Photocatalytic Oxidation of PLA/TiO$_2$-Composite Films for Indoor Air Purification

Pattamaphon Chanklom, Torpong Kreetachat, Rotruedee Chotigawin, and Kowit Suwannahong*

Cite This: ACS Omega 2021, 6, 10629−10636

ABSTRACT: Non-decomposable plastic has been replaced with polylactic acid, which is a biodegradable aliphatic polyester stationary phase, in composite films embedded with a TiO$_2$ photocatalyst for mitigation of indoor air pollution. PLA has superior properties relative to those of other biopolymers, such as a relatively high melting point, crystallinity, and rigidity. This study aimed to incorporate TiO$_2$-anatase into PLA for use as a photocatalyst using the blown film method. Photocatalytic oxidation, an advanced oxidative process, has been recognized as an economical technique providing convenience and efficiency with indoor air treatment. Therefore, the use of new environmentally friendly biodegradable polymers provides an alternative way to address the severe environmental concerns caused by non-decomposable plastics. UV−vis spectrophotometry and scanning electron microscopy−energy-dispersive X-ray spectroscopy (SEM−EDX) were used to observe the dispersibility and mixing capacity of the TiO$_2$-anatase PLA matrix. TiO$_2$ dosages were 5, 10, and 15% (wt/wt), and they were incorporated with a twin-screw extruder. SEM−EDX images demonstrated the homogeneity of TiO$_2$ distribution in the PLA matrix. The energy band gaps of TiO$_2$ in the PLA/TiO$_2$-composite films were between 3.14 and 3.22 eV. The relationship between the photocatalytic oxidation rate and the TiO$_2$ dosage in the PLA/TiO$_2$-composite films was determined. A prototype reactor model is geared toward the development of air purifiers for indoor air conditioning. Rate constants for benzene degradation were obtained using first-order kinetics to find rate constants matching experimental findings. In the PLA/TiO$_2$-composite film, the TiO$_2$-anatase photocatalyst was able to degrade 5 ppm benzene. This work contributes to the use of ecoefficient photocatalytic oxidation.

HIGHLIGHTS

- TiO$_2$ loaded on a plant-based biodegradable polylactic acid was used as a photocatalyst for benzene degradation in simulated indoor air.
- The photocatalyst was placed in a commercial air purifier, catalysis was performed with a high volume of simulated indoor air, and the highest photocatalytic oxidation efficiency was seen with a 5% PLA/TiO$_2$ film.

INTRODUCTION

Adults inspire and expire 400−500 mL of air in each respiratory cycle.$^1$ People spend approximately 90% of their time indoors, in offices, homes, malls, gyms, and schools.$^7$ Therefore, indoor air quality (IAQ) can significantly affect the health and quality of life.$^5$ Poor indoor air quality, particularly involving indoor air microbiomes, e.g., Mycobacterium tuberculosis$^6$ and severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2),$^5$ seriously affects human health.$^5$ The coronavirus spreads through liquid droplets when an infected person coughs,$^8$ sneezes,$^9$ speaks,$^9$ sings,$^9$ and/or shouts.$^9$

During the coronavirus (COVID-19) pandemic, people spend almost all of their time at home; as a result, they are exposed to high levels of indoor air pollution, not only bioaerosols but also volatile organic compounds (VOCs). Sources of VOCs that cause poor indoor air quality are tobacco,$^{11}$ cooking,$^{12}$ solvents,$^{13}$ wood preservatives,$^{14}$ painting,$^{15}$ cleansers, and disinfectants.$^{16}$ The main indoor and outdoor environmental problems caused by VOCs are increased tropospheric ozone,$^{17}$ adverse health effects,$^{18}$ and carcinogenicity.$^{19}$ VOCs increase the risk of obstructive pulmonary diseases, skin cancers, birth defects, and neurocognitive impairment.$^{20}$ Benzene is one of the VOCs identified as carcinogenic to humans by the
TiO₂ (anatase phase) was purchased from Dupont Company. Food-grade polylactic acid was purchased from NatureWorks.

Preparation of the Photocatalyst; PLA/TiO₂-Composite Film. Titanium dioxide (TiO₂) dosages of 5, 10, and 15% (wt/wt) were mixed with polylactic acid (PLA) and incorporated utilizing a twin-screw extruder (Lab Tech, LTE16-40). TiO₂ anatase levels were altered to increase TiO₂ dispersion and boost the compatibility between the TiO₂ and the PLA matrix. PLA/TiO₂-composite films with a thickness of 30 μm were obtained at operating temperatures ranging from 100 to 190 °C and at 200 rpm using the blown film technique. Photocatalytic oxidation (PCO) has been widely used and is well known for the treatment of VOCs because it can transform not only VOCs but also a wide range of pollutants to end products obtained from processes involving H₂O and CO₂; it exhibits various advantages, such as operation at low pressure and temperature. The main industrial hygiene principles to follow to reduce exposure to hazards are recognition, measurement, evaluation, and control. An air purifier is an affordable, user-friendly, and easily accessible way to control chemical hazards. Technologies for VOC reduction include adsorption, liquid absorption, membrane separation, bio-filtration, ozonation, plasma catalysis, biological degradation, and advanced oxidation processes such as photocatalytic oxidation. Photocatalytic oxidation (PCO) has been widely used and is well known for the treatment of VOCs because it can transform not only VOCs but also a wide range of pollutants to end products obtained from processes involving H₂O and CO₂; it exhibits various advantages, such as operation at low pressure and temperature. The authors of this paper chose titanium dioxide (TiO₂) as a photocatalyst to explain the rate of pollutant removal.

Characterization of the Photocatalyst; PLA/TiO₂-Composite Film. Scanning electron microscopy (SEM) (LEO 1455 VP, 20 kV) was used to study the morphologies of the films. Energy-dispersive X-ray spectroscopy (EDX) (LEO 1455 SVP, SEM—EDX 20 kV) was used for qualitative and quantitative analysis of elements in films. A UV—visible spectrophotometer (UV–vis) (Analytik Jena SPECORD 210 PLUS) was used to measure the photocatalyst absorptions in the ultraviolet—visible spectrum with a scan range of 200—800 nm, a scan speed of 50 nm/s, a slit of 1 nm, and a delta lambda of 1 nm. All spectra were monitored in absorbance mode under ambient conditions. The band gap energy of TiO₂ on a film was calculated from the absorbance results. Attenuated total reflectance Fourier transform infrared spectroscopy (ATR-FTIR) (PerkinElmer Frontier) was used to determine the functional groups of the chemicals. Spectra were recorded in the range of 400—4000 cm⁻¹ with a scan step of 1 cm⁻¹; the functional groups of the films were determined before and after photocatalytic experiments (360 h duration).

Photocatalytic Oxidation Degradation with Scale-Up of the Photoreactor for Air Purification. A UVC 254 nm lamp was placed in the middle of a cylindrical annular reactor containing the photocatalyst. The annular reactor was set up in a commercial air purifier, as shown in Figure 1. Photocatalytic oxidative degradation was conducted in an annular closed-system reactor. In a 785 L chamber cabinet, a scaled-up photoreactor was used to simulate indoor air conditions, and the total reactor volume was approximately 2 L. The PLA/TiO₂-composite film and a type-C ultraviolet lamp with an output wavelength of 254 nm were mounted inside the reactor. The electrical power of the UVC lamp was 18 W, which is equivalent to a light intensity of approximately 5 mW·cm⁻².
Figure 1 displays a schematic diagram of the experimental setup. The reactor was linked to an air compressor that maintained an air flow rate of 300 L·min⁻¹. The relative humidity in the reactor was changed to 55% by initially circulating air with a particular humidity through the reactor. The humidity and temperature inside the reactor were continuously measured with a thermohygrometer. The original benzene concentration was 5.21 ppm. The UVC lamp was switched on to start the photocatalytic oxidation after a steady state was reached.

Quantitative research was performed using gas chromatography (GC) with an instrument fitted with a flame ionization detector (FID) to track the concentration of benzene in the reactor throughout the experiment. Heterogeneous catalytic processes, including adsorption and photodegradation, were defined in the model. The Langmuir–Hinshelwood model represented by eq 1 was used to determine the bulk photodegradation rate.

\[ r = \frac{kKC}{1 + KC} \]  

(1)

where \( k \) is the apparent kinetic constant (ppm·min⁻¹), \( K \) is the adsorption equilibrium constant (ppm⁻¹), and \( C \) is the concentration of VOCs on the photocatalyst surface in the gas phase (ppm). The adsorption equilibrium and reaction rate constants are intrinsic properties of the photocatalyst for the decomposition of VOCs. Other variables were measured by experimentation.

For determination of the oxidation rate and CO₂ yield, gas samples were collected at the sampling port of the reactor. The gas samples were then studied using gas chromatography–flame ionization detection (GC–FID) and gas chromatography–thermal conductivity detection (GC–TCD) for the analyses of benzene and CO₂, respectively. The analyses of benzene were performed using gas chromatography–mass spectroscopy (GC–MS) as described earlier, whereas the CO₂ concentration was analyzed using GC–TCD with a Shimadzu model GC-8A TCD instrument equipped with a polar pack Q 3 M in a glass column. The analytical conditions were set as follows: an injection temperature of 50 °C, a column temperature of 100 °C, a TCD temperature of 100 °C, a current of 90 mA, an injection volume of 0.2 mL, and a gas pressure of 2 kg·cm⁻².

## RESULTS AND DISCUSSION

### Characterization of the PLA/TiO₂-Composite Film

The compounding of the virgin PLA film and PLA/TiO₂ composite film by the extrusion method is demonstrated in Figure 2. The virgin-PLA film and PLA/TiO₂-composite film were produced by compounding using a blow machine, as shown in Figure 2. SEM–EDX was used to classify the morphology of the PLA/TiO₂-composite film. The dispersion of TiO₂ on the surface of PLA/TiO₂-composite films is shown in Figure 3, and a virgin PLA film is shown for reference in Figure 3a. TiO₂ was well dispersed on the inner surface of the film, especially for 5% and 10% TiO₂ loadings, as shown in Figure 3. In comparison with prior research, better results were obtained during this work. However, a few clumps of TiO₂ particles were observed on the inner surface of the film with high dosages of TiO₂. During the heating phase of the blown film method, aggregation of the TiO₂ particles could occur. EDX mapping of the PLA and the PLA/TiO₂-composite films is described in Table 1.

### Optical Properties of the PLA/TiO₂ Composite Film Determined Using a UV–Visible Spectrophotometer

The UV–vis absorbance spectra of the PLA/TiO₂-composite films with different concentrations of TiO₂-anatase were examined. As seen from the spectra in Figure 4, the virgin PLA film absorbed little UV–visible light in the range of 200–800 nm, while the films with 5 and 10% wt/wt TiO₂-anatase absorbed UV light with wavelengths less than 350 nm. The energy band gap (\( E_g \)) of the TiO₂-anatase in PLA composite films can be calculated from the absorption spectra. A range of 3.14–3.22 eV was determined for the band gaps, as shown in Table 2. The band gap energy is provided when this material is irradiated with photons with wavelengths less than 350 nm. An electron from the valence band is promoted to the conduction band under these conditions. In the space-charge field, the resulting electron–hole pair has a lifetime that allows its participation in chemical reactions.

### Chemical Structure of PLA/TiO₂-Composite Films Determined by ATR-FTIR

The functional groups contained in the PLA/TiO₂ composite films were defined by ATR-FTIR. The same findings were obtained for all samples. The ATR-FTIR spectra are shown in Figure 5. The characteristic bands corresponding to H—C==O:C==H aliphatic hydrocarbons, aldehydes, and COOR groups are at 2850–3000, 2830–2965, and 1640–1690 cm⁻¹, respectively. Additionally, C–C aromatic stretching vibrations gave peaks at 1400–1500 cm⁻¹. The band width at 719 cm⁻¹ should be attributable to the band envelope for Ti–O–Ti groups. After photocatalytic oxidation experiments, all FTIR spectra of the PLA/TiO₂ composite films recorded decreases in the intensities of all adsorption bands. Moreover, after photocatalytic oxidation, the adsorption peak at 1640–1690 cm⁻¹ was shifted to 1710–1760 cm⁻¹. Furthermore, as mentioned in general texts, the
photocatalytic oxidation of PLA under UV light generates various radicals during decomposition.\(^{51}\) In addition, the photocatalytic oxidation of PLA was performed at ambient temperature and has the potential for degradation of PLA into small organic acids or compounds such as HCOOH, CH₃COOH, (COOH)₂, or CH₃CHO.\(^{52}\)

### Photocatalytic Oxidation of Benzene in Simulated Indoor Air.

Benzene photocatalytic oxidation was studied by using PLA/TiO₂-composite films with different TiO₂ dosages. The relationship of the photocatalytic oxidation rate to the catalyst dosage level is presented in Figure 6. Benzene degradation rate constants were obtained using first-order kinetics, and rate constants were determined by fitting experimental results. Table 3 shows the apparent kinetic rate constant for photocatalytic oxidation, obtained by using a simplified Langmuir–Hinshelwood approach. The apparent kinetic constant of the 5% PLA/TiO₂-composite film was the highest. The plots demonstrate that the slopes were determined from straight lines by following first-order kinetic methods and using the least-squares procedure. A first-order reaction at low concentrations was confirmed by previous research, and a linear increase in the reaction rate at low initial benzene concentrations was reported. In this study, benzene was the only pollutant available for degradation, and a single site Langmuir–Hinshelwood model was applied to evaluate the photocatalytic oxidation rates.\(^{45}\)

Figure 6 shows that the film with a TiO₂ dosage of 5% wt/wt yielded the highest removal efficiency (44%); the 10 and 15% wt/wt films exhibited removal efficiencies of 42 and 32%, respectively. On the other hand, there was a small decrease when the dose of TiO₂ rose from 5 to 15% wt/wt. This could be due to the higher doses of TiO₂ and higher abundance of hydroxyl radicals interacting with benzene, resulting in faster film removal. However, over a certain dose of TiO₂, the rate of degradation began to decrease due to mass transfer\(^{55}\) and the attenuation of light penetration.\(^{54}\)

### Table 1. EDX Analysis of PLA/TiO₂ Composite Films and the Corresponding Elemental Compositions

| element     | PLA  | 5% PLA/TiO₂ | 10% PLA/TiO₂ | 15% PLA/TiO₂ |
|-------------|------|-------------|--------------|--------------|
| carbon (C)  | 50.12| 48.01       | 47.98        | 44.54        |
| oxygen (O)  | 49.88| 45.65       | 42.14        | 40.15        |
| titanium (Ti)| 6.34 | 9.88        | 15.32        |              |

### Table 2. Calculated Results from the Absorbance of the PLA/TiO₂ Composite Films with Various Dosages of TiO₂

| no. | PLA/TiO₂-composite film | band gap energy (E_g, eV) |
|-----|-------------------------|--------------------------|
| 1   | 5% wt/wt                | 3.22                     |
| 2   | 10% wt/wt               | 3.19                     |
| 3   | 15% wt/wt               | 3.14                     |

Figure 3. SEM images of the (a) virgin PLA composite film, (b) 5% wt/wt PLA/TiO₂-composite film, (c) 10% wt/wt PLA/TiO₂-composite film, and (d) 15% wt/wt PLA/TiO₂-composite film.

Figure 4. UV–visible absorbance spectra of the virgin PLA film and 5, 10, and 15% PLA/TiO₂-composite films.
Mass transfer affects the rate of degradation, which is explained by the processes of photocatalytic oxidation. These processes are as follows: first, benzene is transferred to the photocatalyst surface; second, benzene is adsorbed on the photocatalyst surface; third, a photocatalytic oxidation reaction occurs on the surface; then, byproducts are desorbed from the surface of the photocatalyst; finally, byproducts are transferred from the surface into the air.\textsuperscript{55} TiO\textsubscript{2} dosages of 10 and 15% may be too high for PLA/TiO\textsubscript{2}-composite films and may cause aggregation, which affects mass transfer and lowers the degradation rate.\textsuperscript{56} Moreover, the photocatalytic oxidation reaction occurs at the liquid–catalyst interface, and therefore, when the catalyst is immobilized, both external and internal mass transfers play significant roles in the overall photocatalytic process.

**Intermediate Products in the Photocatalytic Oxidation of Benzene in Simulated Indoor Air.** Intermediate products were produced in the process of photocatalytic degradation of benzene by the PLA/TiO\textsubscript{2}-composite film, as shown in Figure 7. The mechanism of the photocatalytic degradation of benzene by TiO\textsubscript{2} has been shown in a previous study.\textsuperscript{57} Benzene was converted into phenol, then into other intermediates, and finally into carbon dioxide and water.\textsuperscript{57} The proportions of residual intermediates increased as the oxidation rate and time increased. The CO\textsubscript{2} yield was probably due to a surface reaction. The CO\textsubscript{2} yield rate was related to the apparent oxidation rate of benzene or a secondary intermediate. Hypothetically, benzene can be transformed into CO\textsubscript{2} and H\textsubscript{2}O; however, residual intermediates can be found for incomplete mineralization. The amounts of residual intermediates increased rapidly. After this, the concentrations of intermediates increased slowly at rates corresponding to the oxidation rates. For PCO, accumulation of residual intermediates can occur at the active site and in the benzene gas

![Picture](https://doi.org/10.1021/acsomega.0c06194)

**Table 3. Simplified Langmuir–Hinshelwood Form\textsuperscript{a}**

| initial concentration (ppm) | 5% PLA/TiO\textsubscript{2} | 10% PLA/TiO\textsubscript{2} | 15% PLA/TiO\textsubscript{2} |
|-----------------------------|-----------------------------|-----------------------------|-----------------------------|
|                             | k\textsuperscript{b} | K | R\textsuperscript{2} | k\textsuperscript{b} | K | R\textsuperscript{2} | k\textsuperscript{b} | K | R\textsuperscript{2} |
| 5.21                        | 0.0047 | 0.1975 | 0.9988 | 0.0008 | 0.1956 | 0.9288 | 0.0001 | 0.1940 | 0.9996 |

\textsuperscript{a}Simplified Langmuir–Hinshelwood form is \( \ln(C/Co) = -kKt \). \textsuperscript{b}k is the apparent kinetic constant (ppm·min\textsuperscript{-1}). K is the adsorption equilibrium constant (ppm\textsuperscript{-1}).
The benzene removal efficiency for photocatalytic oxidation in simulated indoor air suggests that PLA/TiO$_2$-composite films can be used for indoor air purifiers.

**REFERENCES**

(1) Hallett, S.; Toro, F.; Ashurst, J. V. Physiology, Tidal Volume [Online]; StatPearls Publishing: Treasure Island, FA, 2020; pp. 1–15. https://www.ncbi.nlm.nih.gov/books/NBK482502/?report=reader (access Dec 10, 2020).

(2) Klepeis, N. E.; Nelson, W. C.; Ott, W. R.; Robinson, J. P.; Tsang, A. M.; Switzer, P.; Behar, J. V.; Hern, S. C.; Engelmann, W. H. The National Human Activity Pattern Survey (NHAPS): a resource for assessing exposure to environmental pollutants. J. Expo. Sci. Environ. Epidemiol. 2001, 11, 231–252.

(3) Cincinelli, A.; Martellini, T. Indoor Air Quality and Health. Int. J. Environ. Res. Public Health 2017, 14, 1286.

(4) Lin, Y.-J.; Lin, H.-C.; Yang, Y.-F.; Chen, C.-Y.; Ling, M.-P.; Chen, S.-C.; Chen, W.-Y.; You, S.-H.; Lu, T.-H.; Liao, C.-M. Association Between Ambient Air Pollution and Elevated Risk of Tuberculosis Development. Infect Drug Resist 2019, Volume 12, 3835—3847.

(5) Meselson, M. Droplets and Aerosols in the Transmission of SARS-CoV-2. N. Engl. J. Med 2020, 382, 2063–2063.

(6) Nwanaji-Enwerem, J. C.; Allen, J. G.; Beamer, P. I. Another invisible enemy indoors: COVID-19, human health, the home, and United States indoor air policy. J. Expo. Sci. Environ. Epidemiol. 2020, 30, 773–775.

(7) Jones, N. R.; Qureshi, Z. U.; Temple, R. J.; Larwood, J. P. J.; Greenhalgh, T.; Bourouiba, L. Two metres or one: what is the evidence for physical distancing in covid-19? BMJ 2020, 370, m3223.

(8) Busco, G.; Yang, S. R.; Seo, J.; Hassan, Y. A. Sneezing and asymptomatic virus transmission. Phys. Fluids 2020, 32, No. 073309.

(9) Sadinytskyy, V.; Bax, C. E.; Bax, A.; Anfinrud, P. The airborne lifetime of small speech droplets and their potential importance in SARS-CoV-2 transmission. Proc. Nat. Acad. Sci. 2020, 117, 11875.

(10) Hamner, L.; Dubbel, P.; Capron, L.; Ross, A.; Jordan, A.; Lee, J.; Lynn, J.; Ball, A.; Narwal, S.; Russell, S.; Patrick, D.; Leibrand, H. High SARS-CoV-2 Attack Rate Following Exposure at a Choir Practice — Skagit County, Washington, March 2020. Morb. Mortal Wkly. Rep. 2020, 69, 606–610.

(11) Vanker, A.; Nduru, P. M.; Barnett, W.; Dube, F. S.; Syl, P. D.; Gie, R. P.; Nicol, M. P.; Zar, H. J. Indoor air pollution and tobacco smoke exposure: impact on nasopharyngeal bacterial carriage in mothers and infants in an African birth cohort study. ERJ Open Res. 2019, 5, 00052–00188.

(12) Zhang, D. C.; Liu, J. J.; Jia, L. Z.; Wang, P.; Han, X. Speciation of VOCs in the cooking fumes from five edible oils and their corresponding health risk assessments. Atmos. Environ. 2019, 211, 6–17.

(13) Zhang, X.; Zhao, W.; Nie, L.; Shao, X.; Dang, H.; Zhang, W.; Wang, D. A new classification approach to enhance future VOCs emission policies: Taking solvent-consuming industry as an example. Environ. Pollut. 2021, 115868.

(14) Rösch, C.; Kohajda, T.; Röder, S.; Bergen, M. V.; Schlunk, U. Relationship between sources and patterns of VOCs in indoor air. Atmos. Pollut. Res. 2014, 5, 129–137.

(15) Molgaard, B.; Vitanen, A.-K.; Kangas, A.; Huhtineni, M.; Larsen, S.; Vanhala, E.; Hussein, T.; Boor, B.; Hämmer, K.; Koivisto, A. Exposure to airborne particles and volatile organic compounds from polyurethane molding, spray painting, lacquering, and gluing in a workshop. Int. J. Environ. Res. Public Health 2015, 12, 3756–3773.
(16) Chin, J. Y.; Godwin, C.; Parker, E.; Robins, T.; Lewis, T.; Harbin, P.; Batterman, S. Levels and sources of volatile organic compounds in homes of children with asthma. *Indoor Air* 2014, 24, 403–415.

(17) Zhang, J.; Wei, Y.; Fang, Z. Ozone Pollution: A Major Health Hazard Worldwide. *Front. Immunol.* 2019, 10, 2518.

(18) Santiago, F.; Lima, S.; Pinheiro, T.; Silvestre, R. T.; Otero, U. B.; Tabalipa, M. M.; Kowyakova, N.; Ornellas, M. H.; Liehr, T.; Alves, G. Benzene poisoning, clinical and blood abnormalities in two Brazilian female gas station attendants: two case reports. *BMC Res. Notes* 2017, 10, 52–52.

(19) Zhang, J.; Wang, P.; Li, J.; Mendola, P.; Sherman, S.; Ying, Q. Estimating population exposure to ambient polyenic aromatic hydrocarbon in the United States - Part II: Source apportionment and cancer risk assessment. *Environ. Int.* 2016, 97, 163–170.

(20) Cheng, S.; Chang-Chien, G.-P.; Huang, Q.; Zhang, Y.-B.; Yan, P.; Zhang, J.; Wang, T.; Zhang, D.; Teng, G. Global Research Trends in Health Effects of Volatile Organic Compounds during the Last 16 Years: A Bibliometric Analysis. *Aerosol Air Qual. Res.* 2019, 19, 1834–1843.

(21) IARC. Chemicals and industrial processes associated with cancer in humans: an updating of IARC monographs volumes 1 to 20. *IARC Monogr. Eval. Carcinog. Risks Hum.* Suppl. 1979, 1, 15.

(22) Talty, J. T. General Methods of Control Available to the Industrial Hygiene Engineer. In *Industrial Hygiene Engineering*; Talty, J. T. Eds.; William Andrew Publishing: Park Ridge, NJ, 1998; pp. 70–78.

(23) Fox, R. W. Air cleaners: A review. *J. Allergy Clin. Immunol.* 1994, 94, 413–416.

(24) Zhu, L.; Shen, D.; Luo, K. H. A critical review on VOCs adsorption by different porous materials: Species, mechanisms and modification methods. *J. Hazard. Mater.* 2020, 389, 122102.

(25) Ma, X.; Wu, M.; Liu, S.; Huang, J.; Sun, B.; Zhou, Y.; Zhu, Q.; Lu, H. Concentration control of volatile organic compounds by ionic liquid absorption and desorption. *Chin. J. Chem. Eng.* 2019, 27, 2383–2389.

(26) Liu, C. Y.; Tseng, C. H.; Wang, H. C.; Dai, C. F.; Shih, Y. H. The Study of an Ultraviolet Radiation Technique for Removal of the Indoor Air Volatile Organic Compounds and Bioaerosol. *Int. J. Environ. Res. Public Health* 2019, 16, 2557.

(27) Kong, W.; Miao, Q.; Qin, P.; Baeyens, J.; Tan, T. Environmental and economic assessment of vegetable oil production using membrane separation and vapor recompression. *Front. Chem. Sci. Eng.* 2017, 11, 166–176.

(28) Huang, Y.; Ho, S.; Lu, Y.; Niu, R.; Xu, L.; Cao, J.; Lee, S. Removal of Indoor Volatile Organic Compounds via Photocatalytic Oxidation: A Short Review and Prospect. *Molecules* 2016, 21, 56.

(29) da Costa Filho, B. M.; Silva, G. V.; Boaventura, R. A. R.; Dias, M. M.; Lopes, J. C. B.; Vilar, V. J. P. Ozonation and ozone-enhanced photocatalysis for VOC removal from air streams: Process optimization, synergy and mechanism assessment. *Sci. Total Environ.* 2019, 687, 1357–1368.

(30) Liu, R.; Song, H.; Li, B.; Li, X.; Zhu, T. Simultaneous removal of toluene and styrene by non-thermal plasma-catalysis: Effect of VOCs interaction and system configuration. *Chemosphere* 2021, 263, 127893.

(31) Mohktari, M.; Hajizadeh, Y.; Jafari, N.; Ebrahimie, A. A.; Abdolahnejad, A. Improved biodegradation of hydrophobic volatile organic compounds from the air stream in a multilayer biofilter. *MethodsX* 2019, 6, 2052–2056.

(32) Tang, G. L. Converting Volatile Organic Compounds to CO2 and Water. *Am. J. Chem. Eng.* 2016, 4, 62–67.

(33) Haider, A. J.; Jameel, Z. N.; Al-Hussaini, I. H. M. Review on: Titanium Dioxide Applications. *Energy Proc.* 2019, 157, 17–29.

(34) Suwannahong, K.; Srivithayapakorn, S.; Noophan, P.; Sanongraj, W. Improvement of TiO2/LDPE Composite Films for Photocatalytic Oxidation of Acetone. *Adv. Mater. Res.* 2014, 931–932.

(35) Pavanupree, S.; Dubas, S. T.; Rangkupan, R. Surface modification of polypropylene non-woven fibers with TiO2 nano-particles via layer-by-layer self assembly method: Preparation and photocatalytic activity. *J Environ. Sci.* 2015, 37, 59–66.

(36) Mishra, G.; Mukhopadhyay, M. TiO2 decorated functionalized halloysite nanotubes (TiO2@HNTs) and photocatalytic PVC membranes synthesis, characterization and its application in water treatment. *Sci. Rep.* 2019, 9, 4345.

(37) Pahasap-anan, T.; Suwannahong, K.; Dechapanya, W.; Rangkupan, R. Fabrication and photocatalytic activity of TiO2 composite membranes via simultaneous electropinning and electro-spraying process. *J. Environ. Sci.* 2018, 72, 13–24.

(38) Sekar, A.; Varghese, G. K.; Ravi Varma, M. K. Analysis of benzene air quality standards, monitoring methods and concentrations in indoor and outdoor environment. *Heliyon* 2019, 5, e02918.

(39) Montero-Montoya, R.; Lopez-Vargas, R.; Arellano-Aguilar, O. Volatile Organic Compounds in Air: Sources, Distribution, Exposure and Associated Illnesses in Children. *Ann. Glob. Health.* 2018, 84, 225–238.

(40) Salahuddin, N.; Abdelwahab, M.; Gaber, M.; Elneanaey, S. Synthesis and Design of Norfluroxacin drug delivery system based on PLA/TiO2 nanocomposites: Antibacterial and antitumor activities. *Mater. Sci. Eng.* 2020, 108, 110375.

(41) Tharasawatpipat, C.; Suwannahong, K.; Kruenate, J.; Kreetachat, T. Removal of VOCs by photocatalytic oxidation using nano-TiO2/PLA biocomposite. *J. Environ. Biol.* 2015, 36, 617–621.

(42) Mahapatra, D. M.; Chanakya, H. N.; Ramachandra, T. V. Chapter 15: algae derived single-cell proteins: economic cost analysis and future prospects. In: *Protein byproducts: transformation from environmental burden into value-added products*; Elsevier: San Diego, 2016; pp. 275–301.

(43) Mo, J.; Zhang, Y.; Xu, Q.; Lamson, J. J.; Zhao, R. Photocatalytic Purification of Volatile Organic Compounds in Indoor Air: A Literature Review. *Atmos. Environ.* 2009, 43, 2229–2246.

(44) Jafari, A. J.; Kalantari, R. R.; Kermani, M.; Firooz, M. H. Photocatalytic degradation data of benzene and toluene by ZnO coated on glass plates under simulated sunlight. *Data Brief* 2018, 20, 490–495.

(45) Kaoen, P.; Dechapanya, W.; Khamwicht, A.; Suwannahong, K. Natural rubber modification as a pre-vulcanized latex impregnated with TiO2 for photo-catalytic degradation of gaseous benzene. *Heliyon* 2020, 6, e03912.

(46) Li, S.; Chen, G.; Qiang, S.; Yin, Z.; Zhang, Z.; Chen, Y. Synthesis and evaluation of highly dispersible and efficient photocatalytic TiO2/poly lactic acid nanocomposite films via sol-gel and casting processes. *Int. J. Food Microbiol.* 2020, 331, 108763.

(47) Kreetachat, T.; Kruenate, J.; Suwannahong, K. Preparation of TiO2/Bio-Composite Film by Sol-Gel Method in VOCs Photocatalytic Degradation Process. *Appl. Mech. Mater.* 2013, 390, 552–556.

(48) Sooodoo, N.; Raghunanand, L.; Bouzidi, L.; Natine, S. Phase behavior of monosulfones: Use of high polarity sulfonyl groups to improve the thermal properties of lipid-based materials for PCM applications. *Sol. Energy Mater. Sol. Cells* 2019, 201, 110115.

(49) Asmatulu, R.; Khan, W. S. Chapter 13 - Characterization of electrospun nanofibers. In *Synthesis and Applications of Electrospun Nanofibers*; Asmatulu, R.; Khan, W. S., Eds.; Elsevier: Amsterdam, 2019; pp. 257–281.

(50) Suwannahong, K.; Liengcharernsit, W.; Sanongraj, W.; Kruenate, J. Application of Nano-TiO2/LDPE composite film on photocatalytic oxidation degradation of dichloromethane. *J. Environ. Biol.* 2012, 33, 955–959.

(51) Salić, J.; Čer, J.; Jurčík, M.; Verney, V.; Marek, A. A.; Koutný, M. Photodegradation and Biodegradation of Poly (Lactic) Acid Containing Orotic Acid as a Nucleation Agent. *Materials* 2019, 12, 481.

(52) Boonmeen, C.; Kositonont, C.; Leeljkapai, T. Degradation of Poly (Lactic Acid) under Simulated Landfill Conditions. *Environ. Nat. Resour.* 2016, 14, 1–9.
(53) Ola, O.; Maroto-Valer, M. M. Review of material design and reactor engineering on TiO\textsubscript{2} photocatalysis for CO\textsubscript{2} reduction. \textit{J. Photochem. Photobiol. C.} \textbf{2015}, \textit{24}, 16–42.

(54) Raza, W.; Haque, M. M.; Muneer, M.; Bahnemann, D. Synthesis of visible light driven TiO\textsubscript{2} coated carbon nanospheres for degradation of dyes. \textit{Arab. J. Chem.} \textbf{2019}, \textit{12}, 3534–3545.

(55) Assadi, A. A.; Palau, J.; Bouzaza, A.; Wolbert, D. Modeling of a continuous photocatalytic reactor for isovaleraldehyde oxidation: Effect of different operating parameters and chemical degradation pathway. \textit{Chem. Eng. Res. Des.} \textbf{2013}, \textit{91}, 1307–1316.

(56) Pellegrino, F.; Pellutì, L.; Sordello, F.; Minero, C.; Ortel, E.; Hodoroaba, V.-D.; Maurino, V. Influence of agglomeration and aggregation on the photocatalytic activity of TiO\textsubscript{2} nanoparticles. \textit{Appl. Catal. B.} \textbf{2017}, \textit{216}, 80–87.

(57) Boyjoo, Y.; Sun, H.; Liu, J.; Pareek, V. K.; Wang, S. A Review on Photocatalysis for Air Treatment: From Catalyst Development to Reactor Design. \textit{Chem. Eng. J.} \textbf{2017}, \textit{310}, 537–559.