiO_2 characterization

The results of the measuring surface properties of the catalysts are shown in Table 1. The results showed that the specific surface area of AC-ZnO (693 m^2/g) and AC-TiO_2 (686 m^2/g) decreased after nanoparticles immobilization on AC (735.6 m^2/g). Also, a decrease was found in the total pore volume of the AC (0.990 cm^3/g) after coating -ZnO (0.3562 cm^3/g) or TiO_2 (0.3407 cm^3/g).

Figure 2 shows FE-SEM images of the catalysts before and after nanoparticle loading. FE-SEM results showed successful immobilization of ZnO and TiO_2 nanoparticles, characterized by spherical shapes and irregular aggregations, on the AC. The distribution of nanoparticles on the AC surface is effective in the photocatalytic degradation process.

zhe XRD patterns of the catalysts are shown in Figure 3. XRD analysis showed that loading the crystal of ZnO and TiO_2 on AC was successful. The XRD patterns of the AC-ZnO showed sharp induced peaks, which are related to ZnO nanoparticles having Wurtzite hexagonal structures. The diffraction peaks of ZnO indeed appeared at $2\theta = 31.6^\circ$, 34.26°, 36.1°, 47.37°, 56.3°, 62.6°, 67.72°, and 69.2°. Also, peaks were observed for the AC-TiO_2 catalyst, which are related to anatase and rutile crystals at $2\theta = 25.2^\circ$, 29.9°, 36.3°, 37.7°, 47.7°, 54.16°, and 62.5°. Although the highest weight percent samples were related to AC, no peak

Table 1. Surface area and total pore volume of prepared catalysts

Parameter	Catalyst	
	AC-ZnO	AC-TiO_2
S_{BET} (m^2/g)	693	686
Total pore volume (P/P0 = 0.990) (cm^3/g)	0.3562	0.3407

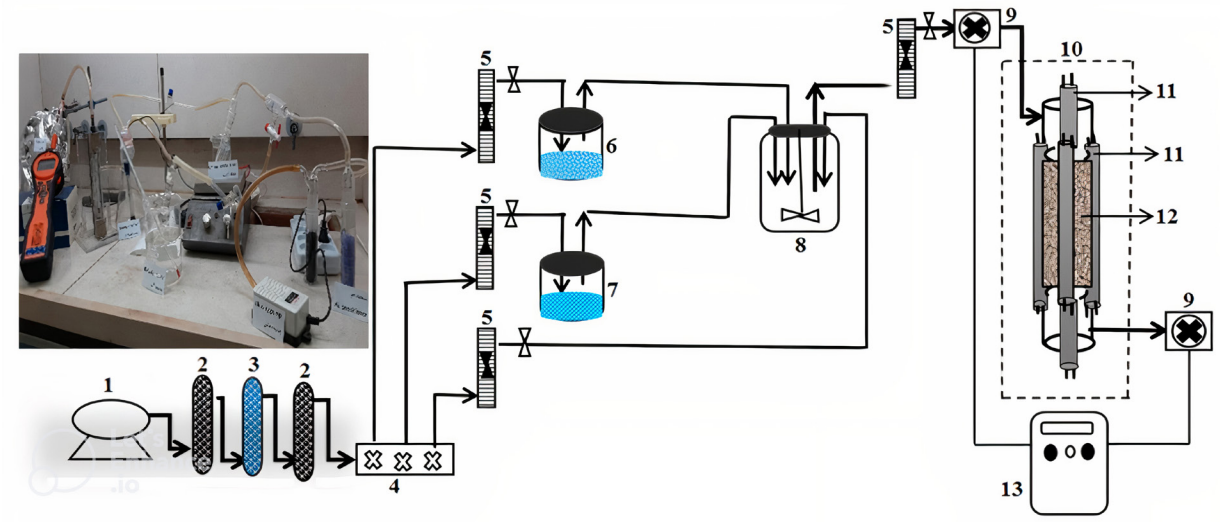


Figure 1. Experimental schematics consisting of (1) air pump, (2) active carbon, (3) silica gel, (4) branch wall boxes, (5) rotameter, (6) styrene container, (7) water container, (8) mixing tank, (9) sampling port, (10) photocatalytic reactor, (11) UV lamps, (12) catalyst, (13) analyzer

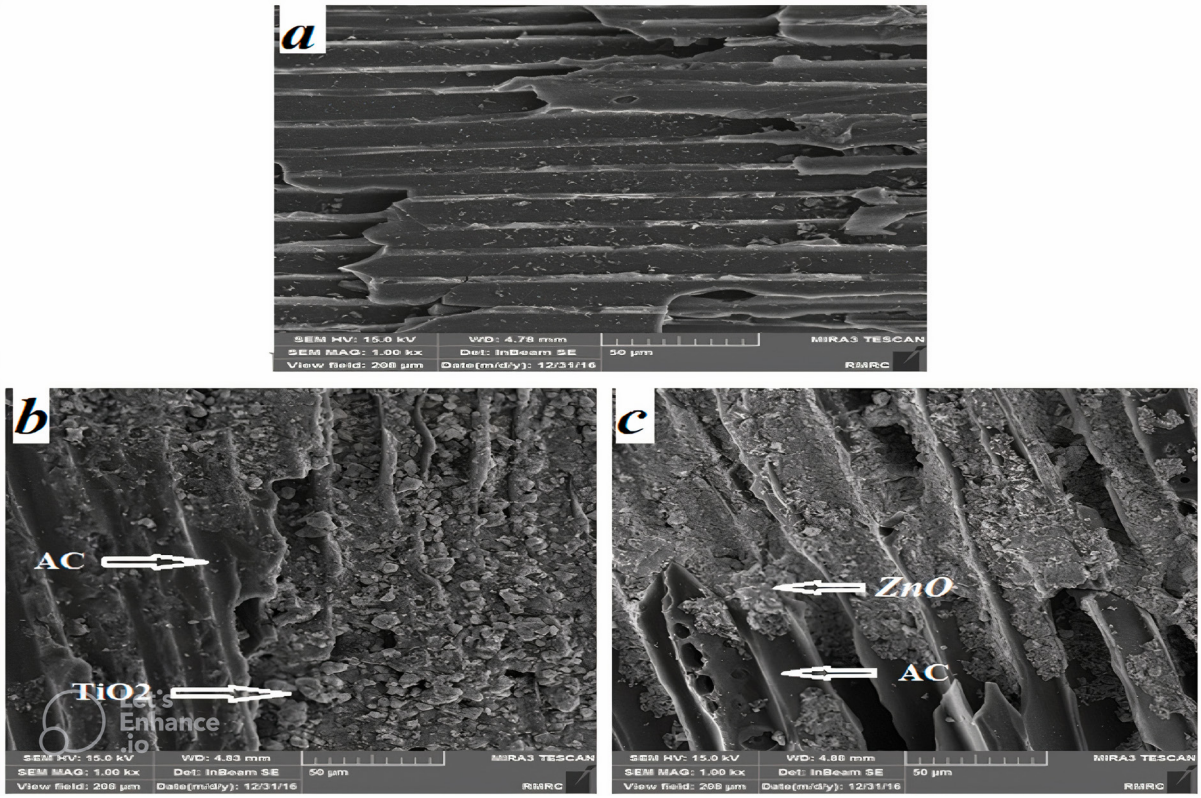


Figure 2. FE-SEM images (a) AC; (b) AC-TiO_2; (c) AC-ZnO

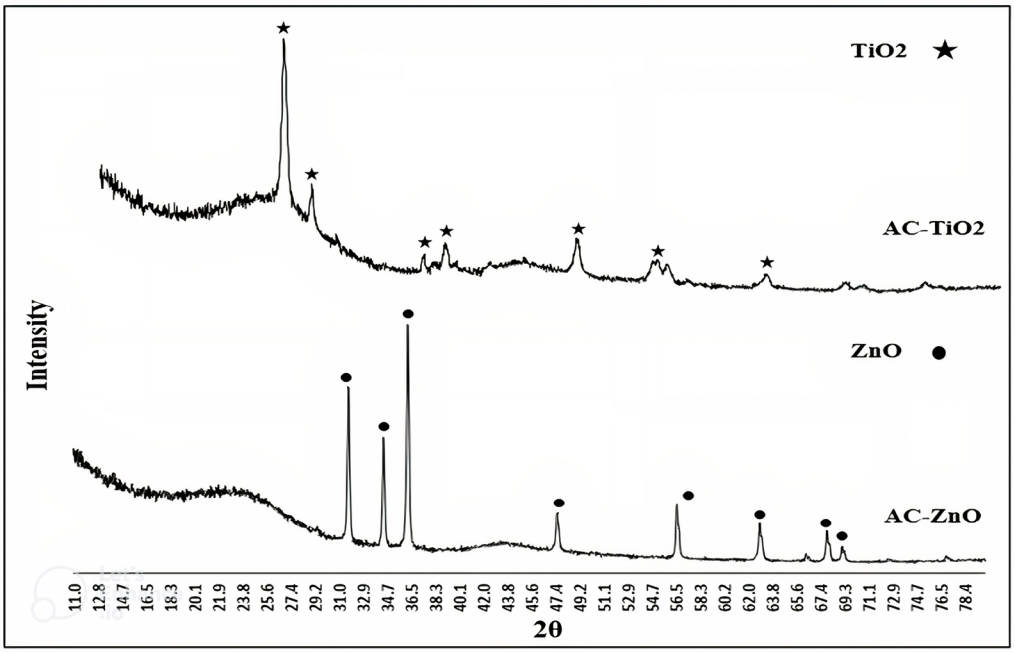


Figure 3. XRD pattern of AC coated with TiO_2 and ZnO

was observed for AC due to the lack of any crystalline structures.

The removal efficiency of styrene using the prepared coated adsorbents

Blank tests on the removal of Styrene vapors were conducted first. The photochemical reaction was tested in the absence of any catalyst. The blank test results indicated that no photochemical reaction under UV irradiation occurs in the absence of a catalyst; for this reason, the results are not shown. The photocatalytic degradation of Styrene vapors was carried out in the continuous flow photoreactor system under UV irradiation at ambient temperatures.

Figure 4 shows the RE of styrene using the AC-ZnO and AC-TiO_2 catalysts under different conditions. The styrene RE of the AC-TiO_2 catalyst was higher than the AC-ZnO catalyst at all concentrations and at all flow rates.

At a flow rate of 0.03 m^3/h and a concentration of 50 ppm, styrene RE was higher for TiO_2 coated by AC (81%) as compared to ZnO coated by AC.

Effect concentration on removal efficiency of styrene

To investigate the effect of gas concentrations on the RE of styrene, the initial concentrations of 50, 100, and 300 ppm were considered for a constant flow rate of 0.03 m^3/h. Figure 5 shows the process of photocatalytic removal of styrene in the reactor using the AC-ZnO and AC-TiO_2 catalysts under UV light irradiation. When the concentration of styrene increased from 50 to 300 ppm, the RE decreased from 74% to 33.5% for AC-ZnO and from 81% to 34.5% for AC-TiO_2 (gas flow rate: 0.03 m^3/h), respectively.

Effect of flow rate on removal efficiency of styrene

The effect of the gas flow rate was investigated on the gas vapor removal using AC-ZnO and AC-TiO_2. As shown in Figure 5, the RE of styrene decreased with increasing gas flow rate, while gas removal occurred faster under a high flow rate. When the gas flow rate of styrene increased from 0.03 to 0.06 m^3/h, the RE decreased from 74% to 57.5% for AC-ZnO and from 81% to 63% for AC-TiO_2 (inlet concentration: 50 ppm), respectively.

Adsorption capacity

To determine the performance of catalysts, the adsorption capacity of each catalyst was calculated. The adsorption capacity of the catalyst to the breakthrough point was obtained using Eq. (2):

$$BC = \frac{Q.C.Tbk}{M\ adsorbent} \quad (2)$$

Where BC is the mass of Styrene adsorbed by the substrate (mg/g), Q is the inflow discharge of the reactor (m^3/h), C is Styrene concentration (mg/m^3), and Tbk is the breakthrough time (h):

Breakthrough point and adsorption capacities for the AC-ZnO and AC-TiO_2 catalysts under various experimental conditions are presented in Figure 5 and Table 2. As can be seen in Table 2, Figure 5, and Eq. (2), the breakthrough time increased from 11 hours and 45 minutes to 23 hours and 45 minutes with a decrease in flow rate from 0.06 to 0.03 m^3/h in the case of AC-ZnO at the same inlet concentration of 50 ppm. Also, the breakthrough time increased from 12 hours and 15 minutes to 24 hours and 50 minutes for AC-TiO_2 at the same condition.

Also, the results of adsorption capacity (mg/g) show that with increasing concentration, the adsorption capacity increases in all catalysts. As shown in Table 2, when the concentration of styrene increased from 50 to 300 ppm, the adsorption capacity increased from 75.767 to 98.882 mg/g for AC-ZnO and from 79.223 to 102.085 mg/g for

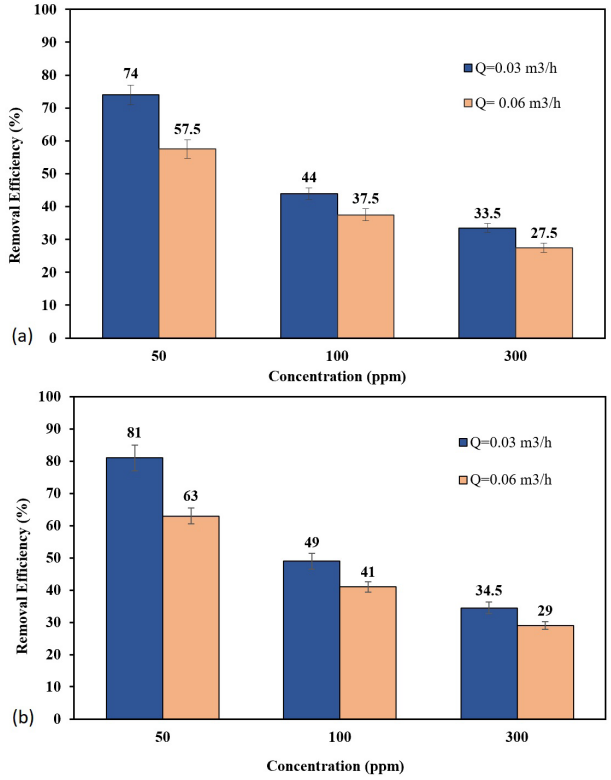


Figure 4. Styrene removal efficiency of (a) AC-ZnO and (b) AC-TiO_2

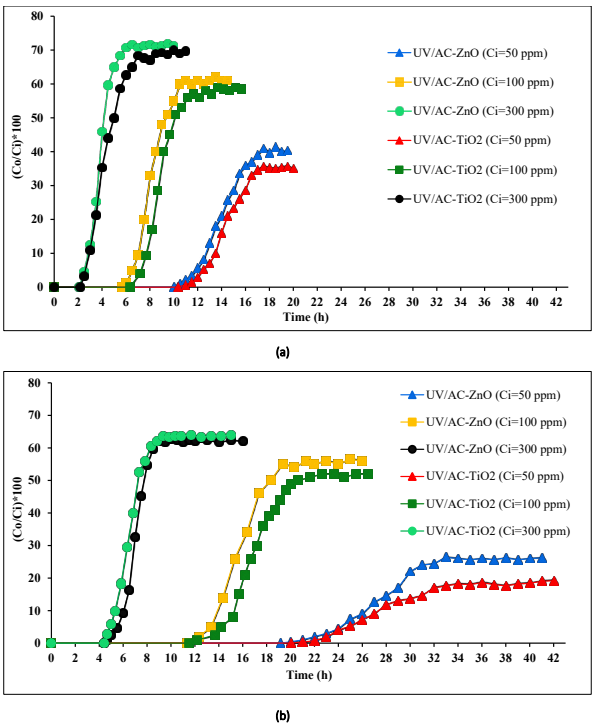


Figure 5. Comparison of the Styrene removal efficiencies of the AC-ZnO and AC-TiO_2 catalysts at different concentrations (a) Q = 0.06 m^3/h, (b) Q = 0.03 m^3/h (Ci: inlet gas concentration and Co: outlet gas concentration)

Table 2. Adsorption capacity and breakthrough time of the two catalysts under different conditions

Catalyst	Flow rate (m^3/h)	Concentration (ppm)	Breakthrough point (h:min)	Adsorption capacity (mg/g)
AC-ZnO	0.03	50	23:45	75.767
		100	13:20	85.072
		300	5:10	98.882
	0.06	50	11:45	74.969
		100	6:30	82.945
		300	2:30	95.705
AC-TiO_2	0.03	50	24:50	79.223
		100	14:10	90.34
		300	5:20	102.085
	0.06	50	12:15	78.159
		100	7:10	91.452
		300	2:10	98.895

AC-TiO_2 (gas flow rate: 0.03 m^3/h), respectively.

Discussion

In this study, AC-ZnO and AC-TiO_2 catalysts were prepared with 12 wt% of ZnO and TiO_2 nanoparticles, respectively. The results of the BET test, XRD patterns, and FE-SEM images of the catalysts are proof of a successful loading nanoparticle. The results showed that the specific surface area of AC decreased after coating ZnO or TiO_2. The main reason for this decline is attributed to the occupation of meso/micro-pores of AC by nanoparticles (ZnO or TiO_2), which has also decreased the total volume of the pores after surface modification with nanoparticles (27,28). Indeed, the specific surface area of a sorption media plays a critical role in its sorption efficiency. This decrease in the specific surface area of the AC-ZnO or AC-TiO_2 can be compensated with the stimulated surface for catalytic and redox reactions, and better electron transport properties after coating AC with nanoparticles of ZnO or TiO_2 (29-31).

The results show that the largest difference in performance among the two photocatalysts (AC-ZnO and AC-TiO_2) was observed at a concentration of 50 ppm. Although the removal performance of the catalysts at a concentration of 300 ppm was low in numerical terms, this difference is statistically significant ($P<0.05$). This shows that active photocatalysis of TiO_2 was higher than ZnO under UVA irradiation. These results are consistent with the results of the study by Rangkooy et al (21). Also, Matos et al showed AC-TiO_2 samples to be more photoactive than AC-ZnO in the degradation of 2-propanol in a gas-solid regime (12).

Generally, styrene degradation mechanisms and degradation pathways by TiO_2 and ZnO are as follows:

$$\text{ZnO or } TiO_2 + h\nu \rightarrow h^+ + e^-$$

$$e^- + O_2 \rightarrow O_2\text{-}$$

$$h^+ + H_2O \rightarrow OH^* + H^+$$

$$h^+ + C_8H_8 \rightarrow CO_2 + \text{other product}$$

$$OH^* + C_8H_8 + O_2 \rightarrow nCO_2 + nH_2O + \text{non-toxic product}$$

These reactions indicate that when light is irradiated on nanoparticles, an electron (e^-) is excited from the valence band to the conduction band, and a positive hole (h^+) is created in the valence band. These electrons and positive holes, cause reduction and oxidation of the absorbed styrene on the photocatalyst surface, respectively. Also, the above-mentioned reactions indicate that the chemical degradation of styrene is carried out with the help of hydroxyl radicals (OH). This radical has been a strong oxidizing agent and is created from the oxidation of absorbed water or OH- on the surface of the photocatalyst. The created h^+can directly oxidize the styrene, and also, react with water to generate hydroxyl radicals. The electron in the conduction band can also lead to the reduction of absorbed oxygen on the surface of ZnO or TiO_2. Under optimized operating conditions, the styrene can be mineralized to CO_2, H_2O, and non-toxic products. Sometimes styrene can become by-products if total mineralization does not occur.

The reasons that may lead to the better photocatalytic activity of TiO_2 compared to ZnO include:

1. Electronic properties: Titanium dioxide typically has an electronic band gap that facilitates the utilization of visible light and provides the necessary energy to excite electrons. This enables TiO_2 to perform better in the presence of visible light.
2. Chemical stability: Titanium dioxide is generally more chemically stable than zinc oxide under photocatalytic conditions for long-term applications. This chemical stability can contribute to the improved performance and lifespan of TiO_2 photocatalyst compared to ZnO.
3. Performance in the light wavelength range: Titanium dioxide can absorb both visible and ultraviolet light

and utilize them effectively for photocatalytic activity, whereas zinc oxide often works more efficiently in the ultraviolet wavelength range. This higher efficiency in the visible light range can contribute to the better performance of TiO_2 compared to ZnO in the photocatalysis process.

In addition to the above-mentioned reasons, the main limitation of ZnO photocatalysts can be the fast recombination of photogenerated charges and photocorrosion (32).

One of the factors that affects the adsorption and photocatalytic degradation, is the inlet flow rate of pollutants. The results show that by increasing the inlet flow rate, photocatalytic degradation in both photocatalysts decreases. Generally, with an increase in flow rate, the pollutant has less opportunity for penetrating the catalyst, and therefore, the probability of its binding to the active site of the catalyst is decreased. This is because the nanoparticles, which are the agents of photocatalytic degradation, have less contact with pollutants, and thus, RE is diminished. Also, with increasing flow rates, the filtration air volume per unit of time increases, and subsequently, leads to the saturation of the catalyst in a shorter period (33). Chao et al showed that the reduction in flow rate leads to an increase in efficiency by 50% in the oxidation process for toluene removal (34).

One of the other factors that affects photocatalytic degradation, is the concentration of pollutants. The results show that in both catalysts, an increase in the initial concentration of styrene reduces effective removal. This may be due to several reasons:

a) As styrene concentration increases, the number of photons reaching the catalysts' surface is reduced because fewer molecules undergo excitation, lowering the rate at which the formation of holes occurs. Hydroxyl radicals and supra oxide ions (O^-) are thus decreased, diminishing the removal rate.

b) Since the catalyst's surface area is fixed, as styrene vapor concentration increases, the rate of removal decreases because a limited number of styrene molecules attach to the active site on the catalyst, and the remaining styrene molecules must wait until earlier attached molecules are degraded. The number of active sites of the catalyst also decreases due to less availability of photons for the excitation of catalyst molecules.

c) At higher concentrations, increasing the number of styrene molecules means that there will be more competition among the styrene molecules trying to attach themselves to active sites on the catalyst, subsequently, reducing the degradation rate. At all concentrations, AC-TiO_2 exhibited a higher activity rate than AC-ZnO.

Some studies have shown that increasing pollutant concentration also increases the reaction rate. A higher concentration level causes the adsorption of more styrene molecules on the photocatalyst surface. These molecules will block more active sites on the catalyst surface and reduce hydroxyl radical generation on the photocatalyst surface. It is observed that an increase in concentration also increases the ratio of available pollutant molecules to the number of active sites on the catalyst surface. This means that adsorption will happen faster due to higher propagation and penetration velocity within the pores of the catalyst. Thus, full saturation of active adsorption sites on the catalyst surface will occur in a shorter time (35-37).

The results of styrene breakthrough time and adsorption capacity (Table 2, Figure 5) show that the adsorption capacity and breakthrough time of AC-ZnO and AC-TiO_2 decreased with increasing flow rate from 0.03 to 0.06 m^3/h. The results of this study are consistent with those reported by Liu et al (33). By increasing the flow rate, the retention time decreases but the volume of filtered air per unit of time increases. This causes adsorption saturation to occur in a shorter time. Gangupomu et al reported that reducing the input pollutant concentration will increase breakthrough time (38). Studies show that increasing concentration causes a higher mass of pollutants per unit of time to be removed from the airflow reducing breakthrough time and saturation of the adsorbent (39,40). However, this also increases the ratio of pollutant molecules to the number of active sites on the catalyst surface, increasing the speed of propagation and penetration within the pores hastening adsorption, and shortening the time needed for full saturation of adsorption sites on the surface (41).

As shown in Figure 5, the sharpness of breakthrough curves of styrene adsorption is more upright for $Q_{styrene}$ of 0.03 m^3/h rather than $Q_{styrene}$ of 0.06 m^3/h. It can be justified that the residence time of styrene is higher at lower $Q_{styrene}$, consequently, the intra-particle diffusion and the external mass transfer will control the adsorption process. At higher $Q_{styrene}$ of 0.03 m^3/h, the adsorption capacity was lower because of the insufficient residence time of xylene. However, increasing inlet gas concentration led to an increase in the adsorption capacity (mg/g) of beds, but reduced the efficient time for degradation, thus, the RE was reduced.

Comparing the breakthrough time of both catalysts shows no significant difference ($P>0.05$). Comparing the adsorption capacity of these catalysts at various input styrene concentrations shows that the AC-TiO_2 had a higher adsorption capacity compared to the AC-ZnO catalyst (for inlet flow rates of 0.06 and 0.03 m^3/h). The greater styrene adsorption capacity of AC-TiO_2 surely plays a role in the photoactivity of TiO_2 nanoparticles.

In this study, various variables, such as humidity, type of light, wt% of nanoparticles, type of substrate, etc., were not investigated, therefore, future studies can address these variables as well. Also, future studies can address

the formation of by-products during the photocatalytic process of styrene degradation. To increase the efficiency of ZnO and TiO_2 photocatalysts in removing pollutants, three strategies should be considered: 1) stabilization on other functional substrates, (2) combination with other semiconductors, and (3) morphological changes.

Conclusion

The photocatalytic degradation of styrene occurred in the gas phase using ZnO and TiO_2 catalysts coated on AC at similar conditions. In general, the styrene RE of the AC-TiO_2 catalyst was higher than the AC-ZnO catalyst. The best styrene RE was obtained using the AC-TiO_2 catalyst at the lowest concentration and flow rate. So, it can be concluded that AC-TiO_2 photocatalyst is suitable for removing styrene at low concentrations and flow rates. Also, the adsorption capacity of AC-TiO_2 was higher than AC-ZnO under the same conditions. Styrene RE decreased by increasing the gas flow rate and concentration. Based on the results, both catalysts exhibit good photocatalytic performance in the decomposition of styrene in the gas phase under UV irradiation but the AC-TiO_2 catalyst had a better performance as compared to AC-ZnO.

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Funding acquisition: Mojtaba Nakhaeipour.
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Validation: Hosseinali Rangkooy, Farhad Forouharmajd.
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Writing–original draft: Mojtaba Nakhaeipour, Hasan Irvani.
Writing–review & editing: Hosseinali Rangkooy, Farhad Forouharmajd.

Competing interests

The authors declare no conflict of interests.

Ethical issues

This study was approved as a research project by the Ethics Committee of Isfahan University of Medical Sciences (Ethical code: IR.MUI.DHMT.REC.1402.062).

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