

Reduced Graphene Oxide-TiO₂ Nanocomposite Facilitated Visible Light Photodegradation of Gaseous Toluene

Reza Ahmadvani¹, Faezeh Izadpanah², Noushin Rastkari^{2*}

¹Department of Human Ecology, School of Public Health, Tehran University of Medical Sciences, Tehran, Iran

²Center for Air Pollution Research (CAPR), Institute for Environmental Research (IER), Tehran University of Medical Sciences, Tehran, Iran

Email: *nr_rastkari@yahoo.com

How to cite this paper: Ahmadvani, R., Izadpanah, F. and Rastkari, N. (2017) Reduced Graphene Oxide-TiO₂ Nanocomposite Facilitated Visible Light Photodegradation of Gaseous Toluene. *Journal of Environmental Protection*, 8, 591-602. <https://doi.org/10.4236/jep.2017.85039>

Received: April 5, 2017

Accepted: May 24, 2017

Published: May 27, 2017

Copyright © 2017 by authors and Scientific Research Publishing Inc. This work is licensed under the Creative Commons Attribution International License (CC BY 4.0).

<http://creativecommons.org/licenses/by/4.0/>



Open Access

Abstract

The photocatalytic degradation of gaseous toluene was investigated on TiO₂ nanoparticles coated on reduced graphene oxide. Reduced graphene oxide-TiO₂ composite (RGO-TiO₂) was synthesized via two step processes. The prepared RGO-TiO₂ composite was characterized using SEM, XRD, and UV-visible spectra. A significant increase in light absorption to visible light was observed by RGO-TiO₂ compared with that of pure TiO₂ nano particles. The photocatalytic degradation efficiency of the RGO-TiO₂ composite was much higher than that of the P25 TiO₂, 95% and 40% respectively. In our investigated conditions, the initial concentration, flow rate and relative humidity had significant influences on the photocatalytic degradation of gaseous toluene. The most efficiency was recorded at the 0.3 ppm concentration, 1L/min flow rate and 30% relative humidity. We believe that this TiO₂ based composite material can be effectively used as a highly active and stable photocatalyst to remove various indoor air pollutants especially gaseous toluene. The photocatalytic degradation efficiencies of toluene increased slowly below 20% relative humidity and then decreased as the relative humidity increased further. The main reason of enhanced photocatalytic property might be the strong electron transfer ability, and the increased adsorption capacity of RGO sheets in the composites as well as the retarded charge recombination rate contributed by the energy level of the two materials. We believe that this TiO₂ based composite material can be effectively used as a highly active and stable photocatalyst to remove various gaseous pollutants.

Keywords

Photocatalytic, RGO-TiO₂, Nano Particles

1. Introduction

Heterogeneous photocatalytic oxidation has been studied for several decades and shown to be an effective method for dealing with the environmental pollution problems, such as air cleanup, water disinfection, hazardous waste remediation, and water purification [1]-[7]. Among the many types of semiconductors, titanium dioxide (TiO_2) has been received lots of attention due to its high photocatalytic activity as well as the low cost and non-toxicity [8]-[14]. However, the photocatalytic performance of TiO_2 still restricted by the fast electro-hole pair recombination rate [15] [16]. In order to improve the photocatalytic performance of TiO_2 , many materials have been studied to couple with TiO_2 for suppressing the charge recombination rate. Recently, studies showed the introduction of carbon materials can effectively decrease the charge recombination rate, thus enhancing the photocatalytic performance of TiO_2 [17].

Among the carbon materials, graphene, a monolayer two-dimensional graphitic carbon system, has attracted much attention since it was isolated in 2004 [18]. The two-dimensional structure, large surface area, outstanding electronic and catalytic properties of graphene make it become a suitable candidate for incorporating with TiO_2 . For both graphene and reduced graphene oxide composites, the electrons in TiO_2 generated by photons can be moved across the carbon sheets, which reduce the recombination of photon-generated electron-holes [18]. These kinds of materials have a high adsorption capacity, which enhances the photocatalytic performance of TiO_2 nanoparticles [19].

Moreover, carbon derivatives also behave as impurities, leading to the generation of Ti-O-C bonds which extends light absorption to the visible range [20].

Several studies [21] [22] [23] have utilized RGO- TiO_2 composites for the degradation of water pollutants such as methylene blue, methyl orange, diphenhydramine and rhodamin B. However, to the best of our knowledge, no studies investigate application of RGO- TiO_2 composite to air pollutants. Air applications of such photocatalysts require a supporting material to prevent their blowing away with photocatalytically treated air. Therefore, in this research, a RGO- TiO_2 composite was synthesized using a chemical mixing process and its heterogeneous photocatalytic activity for the degradation of a toxic organic vapor (toluene) under visible-light irradiation was investigated using a cylindrical glass tube as a supporting material. The experiments were conducted under different operation conditions by varying the treatment airflow and initial concentration of toluene, which are two important parameters for photocatalytic processes of vaporous pollutants [24]. In addition, the photocatalytic activity of commercially available P25 TiO_2 was also evaluated.

The target compound, toluene, was chosen as the model VOC because of its prevalence in indoor air and toxic effect [25] [26].

2. Materials and Methods

2.1. Materials and Reagents

Graphite powder, tetrabutyltitanate, ammonium chloride, ammonium hydrox-

ide (28%), ascorbic acid, and 1-butyl-3-methylimidazolium hexafluorophosphate ([BMIM] [PF6]) were supplied by Sigma-Aldrich (St. Louis, MO, USA). All reagents were of analytical reagent grade and were used without further purification.

2.2. Synthesis of RGO-TiO₂ Composites

Graphite oxide was prepared through a modified Hummers method by the oxidation of graphite powder [27]. RGO-TiO₂ composite was prepared according to Shen *et al.* 2011 as described below [28].

Solution A: 850 mg of tetrabutyltitanate was added to a mixture of 1 mL of [BMIM] [PF6] and 9 mL of water. The above mixture was stirred for 2 h. Solution B: 100 mg of GO was added to 50 mL of water. The mixture was sonicated for 30 min followed by high-speed stirring for further 1 h. 100 mg of ascorbic acid and 1 mL of ammonium hydroxide solution was added to the GO solution. Subsequently, solutions A and B were mixed. The mixture was put into an autoclave and heated at 160°C for 4 h. When the reduction reaction was finished, the as-synthesized product (RGO-TiO₂) was isolated by centrifugation, washed several times with pure water and ethanol, and dried at 90°C for 12 h.

Prepared RGO-TiO₂ composite was characterized by scanning electron microscopy (SEM), X-ray diffraction (XRD), Fourier transforms infrared (FTIR) spectroscopy, ultraviolet (UV)—visible spectroscopy.

2.3. Performance Evaluation

The photocatalytic activities of prepared RGO-TiO₂ composite were investigated for degradation of gaseous toluene under different operational conditions using a glass tube reactor. The inner wall of the photocatalytic reactor was coated with a thin film of the RGO-TiO₂ composites. A visible light lamp was then inserted inside the glass tube, where it served as the inner surface of the annular reactor, through which the gas flowed. The temperature inside the photocatalytic reactor heated by the lamp ranged from 56°C - 63°C. Three major parameters, initial concentration (IC), flow rate (FR) and relative humidity were tested for their effects on the degradation efficiency of toluene. The range of FRs investigated ranged from 1 - 4 L·min⁻¹, and the ICs surveyed ranged from 0.1 - 1.0 ppm, which includes typical indoor air quality levels. Visible radiation was supplied by an 8-W fluorescent daylight lamp (F8T5DL, Sunlite Co.) with a full spectrum, and its intensity was measured using a Digital Lux Meter (51021, Yokogawa Co.). Time series of gas samples were collected at the inlet and outlet of the photocatalytic reactor before and after activating the lamp. Air samples were collected directly from rubber septum sampling ports using 10 mL Hamilton gas-tight syringes and were injected immediately into GC unit for analysis. Gaseous toluene was analyzed by using a Varian cp-3800 gas chromatograph (GC) equipped with a flame ionization detector. The quality assurance program for the measurement of gaseous compounds included laboratory blank and spiked samples.

3. Results and Discussion

3.1. Catalyst Characterization

The prepared RGO-TiO₂ composite was characterized using SEM, UV-visible, X-ray diffraction (XRD), and Fourier transforms infrared (FTIR) spectroscopy.

Figure 1 shows the SEM images and energy-dispersive X-ray (EDX) spectra of the RGO-TiO₂ composite.

The EDX spectra of the RGO-TiO₂ composite contained peaks corresponding to the Ti, Pt, O, and C atoms, the peaks of Ti and O atoms were likely associated with TiO₂, while the C atom peak may have been related to RGO. The Pt peaks were likely due to Pt coating of the samples for SEM analysis. The UV-visible absorbance spectra of RGO-TiO₂ composite and the P25 TiO₂ powder are shown in **Figure 2**. The P25 TiO₂ revealed an absorption edge around 410 nm, which

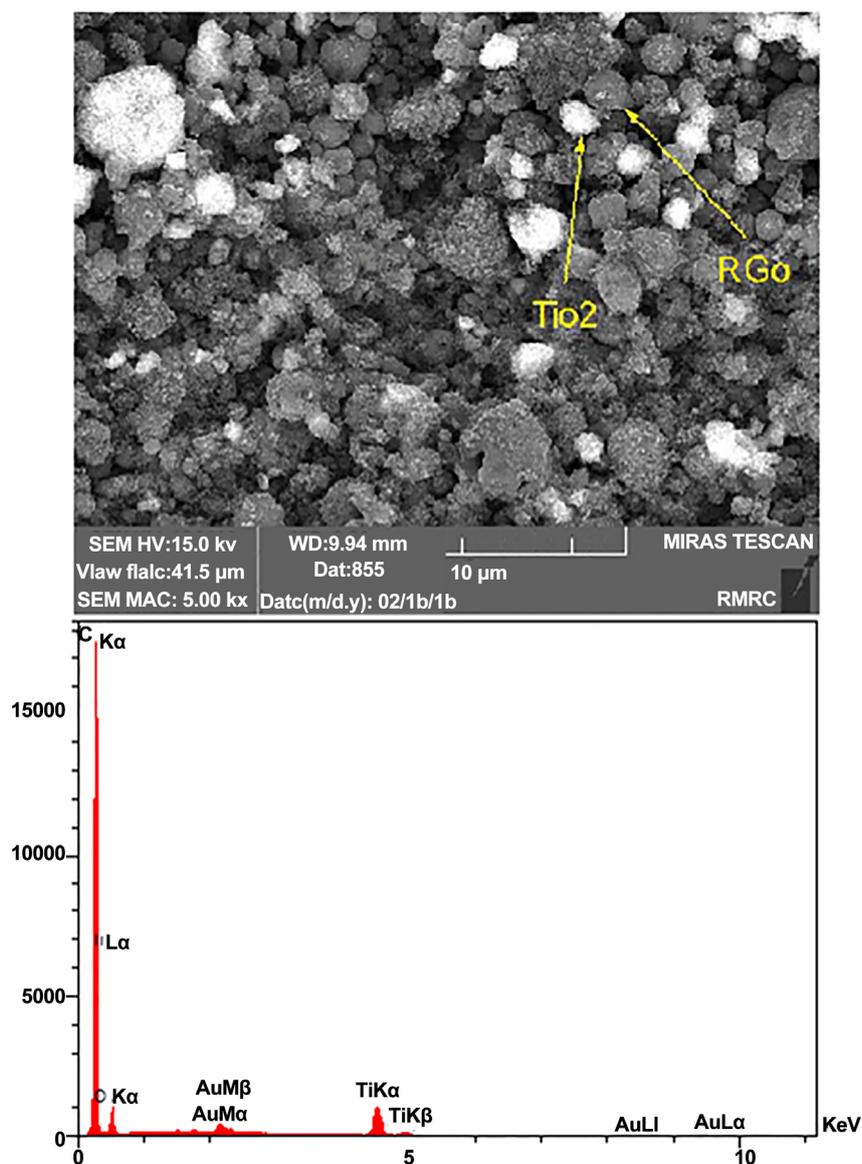


Figure 1. Scanning electron microscopy of RGO-TiO₂ composite.

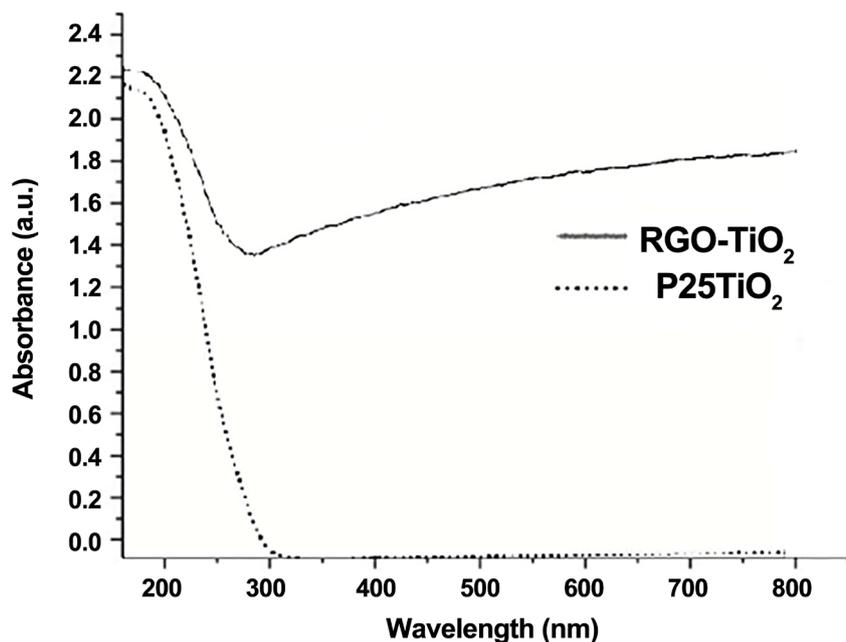


Figure 2. UV-visible absorption spectra of RGO-TiO₂ composite and P25 TiO₂ powder.

was similar to that reported in previous studies [29] [30]. However, a substantial shift in the absorbance spectrum toward the visible region was observed for the RGO-TiO₂ composite, which was in good agreement with the results of previous studies [29] [31]. The light absorption edge for the RGO-TiO₂ composite was shifted to larger than 800 nm, which was ascribed to the interaction of RGO with TiO₂. These findings indicated that the RGO-TiO₂ composite could function effectively under visible-light irradiation. FTIR is a convenient tool to identify chemical bonds in complex composite materials. The representative absorption peaks of GO (Figure 3), including those at 3400 cm⁻¹ (O-H stretching vibration), 1720 cm⁻¹ (C = O stretching vibration of COOH groups), 1390 cm⁻¹ (tertiary C-OH stretching vibration), and 1052 cm⁻¹ (C-O stretching vibration), decreased dramatically in intensity or even disappeared after hydrothermal preparation, indicating that the oxygen-containing functional groups in GO were decomposed in the hydrothermal environment [32]. In the spectrum of RGO-TiO₂, band at 3250 cm⁻¹ is due to O-H stretching, which means that the TiO₂ nanocrystal will easily absorb water in air. XRD was used to further study the changes in structure. Figure 4 shows powder XRD patterns of raw graphite, GO, RGO, and RGO-TiO₂. For the RGO-TiO₂ sample, the (002) reflection peak was broad and was centered at around 25 degrees.

3.2. Photocatalytic Decomposition

As shown in Figure 5, the photocatalytic degradation efficiency (PDE) of the RGO-TiO₂ composite was much higher than that of the P25 TiO₂. The degrading possible deactivation, even the time period was short (4 h). This finding is a confirmation that the photocatalytic efficiency of the TiO₂ is too low and decreased gradually over the 4h, in dis-

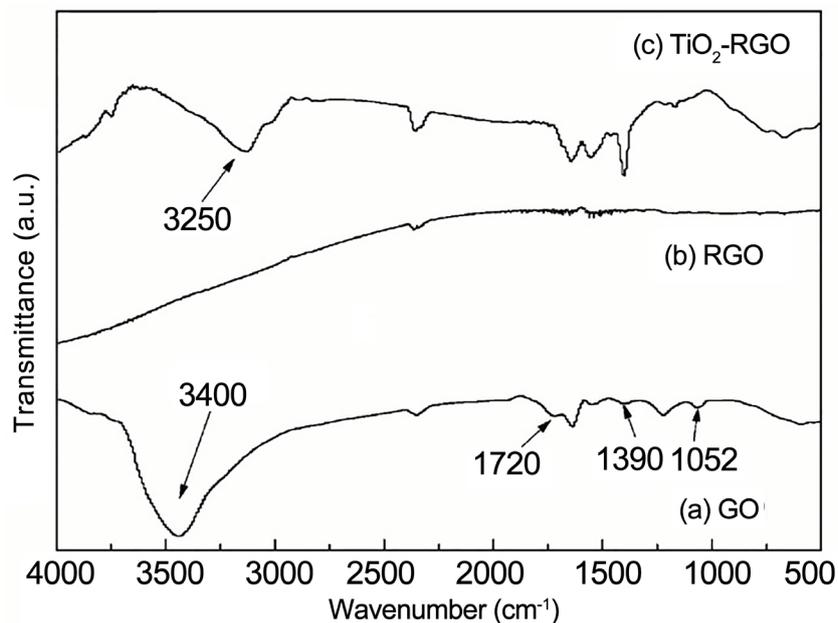


Figure 3. FTIR spectra of GO, RGO and RGO- TiO_2 composite.

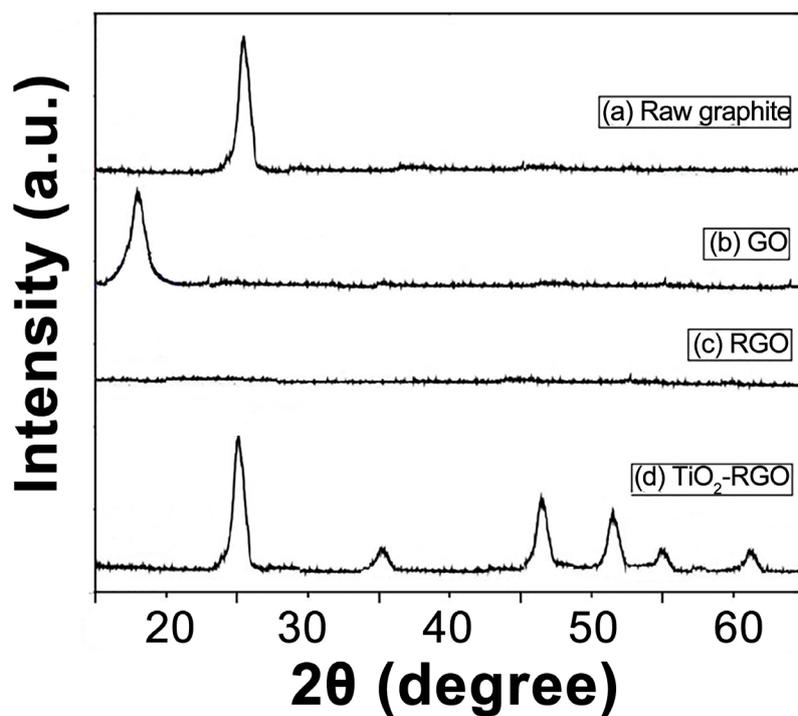


Figure 4. XRD pattern of raw graphite, GO, RGO and RGO- TiO_2 composite.

milar to other researchers results that the photocatalytic activity of TiO_2 decreases dramatically after only a few minutes irradiation [33] [34]. In this study, it was found that photocatalytic activity of the RGO- TiO_2 composite was higher than TiO_2 powder and this improvement may be attributed to the unique structure of GO sheets in the composite. GO likely acts as an excellent support for adsorption of toluene, enhancing the photocatalytic activity of the RGO- TiO_2

composite. GO like other carbon derivatives, has a photosensitizing nature that extends the light absorbance into the visible range, causing the RGO-TiO₂ composite to be activated by visible-light irradiation.

3.3. Effect of Initial Concentration

In order to discuss the effect of VOCs initial concentration (IC) on photo-catalytic degradation rates, we studied the removal efficiency of toluene under different initial concentrations. The toluene concentrations in the experiment ranged between 0.1 - 1 ppm. The conditions were as follow: gas flow-rate of 1 L/min, relative humidity of 30%, RGO-TiO₂ as photo-catalyst, and irradiation time of 4 hr. The results showed that the photo-catalytic degradation rates decreased with increasing toluene initial concentration more than 0.3 ppm, just shown in **Figure 6**. Based on the Langmuir-Hinshelwood model, which is most commonly used to link the photocatalytic degradation reaction rate of VOCs to their ICs [35], the reaction rate decreased with increasing initial concentration while the absolute amount of degraded pollutants may increase. These findings

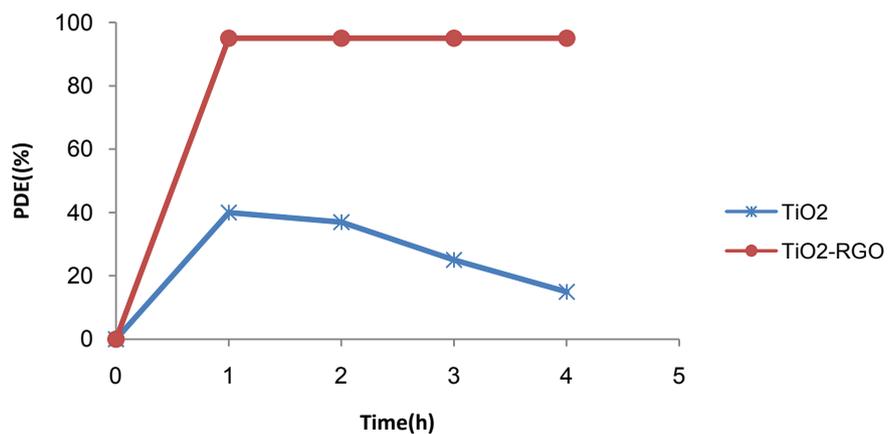


Figure 5. Photocatalytic degradation efficiency (PDE, %) of toluene determined using RGO-TiO₂ composite and P25 TiO₂ powder under visible-light irradiation.

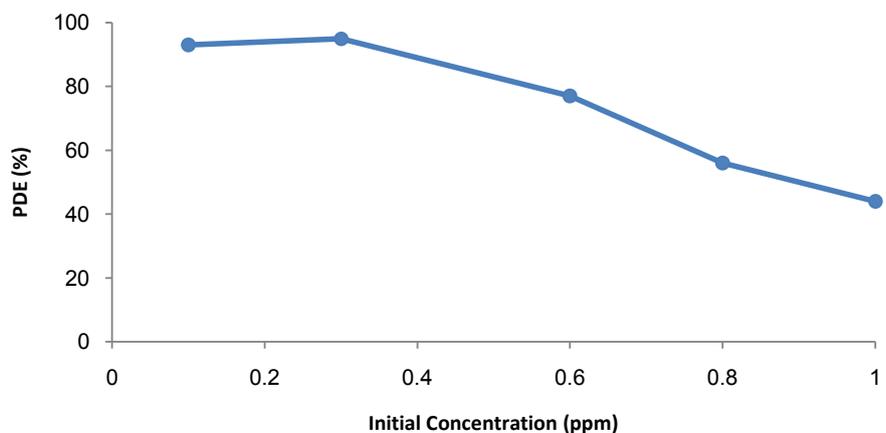


Figure 6. Photocatalytic degradation efficiency (PDE, %) of toluene determined using RGO-TiO₂ composite under visible-light irradiation according to initial concentration.

are consistent with those reported in other researches [36] that used undoped TiO₂ under UV irradiation. The IC dependence was ascribed to adsorptive competition between toluene molecules for the active adsorption sites on the surface of the RGO-TiO₂ composite. Regarding higher ICs, the active adsorption sites on the photocatalyst surface might be more limited for adsorption of toluene molecules.

3.4. Effect of Gas Flow Rate

The effect of gas flow rate (FR) on toluene degradation reaction was investigated at an initial concentration of 0.3 ppm and relative humidity of 30 %, just as illustrated in **Figure 7**. When the flow rate was increased from 1 - 4 L/min, degradation rate of toluene decreased. With a flow rate >1 L/min the reactants have shorter residence time on the photocatalyst surface and consequently do not bind to the active sites. In general, an increase in gas flow rate probably results in two antagonistic effects. These are a decrease in residence time within the photocatalytic reactor, and an increase in the mass transfer rate. Therefore, these

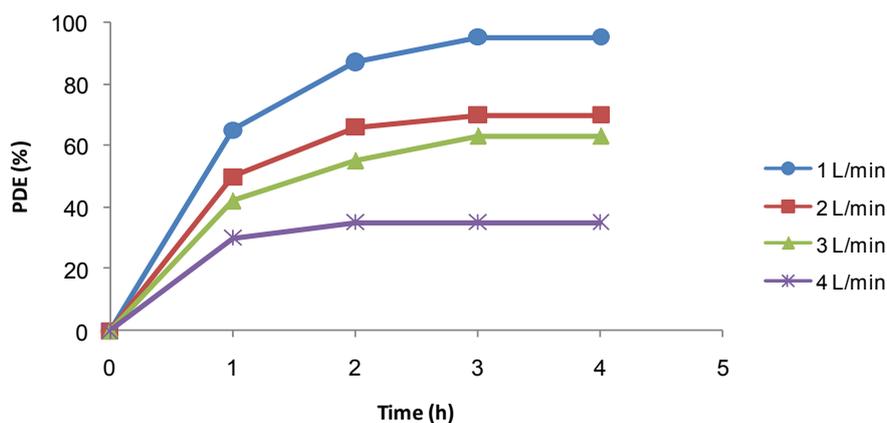


Figure 7. Photocatalytic degradation efficiency (PDE, %) of toluene determined using RGO-TiO₂ composite under visible-light irradiation according to stream flow rate.

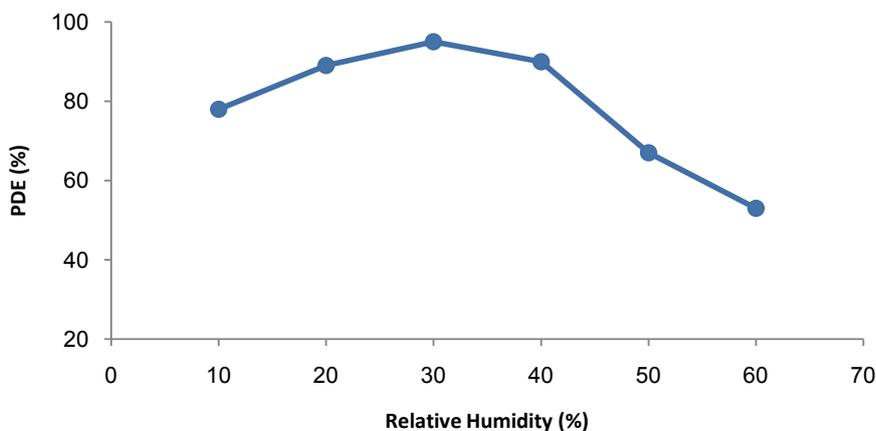


Figure 8. Photocatalytic degradation efficiency (PDE, %) of toluene determined using RGO-TiO₂ composite under visible-light irradiation according to relative humidity.

results suggested that FR was still a critical factor for the photocatalytic application of the RGO-TiO₂ composite. Decreased FRs would result in a decrease in the bulk mass transport of target compounds from the gas-phase to the surface of the catalyst particle due to convection and diffusion, which is an important heterogeneous catalytic reaction process [30].

3.5. Effect of Relative Humidity of Air Stream

The effect of relative humidity (0% - 60% RH) of air stream on toluene decomposition was examined by adding water vapor to a fixed concentration of toluene. RGO-TiO₂ photocatalyst was used in this experiment. **Figure 8** showed the experimental results at different relative humidity. The degradation rate increased with increasing relative humidity up to 30% and then started to decrease as the RH goes up, which meant that 30% was the optimal humidity for photocatalyst process under the experimental conditions. When the reaction time was 4h, the highest removal efficiency of toluene was 95% when RH was 30%. The results revealed that a little water vapor could promote the photocatalytic degradation of VOCs, while excessive water vapor could inhibit the photocatalytic degradation. This phenomenon is in agreement with the observations reported previously [37]. The reason of this phenomenon could be due to more saturation of the surface by RH at higher levels of humidity.

4. Conclusion

In this study the RGO-TiO₂ composite was coated on inner wall of the photocatalytic reactor and toluene was chosen as the model VOC. We studied the photocatalytic activities of RGO-TiO₂ composite for the photocatalytic degradation gaseous toluene under different conditions. The RGO-TiO₂ composite exhibited a shift in the absorbance spectrum toward the visible light region when compared to undoped TiO₂ powders, indicating that the as-prepared RGO-TiO₂ composite could be effectively activated by visible-light irradiation. Another major finding was that the RGO-TiO₂ composite photocatalytic system showed superior toluene photocatalytic conversion efficiencies to undoped TiO₂ under visible-light irradiations. Overall, the results indicated that the RGO-TiO₂ composite could be effectively applied for the purification of indoor-level gaseous toluene under optimal operational conditions.

References

- [1] Fox, M.A. and Dulay, M.T. (1993) Heterogeneous Photocatalysis. *Chemical Reviews*, **93**, 341-357. <https://doi.org/10.1021/cr00017a016>
- [2] Hofmann, M.R., Martin, S.T., Choi, W. and Bahnemann, D.W. (1995) Environmental Applications of Semiconductor Photocatalysis, *Chemical Reviews*, **95**, 69-96. <https://doi.org/10.1021/cr00033a004>
- [3] Yu, J., Wang, W., Cheng, B. and Su, B.L. (2009) Enhancement of Photocatalytic Activity of Mesoporous TiO₂ Powders by Hydrothermal Surface Fluorination Treatment. *The Journal of Physical Chemistry C*, **113**, 6743-6750. <https://doi.org/10.1021/jp900136q>

- [4] Yu, X., Liu, S. and Yu, J. (2011) Superparamagnetic γ -Fe₂O₃@SiO₂/TiO₂ Composite Microspheres with Superior Photocatalytic Properties. *Applied Catalysis B: Environmental*, **104**, 12-20. <https://doi.org/10.1016/j.apcatb.2011.03.008>
- [5] Cheng, Y.W., Chan, R.C. and Wong, P. (2007) Disinfection of Legionella Pneumophila by Photocatalytic Oxidation. *Water Research*, **41**, 842-852. <https://doi.org/10.1016/j.watres.2006.11.033>
- [6] Park, H. and Choi, W. (2004) Effects of TiO₂ Surface Fluorination on Photocatalytic Reactions and Photoelectrochemical Behaviors. *The Journal of Physical Chemistry B*, **108**, 4086-4093. <https://doi.org/10.1021/jp036735i>
- [7] Herrmann, J.M., Tahiri, H., Ait-ichou, Y., Lassaletta, G., Gonzalez, E.A. and Fernandez, A. (1997) Characterization and Photocatalytic Activity in Aqueous Medium of TiO₂ and Ag-TiO₂ Coatings on Quartz. *Applied Catalysis B: Environmental*, **13**, 219-228. [https://doi.org/10.1016/S0926-3373\(96\)00107-5](https://doi.org/10.1016/S0926-3373(96)00107-5)
- [8] Liu, S., Yu, J. and Jaroniec, M. (2010) Tunable Photocatalytic Selectivity of Hollow TiO₂ Microspheres Composed of Anatase Polyhedra with Exposed {001} Facets. *Journal of the American Chemical Society*, **132**, 11914-11916. <https://doi.org/10.1021/ja105283s>
- [9] Xiang, Q., Yu, J. and Jaroniec, M. (2012) Graphene-Based Semiconductor Photocatalysts. *Chemical Society Reviews*, **41**, 782-796. <https://doi.org/10.1039/C1CS15172J>
- [10] Pomoni, K., Vomvas, A. and Trapalis, C. (2005) Transient Photoconductivity of Nanocrystalline TiO₂ Sol-Gel Thin Films. *Thin Solid Films*, **479**, 160-165. <https://doi.org/10.1016/j.tsf.2004.12.005>
- [11] Ksibi, M., Rossignol, S., Tatibouët, J.M. and Trapalis, C. (2008) Synthesis and Solid Characterization of Nitrogen and Sulfur-Doped TiO₂ Photocatalysts Active under Near Visible Light. *Materials Letters*, **62**, 4204-4206. <https://doi.org/10.1016/j.matlet.2008.06.026>
- [12] Kumar, S.G. and Devi, L.G. (2011) Review on Modified TiO₂ Photocatalysis under UV/Visible Light: Selected Results and Related Mechanisms on Interfacial Charge Carrier Transfer Dynamics. *The Journal of Physical Chemistry A*, **115**, 13211-13241. <https://doi.org/10.1021/jp204364a>
- [13] Devi, L.G., Kottam, N. and Kumar, S.G. (2009) Preparation and Characterization of Mn-Doped Titanates with a Bicrystalline Framework: Correlation of the Crystallite Size with the Synergistic Effect on the Photocatalytic Activity. *The Journal of Physical Chemistry C*, **113**, 15593-15601. <https://doi.org/10.1021/jp903711a>
- [14] Wen, C.Z., Jiang, H.B., Qiao, S.Z., Yang, H.G. and Lu, G.Q.M. (2011) Synthesis of High-Reactive Facets Dominated Anatase TiO₂. *Journal of Materials Chemistry*, **21**, 7052-7061. <https://doi.org/10.1039/c1jm00068c>
- [15] Gaya, U.I. and Abdullah, A.H. (2008) Heterogeneous Photocatalytic Degradation of Organic Contaminants over Titanium Dioxide: A Review of Fundamentals, Progress and Problems. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, **9**, 1-12. <https://doi.org/10.1016/j.jphotochemrev.2007.12.003>
- [16] Maeda, K. (2011) Photocatalytic Water Splitting Using Semiconductor Particles: History and Recent Developments. *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, **12**, 237-268. <https://doi.org/10.1016/j.jphotochemrev.2011.07.001>
- [17] Muthirulan, P., Devi, C.N. and Sundaram, M.M. (2014) TiO₂ Wrapped Graphene as a High Performance Photocatalyst for Acid Orange 7 Dye Degradation under Solar/UV Light Irradiations. *Ceramics International*, **40**, 5945-5957. <https://doi.org/10.1016/j.ceramint.2013.11.042>

- [18] Novoselov, K.S., Geim, A.K., Morozov, S., Jiang, D., Zhang, Y., Dubonos, S., Grigorieva, I. and Firsov, A. (2004) Electric Field Effect in Atomically Thin Carbon Films. *Science*, **306**, 666-669. <https://doi.org/10.1126/science.1102896>
- [19] Lui, G., Liao, J.Y., Duan, A., Zhang, Z., Fowler, M. and Yu, A. (2013) Graphene-Wrapped Hierarchical TiO₂ Nanoflower Composites with Enhanced Photocatalytic Performance. *Journal of Materials Chemistry A*, **1**, 12255-12262.
- [20] Jo, W.K. and Kang, H.J. (2013) Titanium Dioxide-Graphene Oxide Composites with Different Ratios Supported By Pyrex Tube for Photocatalysis of Toxic Aromatic Vapors, *Powder Technology*, **250**, 115-121. <https://doi.org/10.1016/j.powtec.2013.10.017>
- [21] Pastrana, L.M.M., et al. (2012) Advanced Nanostructured Photocatalysts Based on Reduced Graphene Oxide-TiO₂ Composites for Degradation of Diphenhydramine Pharmaceutical and Methyl Orange Dye. *Applied Catalysis B: Environmental*, **123**, 241-256. <https://doi.org/10.1016/j.apcatb.2012.04.045>
- [22] Wang, F. and Zhang, K. (2011) Reduced Graphene Oxide-TiO₂ Nanocomposite with High Photocatalytic Activity for the Degradation of Rhodamine B. *Journal of Molecular Catalysis A: Chemical*, **345**, 101-107. <https://doi.org/10.1016/j.molcata.2011.05.026>
- [23] Yin, X., Zhang, H., Xu, P., Han, J., Li, J. and He, M. (2013) Simultaneous N-Doping of Reduced Graphene Oxide and TiO₂ in the Composite for Visible Light Photodegradation of Methylene Blue with Enhanced Performance. *RSC Advances*, **3**, 18474-18481. <https://doi.org/10.1039/c3ra43403f>
- [24] Demeestere, K., Dewulf, J. and Van H. (2007) Langenhove, Heterogeneous Photocatalysis as an Advanced Oxidation Process for the Abatement of Chlorinated, Monocyclic Aromatic and Sulfurous Volatile Organic Compounds in Air: State of the Art. *Environmental Science and Technology*, **37**, 489-538. <https://doi.org/10.1080/10643380600966467>
- [25] Revilla, A.S., Pestana, C.R., Pardo, G.L.A., Santos, A.C., Uyemura, S.A., Gonzales, M.E. and Curti, C. (2007) Potential Toxicity of Toluene and Xylene Evoked by Mitochondrial Uncoupling. *Toxicology in Vitro*, **21**, 782-788. <https://doi.org/10.1016/j.tiv.2007.01.012>
- [26] Jia, C., Batterman, S.A. and Relyea, G.E. (2012) Variability of Indoor and Outdoor VOC Measurements: An Analysis Using Variance Components. *Environmental Pollution*, **169**, 152-159. <https://doi.org/10.1016/j.envpol.2011.09.024>
- [27] Sikong, L., Kongreong, B., Kantachote, D. and Sutthisripok, W. (2010) Photocatalytic Activity and Antibacterial Behavior of Fe³⁺-Doped TiO₂/SnO₂ Nanoparticles. *Energy Research Journal*, **1**, 120. <https://doi.org/10.3844/erjrp.2010.120.125>
- [28] Shen, J., Shi, M., Yan, B., Ma, H., Li, N. and Ye, M. (2011) Ionic Liquid-Assisted One-Step Hydrothermal Synthesis of TiO₂-Reduced Graphene Oxide Composites, *Nano Research*, **4**, 795-806. <https://doi.org/10.1007/s12274-011-0136-7>
- [29] Zhang, H., Lv, X., Li, Y., Wang, Y. and Li, J. (2009) P25-Graphene Composite as a High Performance Photocatalyst. *ACS Nano*, **4**, 380-386. <https://doi.org/10.1021/nn901221k>
- [30] Jo, W.K. and Kim, J.T. (2009) Application of Visible-Light Photocatalysis with Nitrogen-Doped or Unmodified Titanium Dioxide for Control of Indoor-Level Volatile Organic Compounds. *Journal of Hazardous Materials*, **164**, 360-366. <https://doi.org/10.1016/j.jhazmat.2008.08.033>
- [31] Nguyen, T.D.P., Pham, V.H., Shin, E.W., Pham, H.D., Kim, S., Chung, J.S., Kim, E.J. and Hur, S.H. (2011) The Role of Graphene Oxide Content on the Adsorption-Enhanced Photocatalysis of Titanium Dioxide/Graphene Oxide Composites,

Chemical Engineering Journal, **170**, 226-232.

<https://doi.org/10.1016/j.cej.2011.03.060>

- [32] Murugan, A.V., Muraliganth, T. and Manthiram, A., (2009) Rapid, Facile Microwave-Solvothermal Synthesis of Graphene Nanosheets and Their Polyaniline Nanocomposites for Energy Storage. *Chemistry of Materials*, **21**, 5004-5006. <https://doi.org/10.1021/cm902413c>
- [33] Raupp, G.B. and Junio, C.T. (1993) Photocatalytic Oxidation of Oxygenated Air Toxics. *Applied Surface Science*, **72**, 321-327. [https://doi.org/10.1016/0169-4332\(93\)90369-M](https://doi.org/10.1016/0169-4332(93)90369-M)
- [34] Dibble, L.A. and Raupp, G.B. (1990) Kinetics of the Gas-Solid Heterogeneous Photocatalytic Oxidation of Trichloroethylene by Near UV Illuminated Titanium Dioxide. *Catalysis Letters*, **4**, 345-354. <https://doi.org/10.1007/BF00765320>
- [35] Demeestere, K., Dewulf, J. and Langenhove, H.V. (2007) Heterogeneous Photocatalysis as an Advanced Oxidation Process for the Abatement of Chlorinated, Monocyclic Aromatic and Sulfurous Volatile Organic Compounds in Air: State of the Art. *Critical Reviews in Environmental Science and Technology*, **37**, 489-538. <https://doi.org/10.1080/10643380600966467>
- [36] Pengyi, Z., Fuyan, L., Gang, Y., Qing, C. and Wanpeng, Z. (2003) A Comparative Study on Decomposition of Gaseous Toluene by O₃/UV, TiO₂/UV and O₃/TiO₂/UV, *Journal of Photochemistry and Photobiology A. Chemistry*, **156**, 189-194. [https://doi.org/10.1016/S1010-6030\(02\)00432-X](https://doi.org/10.1016/S1010-6030(02)00432-X)
- [37] An, T., Zhang, M., Wang, X., Sheng, G. and Fu, J. (2005) Photocatalytic Degradation of Gaseous Trichloroethene Using Immobilized ZnO/SnO₂ Coupled Oxide in a Flow-Through Photocatalytic Reactor. *Journal of Chemical Technology and Biotechnology*, **80**, 251-258. <https://doi.org/10.1002/jctb.1187>



Scientific Research Publishing

Submit or recommend next manuscript to SCIRP and we will provide best service for you:

Accepting pre-submission inquiries through Email, Facebook, LinkedIn, Twitter, etc.

A wide selection of journals (inclusive of 9 subjects, more than 200 journals)

Providing 24-hour high-quality service

User-friendly online submission system

Fair and swift peer-review system

Efficient typesetting and proofreading procedure

Display of the result of downloads and visits, as well as the number of cited articles

Maximum dissemination of your research work

Submit your manuscript at: <http://papersubmission.scirp.org/>

Or contact jep@scirp.org

