

Study of the indoor decontamination using nanocoated woven polyester fabric

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Abstract This research primarily deals with the photocatalytic degradation of methanol in indoor air using nanocoated indoor textiles used for curtains as household textiles. The woven polyester was coated by titanium dioxide by sol gel method, using silicon-based binder. The characterization of the coating has been done using scanning electron microscopy (SEM) image analysis, energy dispersive analysis using X-ray (EDAX) and Fourier transform infrared spectroscopy (FTIR). The DIY instrument providing the similar environment as of indoor was designed to assess the performance of the degradation of formaldehyde under UV light. The photocatalytic degradation rate was measured using the absorption value of the solutions obtained in the result of liquid chromatography of test solution and reagent solution. Different amount of dosages (1–3 %) and different time period of coatings (half hour to 3 h) have been evaluated for optimization.

Keywords Indoor decontamination · Degradation rate · Photocatalysis · Chromatography · Optimization

Introduction

With the development of global economy and economic conditions at national level, people's quality of life and buying power of the people have been increased. The people living in the urban areas are much suffered by indoor decontamination [1]; as they pass their most of the time inside the buildings, and the inner environment of the building possesses large variety of contaminating items including dusty and continually releasing VOCs such as furniture [2], wall paints, fecal matter of dust mites and bed bugs, printers [3], decorative items [4], cleaning items, wood fire for indoor heating purpose [5], and pets and cigarette smokes [6, 7]. According to an estimate, 6.25 trillion cigarettes were smoked by people during the year 2012 compared with 4.96 trillion in 1980. In 2012, 967 million people smoked every day compared with 721 million in 1980, as shown by data from 187 countries [8]. The global consumption of cigarettes also jumped from about 5 to 6.25 trillion [9]. This all leads to more formaldehyde in the indoor environment. The compressed wood products are used in the furniture using urea–formaldehyde (UF) resin as an adhesive; this can be considered as major indoor contaminating source [2]. Volatile organic compounds present in the indoor atmosphere, particularly formaldehyde, have become great concern. Formaldehyde has a strong carcinogenic and tumor promotion, and its long-term exposure or ingestion of formaldehyde by human possesses severe health problems and many chronic respiratory diseases. Today, indoor air pollution is not as hot social issues, but it has

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been raised to the important issues relating to the livelihood of the people.

Recently, the strategies to degrade formaldehyde photocatalytically under visible light using ZnO have been examined [10]. In one recent detailed study, oxygen reduction reaction in photocatalysis process has been well studied [11]. The catalytic activity of hollow chains of TiO₂ in the presence of platinum for the photodegradation of formaldehyde at room temperature was studied [12]. In one another similar study, the removal of formaldehyde at room temperature in the presence of platinum was analyzed [13]. In one another research, the photocatalytic reaction rate constant in terms of light intensity and humidity was derived, and it was maintained that humidity impact factor effect on photocatalytic rate [14]. In one more study, the modeling has been done to analyze the photocatalytic degradation of formaldehyde by fixed bed reactor. Thus, the photocatalytic degradation of formaldehyde has been studied by several researchers and it has remained a hot research area for the scientists focusing on indoor air pollution.

Currently, the strategies for the removal of indoor formaldehyde technology can be summarized in: physical adsorption, chemical reaction, photocatalytic oxidation, plasma catalysis, bio-degradation method. Various researches have been done to clean the inner air of the building by different strategies such as managing temperature and altering surface coolness [15], controlling the humidity [16] of the environment by humidification and dehumidification, or by circulating the air by exhaust fans, or by cleaning the indoor air [17]. Indeed, these methods are temperature dependent and sometimes due to change in temperature they cause even worse environmental conditions. Moreover, they may also cause the rise in relative humidity to higher extents which rises moist dust in the air. Furthermore, the maintenance cost of these all strategies is an extra surplus making them uneconomical. Approaches have also been made for decontaminating a section without dehumidification [18]. In addition, one strategy that has been practiced to be safe from chemical contamination of the environment is to make barrier against these chemicals [19]; this strategy has been mostly practiced to be safe from hazardous chemicals and thus not user friendly. The activated carbon liners and insulating rubber have been examined to create barrier against hazardous chemical contamination. This strategy is not appreciated, because of this the hazardous chemicals remained inside the barrier and later they require being eliminated properly or disposing off of the barrier. The use of various chemicals for the indoor decontamination has also been reported; such as use of hydrogen peroxide [20]. The indoor air may also be cleaned and decontaminated by electrostatic forces, yet the mechanism of

ionizing air is only suitable for a bit larger particles in the form of dust around the size about 0.3 μm [21]. The indoor air may also be cleaned by the plants, as some plants possess better decontamination ability for both organic and inorganic compounds [22]. In this study, photocatalytic degradation of formaldehyde using non-toxic and chemically stable titanium based photocatalyst has been analyzed.

Materials and experimental

Materials

The 100 % polyester woven fabric with the mass per unit area of ~193 g m⁻², warp and weft density of 60 and 20 threads per cm, respectively, was donated by Hangzhou Huachen Flocking Co. Ltd, China. The analytical grade of tetra ethyl ortho silicate (TEOS), ethanol and nitric acid was purchased from Hangzhou Gao Jing Fine Chemical Co. China. The nanosized TiO₂ powder with an average particle size of 25 nm was purchased from Aladdin Reagent Company, China. The analytical grade of formaldehyde solution, ammonium acetate, acetyl acetone and glacial acetic acid was purchased from Tianjin Kermel Chemical Reagent Co., Ltd. All the instruments including beakers, Petri dishes, funnels, conical flasks, pipettes, etc. were purchased from Hangzhou Chemical Instrument Co. China.

Sol gel coating

TEOS and ethanol were mixed thoroughly into a homogeneous solution at room temperature using magnetic stirring for 10 min. Six times diluted nitric acid in distilled water was slowly added drop by drop to solution of TEOS and ethanol. The mixture was warmed to 50 °C and kept stirred for 60 min, then the mixture was kept in dark for aging for 24 h at room temperature to obtain silica sol. Appropriate dosing of the nanoparticles of the TiO₂ was done, and the mixture was magnetically stirred for 30 min that yielded white, stable TiO₂-based coating solution.

Polyester fabric was coated by titania catalysts with different titania loadings (1–3 % of sol) by sol–gel method. Prior to coating, the fabric was hot washed at 60 °C using a nonionic detergent and then it was rinsed in cold water and then vertically hung for drying overnight in the room temperature. The cleaned fabric was put in the oven at 105 °C about an hour to remove the remaining moisture. The dried fabric samples were cut into the size of 9 cm × 9 cm, and were suspended by the aid of polyester yarn into the beaker containing the nanosol for different times from half an hour to 3 h.

Experimental

Characterization of nanocoating

Scanning electron micrographs (SEMs) were obtained to observe and analyze the surface morphology in terms of the physical deposition, size, aggregates and distribution of nanoparticles of TiO₂ on the fiber surface. The SEM analysis was done on the SEM instrument named JSM 5610 L manufactured by JEOL Electronics, Japan at the resolution of 3 nm. To avoid the charge effect, the samples were coated with gold layer. Energy dispersive analysis using X-ray (EDAX) was performed on the INCA 6587, Oxford Instrument attached to SEM instrument JSM 5610 L to obtain the elements in the samples of nanocoated woven polyester fabric. Fourier transform infrared spectroscopy (FTIR) can analyze the surface group and main structure. When the infrared light passes through different frequencies from the molecule, different values of absorption phenomenon are observed and they are known as infrared absorption spectrum. Wavelength infrared absorption band position generally can be used to identify the structure and composition of its chemical groups. The Fourier transform infrared spectroscopy (FTIR) Nicolet 5700 of Nexus Series was used in this research. The X-ray diffraction spectroscopy (XRD) was done on the X-ray diffractometer, DX-2700-Ray, Dandong Fang Yuan Instrument Co., Ltd., China) equipped with the copper K α radiation ($\lambda = 15,418 \text{ \AA}$) operating at 40 kV and 40 mA to confirm the crystalline nature of the titanium coated woven polyester fabric.

Characterization of degradation property

Liquid chromatography was done to assure the degradation of formaldehyde under UV light. The formaldehyde volatile solution was prepared by diluting formaldehyde by distilled water until the 0.1 mol dm^{-3} solution was achieved. In addition, the acetyl acetone reagent (chromatographic solution) was prepared according to the Chinese standard “Water quality-determination of formaldehyde-acetyl acetone spectrophotometric method, HJ 601-2011”, GB 13197-91. According to which the solution of 150 g of ammonium acetate into 800 mL distilled water was prepared at room temperature, then 2 mL acetyl acetone and 3 mL acetic acid were added into the solution; and it was kept for 24 h in the dark bottle.

The DIY instrument was designed to assess the performance of the fabric against the degradation of formaldehyde. The 100 mL formaldehyde volatile solution was put into the Petri dish at the bottom of the closed pot. Ceramic ventilation plate was inserted in the middle. 100 mL distilled water as the test solution in a Petri dish with a fabric

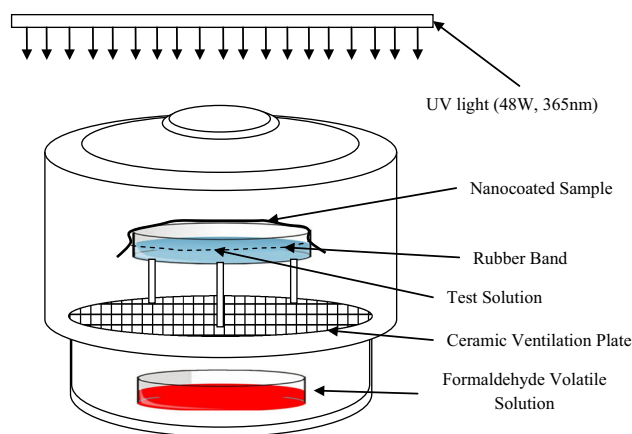


Fig. 1 The DIY instrument to assess the photocatalytic degradation of methanol using nanocoated woven polyester fabric

sample tied by a rubber band on the top was placed on the stand. The UV lamp (48 W, $\lambda = 365 \text{ nm}$) was placed on the entire top of the pot. Figure 1 shows a schematic diagram of the DIY instrument to assess the photocatalytic degradation of methanol using nanocoated woven polyester fabric.

After different intervals of time, 5 mL of the test solution and 5 mL of acetyl acetone reagent solution (prepared at laboratory) were mixed gradually, in a test tube. A steady yellow compound was formed due to the chemical reaction of HCHO absorbed in the water and acetyl acetone reagent solution. The tube was kept in a water bath at $40 \text{ }^\circ\text{C}$ for 30 min, and then cooled at room temperature for about 30 min. The 10 mL mixture solution was tested for absorbency at 412 nm of wavelength on UV-2600 UV-Vis spectrophotometer, Shimadzu Corporation. The degradation rate of formaldehyde was measured by

$$\eta_{\text{HCHO}} = \frac{C_0 - C}{C_0} \times 100 \quad (1)$$

where η_{HCHO} is the degradation rate of formaldehyde in percentage, C_0 is the absorbance of the test solution of uncoated fabric, and C is the absorbance of the test solution of coated fabric.

Results and discussion

SEM images

The scanning electron micrographs (SEMs) are shown in Fig. 2; Figure 2a shows the smooth polyester fiber having a small amount of impurities, the image taken before nanocoating. The rough surface of nanocoated fiber coated using $\sim 2 \%$ of dosage for $\sim 2 \text{ h}$ of immersing time is shown in Fig. 2b. The smooth surface of the fiber is fully

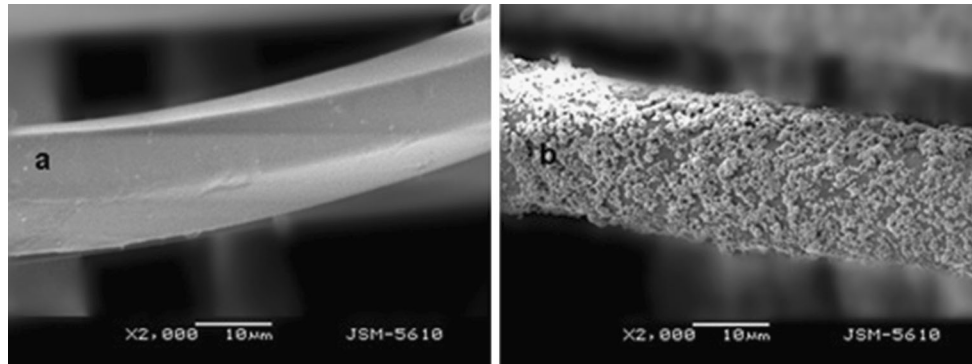


Fig. 2 The SEM image. **a** The SEM image of smooth polyester fiber. **b** The SEM image of rough surface of nanocoated fiber

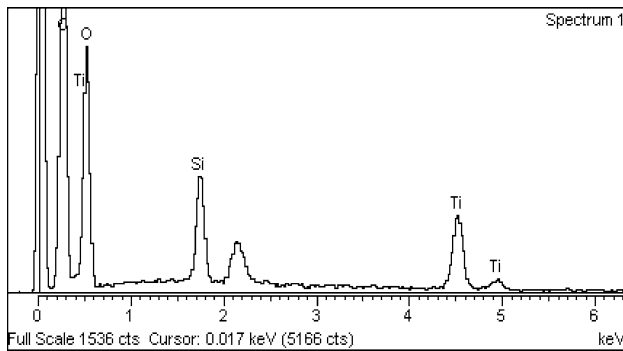


Fig. 3 The energy dispersive analysis using X-ray (EDAX) of nanocoated woven polyester fabric

covered by a number of particulate matters indicating the presence of TiO_2 particles on the surface of the fiber. There were a high number of titanium particles on the surface but they had made agglomerates, which was due to the enough amount of deposition of Titania particles on the fiber surface.

X-ray energy dispersive spectroscopy (EDS)

The energy dispersive analysis using X-ray (EDAX) of the woven polyester nanocoated sample using $\sim 2\%$ of dosage for ~ 2 h of immersing time is shown in Fig. 3. The graph reveals that Si characteristic peak is at 1.8 keV. The Ti major characteristic peak at 4.5 keV and Ti minor characteristic peak at 5 keV characteristic peaks appear at Ti, when the atomic percentage of Ti element was 2.7 %. This proves that TiO_2 is attached to the fabric surface. The characteristic peak at 2.2 keV of EDS represents the Au, which was sprayed on the fabric layer to facilitate analysis. The characteristic peak at the 0.2 keV represents C peak and the characteristic peak at the 0.5 keV represents O, because the fabric contains C and O elements.

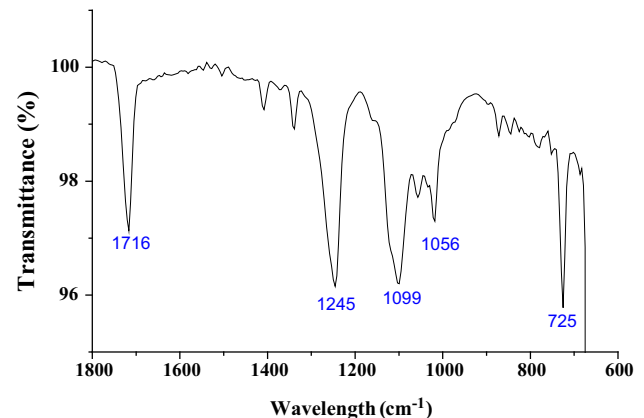
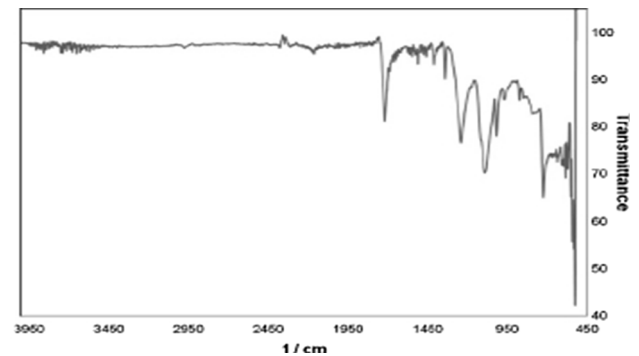


Fig. 4 The Fourier transform infrared spectroscopy (FTIR) of the nanocoated woven polyester fabric

FTIR studies

The infrared spectra obtained by Fourier transform infrared spectroscopy (FTIR) of the nanocoated woven polyester fabric are shown in Fig. 4. It can be seen that the vibration absorption peak of Ti–O–Ti bond is in between 800 and 500 cm^{-1} , i.e., 725 cm^{-1} . The peak at 1716 cm^{-1} can be considered as bending vibration peak of Ti–OH. The peaks at 1099 and 1245 cm^{-1} can be considered as Si–OH bending vibration peak and Si–O stretching vibration absorption peaks. These peaks confirm the formation of SiO_2 by the hydrolysis of tetra ethyl ortho silicate (TEOS).

The weak absorption peak is appeared at 1056 cm^{-1} , from which it may be assumed that there exists a bond of Ti–O–Si. Possibly, the titanium on the surface of TiO_2 has made the bond with silicon formed by the hydrolysis of TEOS.

XRD studies

The XRD patterns of the nanocoating of the titanium on the nanocoated woven polyester fabric are shown in Fig. 5. All the diffraction peaks can be indexed to the anatase form of titanium. XRD measurements of the fabric were performed, and the XRD peaks at 25.31° , 37.88° , 48.03° , 53.90° and 55.10° were attributed to the (101), (004), (200), (105) and (211) crystal face of anatase type of TiO_2 , respectively. This indicates that the nanoparticles of TiO_2 had been introduced onto the woven polyester fabric surface. Moreover, in one study it had already been concluded that the anatase form of titanium yields better photocatalytic property than rutile or brookite [23]. The anatase form of titanium possessing higher surface area and higher degree of crystallization offers better photocatalytic activity, because it possesses fewer disruptions within its structure of electronic band [24, 25].

Effect of amount of TiO_2 on the degradation % rate of formaldehyde

For photo-catalytic degradation of organic compounds under UV light, the amount of the dosing of TiO_2 is dependent on two factors mainly, i.e., the chemical nature of the organic compound and the geometry of the reactor [26, 27]. After the silica sol was formulated, the nanoparticles of TiO_2 were added into the silica sol. This graph in Fig. 5 represents the effect of different amount of dosing of TiO_2 nanoparticles onto the degradation rate of the formaldehyde within 210 min of irradiation under UV

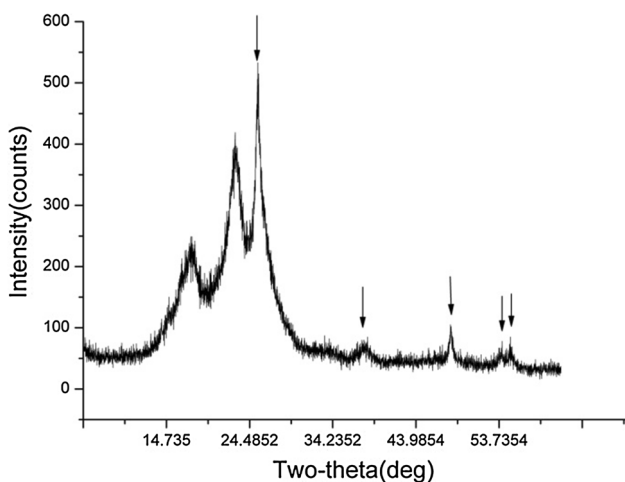


Fig. 5 XRD patterns of the nanocoated woven polyester fabric

lamp. Three different dosings, i.e., 1, 2 and 3 % were introduced, and the fabric immersing time in the coating solution was kept constant of ~ 2 h for each. The aim of this test was to find out the amount of coating in terms of its photocatalytic degradation rate of formaldehyde. During the first half hour of irradiation, the degradation rate was superior and it showed that more than 20 % of degradation was achieved just for the 1 % dosing of TiO_2 ; the progress was doubled in the case of the 3 % dosing of TiO_2 nanoparticles. The degradation rate increased progressively till 90 min of irradiation time; this is because more number of active sites was available for the degradation of methanol. Later, this trend slowed down and approached to stable state after 120 min of irradiation time.

The graph in Fig. 5 clearly represents that there is much difference between the efficiency of the sample coated by 1 % of dosing and 2 % of dosing, whereas there is less difference if the dosing of titanium nanoparticles was further increased. Furthermore, after the irradiation time of 150 min; both 2 % dosing and 3 % dosing have showed quite similar photocatalytic degradation rate. This suggests that 2 % of the dosing of TiO_2 in the silica sol can be considered as dosing for the degradation of formaldehyde under UV light.

Moreover, an uncoated sample was also assessed for the degradation of formaldehyde, but no evidence for the degradation efficiency of formaldehyde was found from it. In addition, 3 % nanocoated sample was also assessed without irradiation of UV, likewise no results of degradation of formaldehyde were found from it. This suggests that both TiO_2 nanoparticles and UV light are essential for photocatalytic degradation of formaldehyde.

Effect of immersing time on the degradation % rate of formaldehyde

The variations in the efficiency of photocatalytic degradation of formaldehyde with four different immersing times for coating as a function, at 2 % dosing of TiO_2 under UV light are shown in Fig. 6. The aim of this test was to find out the time of immersion of the samples in the sol in terms of its photocatalytic degradation rate of formaldehyde. The graph depicts that by increasing the immersing time the efficiency of photocatalytic degradation of formaldehyde was increased marginally. The immersing time up to 2 h increases the rate of degradation of formaldehyde progressively; a further increase of immersing time about ~ 3 h does not show the same performance of photocatalytic degradation. Since, after irradiation time of 120 min the sample that was treated for 3 h showed lesser photocatalytic activity than the sample coated that was treated for 2 h only. This reveals that increase in the immersing time probably mean an increase

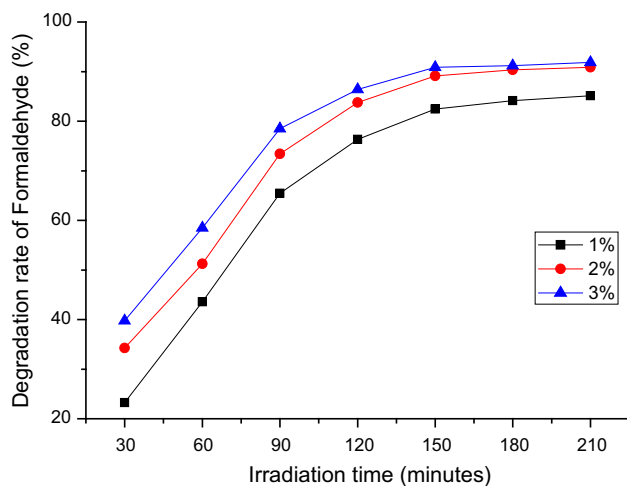


Fig. 6 Effect of amount of TiO₂ on the degradation % rate of formaldehyde

in further coating but it may cause the increase in aggregate size of the catalyst particles. There is considerable occurrence of aggregation and clusters of titania particles that most likely come from the longer reaction time. This increase in the aggregate size of the particle yields lesser active sites of titania-based nanocoating.

It can also be seen from the graph in Fig. 6 that for sample with the immersing time of half an hour the photocatalytic degradation progressed significantly at first but it became stable after the irradiation time of 120 min, while the performance of the sample immersed for 1 h progressed well till irradiation time of 90 min and later it slowed down; moreover, it became stable after 180 min of irradiation time. Likewise, the photocatalytic efficiency of the samples with immersing time of 2 and 3 h increased progressively in the beginning and slowed down after irradiation time of 90 min. In general, the photocatalytic efficiency of the samples immersed for half is much lesser than other samples immersed for longer period of time. Thus, according to the results, it may be assumed that the immersing time of 2 h may be considered as the immersing time for the photocatalytic degradation of formaldehyde under UV light (Fig. 7).

Conclusions

From the results, it may be summed up that this technique for the coating of woven polyester fabric using TiO₂ nanoparticles be effectively utilized. This technique of nanocoating is relatively cheaper than others as it does not require the costly precursors of TiO₂. The uniform dispersion of TiO₂ nanoparticles was obtained by immersing the fabric into the silica sol containing suspended TiO₂ nanoparticles. The simplicity of this method may lead to

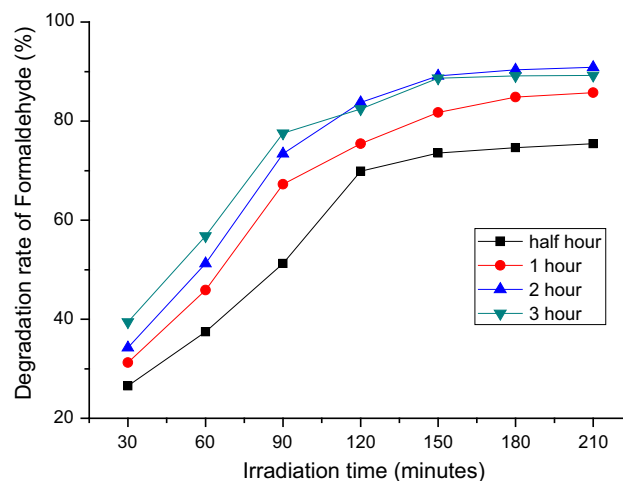


Fig. 7 Effect of immersing time on the degradation % rate of formaldehyde

the concept of commercialization of this technique. The nanocoated fabric was found to be active for photocatalytic degradation of methanol in the air under UV light at the room temperature. The degradation rate of the formaldehyde mainly depends on the number of active sites available for the reaction. The ~2 % of the dosing of the titanium nanoparticles for the immersion time of ~2 h was considered as the values for the nanocoating of woven polyester fabric to degrade formaldehyde by photocatalytic oxidation reaction using this method.

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Compliance with ethical standards

Conflict of interest The author declares that they have no conflict of interest.

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References

- Chen, C.C., Wang, C.C., Yeh, J.T.: Improvement of odor elimination and anti-bacterial activity of polyester fabrics finished with composite emulsions of nanometer titanium dioxide-silver particles-water-borne polyurethane. *Text Res J* **80**(4), 291–300 (2010)
- Panagopoulos, I.K., Karayannis, A.N., Kassomenos, P., Aravossis, K.: A CFD simulation study of VOC and formaldehyde indoor air pollution dispersion in an apartment as part of an indoor pollution management plan. *Aerosol Air Qual Res* **11**(6), 758–762 (2011)

3. Barrese, E., Giofrè, A., Scarpelli, M., Turbante, D., Trovato, R., Iavicoli, S.: Indoor pollution in work office: VOCs, formaldehyde and ozone by printer. *Occup Dis Environ Med* **2**(3), 7 (2014)
4. Dajuan, G.: Indoor air pollution caused by decorative materials. *Shanghai Environ Sci* **13**(10), 3 (1994)
5. Hippelein, M.: Background concentrations of individual and total volatile organic compounds in residential indoor air of Schleswig-Holstein, Germany. *J Environ Monit* **6**(9), 745–752 (2004)
6. Crump, D.R., Squire, R.W., Yu, C.W.F.: Sources and concentrations of formaldehyde and other volatile organic compounds in the indoor air of four newly built unoccupied test houses. *Indoor Built Environ* **6**(1), 45–55 (1997)
7. Daisey, J.M., Hodgson, A.T., Fisk, W.J., Mendell, M.J., Brinke, J.T.: Volatile organic compounds in twelve California office buildings: classes, concentrations and sources. *Atmos Environ* **28**(22), 3557–3562 (1994)
8. Roberts, M.: Smoker numbers edge close to one billion. In: BBC News online. BBC News online, (2014). <http://www.bbc.com/news/health-25635121>
9. Ng, M., Freeman, M.K., Fleming, T.D., Robinson, M., Dwyer-Lindgren, L., Thomson, B., Wollum, A., Sanman, E., Wulf, S., Lopez, A.D., Murray, C.J.: Smoking prevalence and cigarette consumption in 187 countries, 1980–2012. *J Am Med Assoc* **311**(2), 183–192 (2014)
10. Wu, C.: Facile one-step synthesis of N-doped ZnO micropolyhedrons for efficient photocatalytic degradation of formaldehyde under visible-light irradiation. *Appl Surf Sci* **319**, 237–243 (2014)
11. Wang, C., Zhang, X., Liu, Y.: Promotion of multi-electron transfer for enhanced photocatalysis: a review focused on oxygen reduction reaction. *Appl Surf Sci* **358**, 28–45 (2015)
12. Qi, L., Cheng, B., Yu, J., Ho, W.: High-surface area mesoporous Pt/TiO₂ hollow chains for efficient formaldehyde decomposition at ambient temperature. *J Hazard Mater* **301**, 522–530 (2016)
13. Yan, Z., Xu, Z., Yu, J., Jaroniec, M.: Highly active mesoporous ferrihydrite supported Pt catalyst for formaldehyde removal at room temperature. *Environ Sci Technol* **49**(11), 6637–6644 (2015)
14. Zhu, X., Chang, D.L., Li, X.S., Sun, Z.G., Deng, X.Q., Zhu, A.M.: Inherent rate constants and humidity impact factors of anatase TiO₂ film in photocatalytic removal of formaldehyde from air. *Chem Eng J* **279**, 897–903 (2015)
15. Yang, C.G., Li, X.Y., Xiang, Q.Q., Sun, Z.Y.: Temperature control and surface cooler reform in operating room air decontamination system. *Chin Med Equip J* **30**(5), 048 (2009)
16. Wu, C.C., Lee, G.W.M., Yang, S., Yu, K.P., Lou, C.L.: Influence of air humidity and the distance from the source on negative air ion concentration in indoor air. *Sci Total Environ* **370**(1), 245–253 (2006)
17. MacIntosh, D.L., Minegishi, T., Kaufman, M., Baker, B.J., Allen, J.G., Levy, J.I., Myatt, T.A.: The benefits of whole-house in-duct air cleaning in reducing exposures to fine particulate matter of outdoor origin: a modeling analysis. *J Expo Sci Environ Epidemiol* **20**(2), 213–224 (2010)
18. Hill, A.L.: Method and apparatus for decontaminating a region without dehumidification. <http://www.patentsencyclopedia.com/app/20090047174>
19. Surdo, E.M., Khan, I.A., Choudhury, A.A.: Barrier properties of poly(vinyl alcohol) membranes containing carbon nanotubes or activated carbon. *J Hazard Mater* **188**(1–3), 334–340 (2011)
20. Mielnik, T.J., Krieger, E.W., Eddington, D.L., Koos, G.C.: Room decontamination with hydrogen peroxide vapor. US (2008). <http://101.96.10.63/static1.squarespace.com/static/52d6d893e4b0edcb252bf2af/t/52e08b58e4b0233a85284635/1390447448903/vhroomdecontamination.p>
21. Grabarczyk, Z.: Effectiveness of indoor air cleaning with corona ionizers. *J Electrostat* **51**(01), 278–283 (2001)
22. Omasa, K., Tobe, K., Kondo, T.: Absorption of organic and inorganic air pollutants by plants. In: Omasa, K., Saji, H., Youssefian, S., Kondo, N. (eds.) *Air pollution and plant biotechnology*, pp. 155–178. Springer, Berlin (2002)
23. Kato, K., Tsuzuki, A., Taoda, H., Torii, Y., Kato, T., Butsugan, Y.: Crystal structures of TiO₂ thin coatings prepared from the alkoxide solution via the dip-coating technique affecting the photocatalytic decomposition of aqueous acetic acid. *J Mater Sci* **29**(22), 5911–5915 (1994)
24. Linsebigler, A.L., Lu, G., Yates, J.T.: Photocatalysis on TiO₂ surfaces: principles, mechanisms, and selected results. *Chem Rev* **95**(3), 735–758 (1995)
25. Legrini, O., Oliveros, E., Braun, A.M.: ChemInform abstract: photochemical processes for water treatment. *ChemInform* **24**(28), 671–698 (1993)
26. Liu, H., Lian, Z., Ye, X., Shangguan, W.: Kinetic analysis of photocatalytic oxidation of gas-phase formaldehyde over titanium dioxide. *Chemosphere* **60**(5), 630–635 (2005)
27. Shiraishi, F., Yamaguchi, S., Ohbuchi, Y.: A rapid treatment of formaldehyde in a highly tight room using a photocatalytic reactor combined with a continuous adsorption and desorption apparatus. *Chem Eng Sci* **58**(3), 929–934 (2003)

