CHEMICAL ENGINEERING TRANSACTIONS
VOL. 127, 2026
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it
Guest Editors: Laura Capelli, Marzio Invernizzi, Selena Sironi

ISBN 979-12-81206-28-1; **ISSN** 2283-9216
DOI: 10.3303/CET26127029

Coupling of Photocatalysis and Adsorption using a Single Multifunctional Filter for Gas-Phase Toluene Removal

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The removal of volatile organic compounds (VOCs) from air streams remains a key challenge in air purification processes. Conventional technologies such as photocatalysis and adsorption are effective but suffer from significant limitations when applied separately. In this study, five commercial activated carbon materials were first evaluated using adsorption isotherm measurements to identify the most suitable adsorbent. The selected activated carbon powder (AC) was then coated on an innovative textile-based filter composed of optical fibers and TiO_2. UVA LEDs were used to irradiate the optical fibers, allowing uniform and efficient illumination of the TiO_2 coating. Two coating configurations were investigated to study the effect of the distribution of activated carbon and TiO_2 on pollutant removal. This approach promotes the synergistic coupling of adsorption and photocatalysis within the same structure. The first configuration comprises a filter with two distinct functional sides. In contrast, the second configuration consists of a filter coated with a homogeneous mixture of TiO_2 and AC. In both cases, adsorption was first carried out until saturation, followed by photocatalytic treatment under UVA irradiation. Toluene was used as a representative model compound to evaluate the performance of the textile filter. The results showed that the filter configuration significantly affects toluene removal, with up to 70 % degradation achieved when adsorption and photocatalysis were separated on two sides. These findings confirm the potential of integrating both processes in compact air purification devices.

1. Introduction

Due to the presence of volatile organic compounds (VOCs), and other gaseous pollutants that cause respiratory and systemic illnesses, air pollution, especially indoor environments, poses serious dangers to human health (Zhou et al., 2023). Indoor air treatment technologies can be divided into two categories: non-destructive processes where pollutants are removed from the air without any chemical destruction. These processes mainly include adsorption, mechanical filtration, and membrane separation. In contrast, destructive methods aim to convert pollutants into less harmful compounds such as photocatalytic oxidation, ozonation, non-thermal plasma and catalytic oxidation. Although these technologies have shown promising performance for VOCs abatement, each process presents specific limitations that's restrict its large-scale application (Luengas et al., 2015). Among non-destructive methods, adsorption is widely used for pollutant removal because it operates under mild conditions, is simple to implement and requires limited energy. Activated carbon remains one of the most common adsorbents due to its high specific area, well-developed microporosity, and strong affinity for organic molecules (Yang et al., 2018). However, adsorption also suffers from important limitations, such as adsorbent saturation, the need for regeneration, and possible pollutant re-emission under certain operating conditions (Wu et al., 2024). On the other hand, photocatalytic oxidation has emerged as a promising technology for pollutants elimination (Serhane Youcef et al., 2020). TiO_2-based photocatalysts can oxidize VOCs at low concentration under ambient conditions and convert them into CO_2 and H_2O. Nevertheless, the practical application of photocatalysis remains limited by several drawbacks, including rapid electron-hole recombination, limited adsorption capacity toward some pollutants, catalyst deactivation, and the possible formation of partial oxidation

Paper Received: 26 March 2026; Revised: 6 May 2026; Accepted: 31 May 2026
Please cite this article as: Louali R., Assadi A.A., Bouzaza A., Wolbert D., Lamaa L., 2026, Coupling of Photocatalysis and Adsorption using a Single Multifunctional Filter for Gas-Phase Toluene Removal, Chemical Engineering Transactions, 127, 169-174 DOI:10.3303/CET26127029

by-products (Haghighi and Haghighat, 2024). To overcome the limitations of these processes used alone for VOCs removal, recent studies have increasingly investigated hybrid systems that combine adsorption and photocatalysis. In such systems, VOCs are first captured and concentrated on an adsorbent surface, and are then degraded by a photocatalyst, typically TiO_2. This combined approach has been widely explored in the literature (Lu et al., 2024). Liu and his co-workers reported that TiO_2/activated carbon fiber (ACF) composites exhibited enhanced activity under 185 nm irradiation for formaldehyde removal (Liu et al., 2018). This improvement was attributed to higher generation of hydroxyl radicals from surface hydroxyl groups, together with improved electron transfer through Ti-C interactions. In contrast, under 308 nm irradiation, hybrid materials often display lower photocatalytic performance (Biomorgi et al., 2010). Based on the literature, coupling adsorption and photocatalysis appears to be a promising strategy for improving VOC removal while overcoming the individual limitations of each process used separately.
In this context, the objective of this work was to investigate the performance of an innovative textile-based support. The first part of this study aimed to evaluate and compare the performance of five commercial adsorbents to identify and select the most suitable material for integration into a multifunctional textile filter. In a second phase, the selected activated carbon was combined with TiO_2 deposited on an optical-fiber textile support and evaluated under continuous-flow conditions. Attention was paid to the influence of the spatial distribution of activated carbon and TiO_2 on the overall pollutant removal performance under dark and UV-irradiated conditions.

2. Material & methods

2.1 Studied pollutant

Toluene, acetone, acetaldehyde, heptane and formaldehyde are commonly considered model air pollutants for the potential international standard testing of air cleaners (DEGALLAIX, 2017).
The target pollutant chosen in this study is toluene (C_7H_8). The compound was supplied by Honeywell in liquid form with a purity exceeding 99 %.

2.2 Adsorbent materials

Five commercial activated carbons (AC) with different forms were investigated in this study. AC1 corresponds to a Dolder activated carbon foam (5.5 mm thickness, Dolder AG, Basel, Switzerland). AC2 is a non-woven activated carbon filter composed of granular activated carbon embedded between two fibrous layers. AC3 corresponds to Ecosorb powdered activated carbon supplied by Jacobi Carbon Group (Kalmar, Sweden). AC4 and AC5 are activated carbon textiles (Actitex) supplied by Jacobi Actitex (Saint-Jean-de-Braye, France) with thicknesses of 2 mm and 1 mm, respectively. Among the investigated materials, only AC3 (Ecosorb) could be directly deposited onto the innovative textile support. Due to its powdered form, AC3 could be easily dispersed in a coating suspension and uniformly applied onto the textile surface using a spray-coating process. In contrast, AC1, AC2, AC4, and AC5 are self-supported materials and were therefore not suitable for direct deposition onto the textile support.

2.3 Textile support

The textile-based filter, manufactured by Brochier Technologies (Villeurbanne, France), is made of polymer fibers and optical fibers, allowing internal UV light transmission. These optical fibers have an average diameter of 500 µm (Bourgeois et al., 2012). Both fibers were integrated into the textile structure using a binding weave based on the Jacquard weaving process. This support was initially coated with a protective silica layer, followed by a deposition of TiO_2 P25 supplied by Evonik (Essen, Germany). As described in section 2.2 above, AC3 (Ecosorb) was selected for integration into the textile support because it was the only carbon available under powdered form, making it appropriate for deposition by spray-coating. Two coating configurations were investigated. In the first configuration (i), one side of the textile was coated with AC3, while the opposite side was coated with TiO_2. In the second configuration (ii), both AC3 and TiO_2 were deposited on each side of the textile, as illustrated in Figure 1. The activated carbon coating was performed using spray-coating process.
A suspension containing AC3 (Ecosorb powder) dispersed in water was sprayed onto the textile surface. For both textile configurations, the same initial amount of activated carbon suspension was applied. The coated textiles were then dried in an oven at 70 °C for 10 min. After drying, excess and weakly attached activated carbon particles were removed by gentle mechanical tapping of the fabric. The final activated carbon loading was determined by weighing the textile before and after the coating procedure. After removal of the excess particles, the activated carbon loadings were 3.5 g/m² for the single-sided configuration and 9.7 g/m² for the double-sided configuration. We note, that due to deposition process, it is not easy to predict exactly the mass deposited.

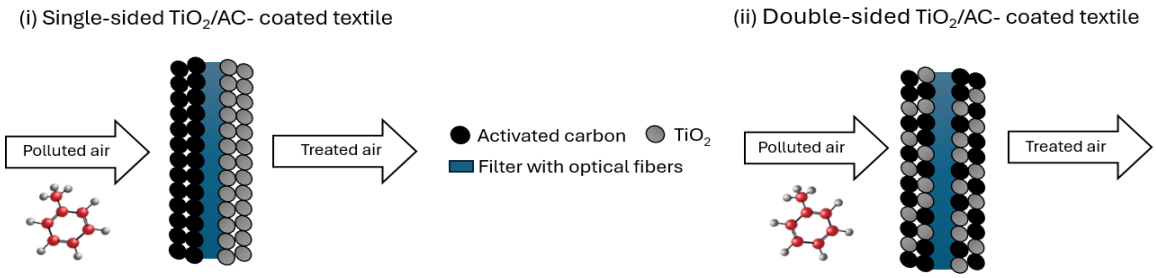

Figure 1: Schematic illustration of the two textile configurations for gas-phase toluene removal.

2.4 Adsorption experiments in batch reactor

Batch experiments were first performed to evaluate the adsorption performance of the five activated carbons. Adsorption isotherms were established by introducing known concentrations of the target pollutant into sealed flasks containing a known mass of activated carbon and a magnetic stirrer to ensure adequate homogeneity at a constant temperature of 25 °C under atmospheric pressure. For each initial concentration, the adsorption kinetics were monitored until equilibrium was reached. The adsorption capacity corresponding to each concentration was then calculated.

2.5 Continuous-flow reactor for adsorption-photocatalysis coupling

The combined adsorption and photocatalysis experiments were carried out in a novel continuous-flow reactor operating in a front-flow configuration, with a cross-sectional area of 0.01 m². The reactor consists of a module designed to hold the functionalized textile based on optical fiber coated with TiO_2 and activated carbon. The dry air was supplied by internal network. Its flow rate was regulated by a valve and measured using an Itron Gallus G4 gas meter. The flow rate was fixed at 0.5 m^3/h, corresponding to a contact time of 72 ms. The pollutant was injected using a syringe at a concentration of 1.5 mg/m^3 and vaporized by means of a heated tap. The resulting air-pollutant mixture was homogenized using a static mixer before entering the reactor. Textile illumination was provided by adjustable UV-LEDs.

2.6 Analytic tools

The concentration of toluene was measured by gas chromatography (Focus GC) using a flame ionization detector (FID) and an FFAP column (length= 25 m and internal diameter = 0.32 mm). Nitrogen was used as a carrier gas. Direct manual sampling using a 500 µl syringe was used for the analysis.
The adsorption capacity at equilibrium was calculated according to Eq (1):

$$q_e = \frac{(C_0 - C_e)V}{m_{AC}} \quad (1)$$

where C_0 and C_e (mg/m^3) are the initial and equilibrium pollutant concentrations respectively, V (m^3) is the volume of the vessel, and m (g) is the mass of activated carbon.
The experimental adsorption isotherms were described using two models. The first, the Langmuir model (Langmuir, 1918), assumes that adsorption occurs on a homogeneous surface containing a finite number of identical active sites. The Langmuir equation is expressed as:

$$q_e = \frac{q_{max} K_L C_e}{1 + K_L C_e} \quad (2)$$

Where q_e (g/g) is the adsorption capacity at equilibrium, q_{max} is the maximum monolayer adsorption capacity, K_L (m^3/mg) is the Langmuir constant related to the affinity of the adsorbent for the adsorbate, and C_e (mg/m^3) is the equilibrium concentration in the gas phase.
The second model, the Freundlich model (Ayawei et al., 2017), is an empirical equation that describes adsorption on heterogeneous surfaces. The Freundlich model is as follows:

$$q_e = K_F C_e^{1/n} \quad (3)$$

Where K_F is the Freundlich constant related to the adsorption capacity and n is the heterogeneity factor, which provides information on the adsorption intensity. In general, values of 1/n between 0 and 1 indicate favourable adsorption (Ayawei et al., 2017).

3. Results and discussion

3.1 Adsorption performance of the supports

As described above, batch experiments were conducted to establish the adsorption isotherms (Figure 2), which were fitted using the models mentioned above. The corresponding adsorption parameters from both models are summarized in table 1.

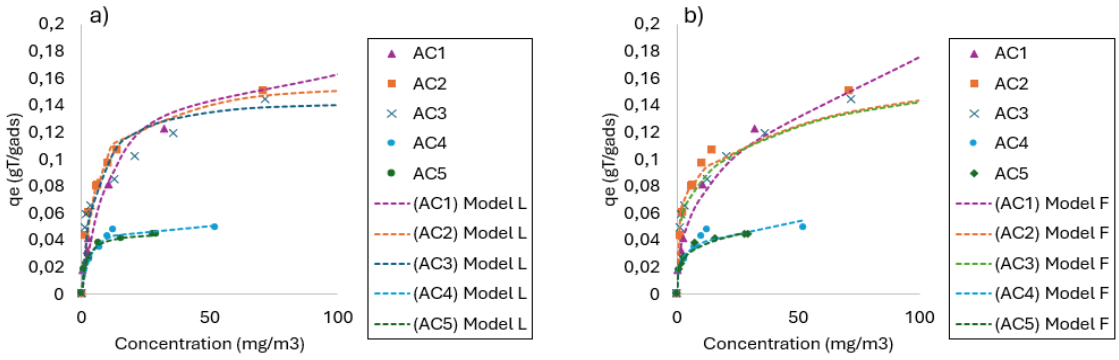

Figure 2: Adsorption isotherm obtained for different adsorbents media at various concentration, fitted with a) Langmuir model and b) Freundlich model.

According to Figure 2, the adsorption capacity followed the order AC1> AC2 >AC3 >AC4 > AC5.
As seen in table 1, both equations accurately describe toluene adsorption on activated carbon. However, regarding isotherm modeling, the Freundlich model provided the best fit for AC1, AC3 and AC5, whereas AC2 and AC4 were better described by the Langmuir model.

Table 1: Adsorption parameters of toluene on different adsorbent materials.

		Langmuir Model			Freundlich Model			
	Support	q_{max} (gT/g_{mat})	K_L (m^3/mg)	R^2 (%)	n	1/n	K_F	R^2 (%)
AC1	Dolder foam	0.184	0.08	95.61	2.57	0.389	29.35	98.48
AC2	non-woven filter	0.159	0.18	97.18	4.8	0.208	55.51	91.43
AC3	Ecosorb powder	0.149	0.20	89.16	4.33	0.230	50.05	98.51
AC4	Actitex 2mm	0.054	0.33	92.93	4.36	0.229	22.10	88.45
AC5	Actitex 1mm	0.047	0.58	92.18	4.28	0.233	21.06	96.59

Among the five activated carbons AC1, AC2 and AC3 exhibited the highest adsorption capacities, with q_{max} values of 0.184, 0.159 and 0.149 respectively, whereas AC4 and AC5 showed significantly lower values 0,054 and 0,047 gT/g_{ads}. AC2 and AC3 appeared to offer the best overall compromise between capacity and affinity, as reflected by relatively high K_L values and highest K_F value obtained from the models. In contrast, despite their higher K_L, AC4 and AC5 exhibited much lower q_{max} values, suggesting a limited number of accessible adsorption sites and therefore a lower adsorption capacity.

3.2 Continuous reactor for coupling adsorption/photocatalysis

Two textile configurations were investigated and compared on the basis of breakthrough curves obtained under dark conditions (adsorption only) and under simultaneous adsorption and UV irradiation (adsorption-photocatalysis coupling). Ecosorb (AC3) was selected because it offered the best compromise between adsorption performance and processability. Although AC1 and AC2 showed slightly higher adsorption capacities. As mentioned above, AC3 was the only adsorbent available in powdered form and therefore the only one compatible with the spray-coating procedure used to functionalize the textile support. When comparing the two-textile configurations, it should be noted that activated carbon loading was much higher for the double-face textile (9,7 g/m²) than for the single-sided (3,5 g/m²). This difference was not intentionally imposed as an experimental variable, but resulted from the coating/deposition process and the greater particle retention obtained in the double-sided configuration. For the single-sided configuration (Figure 3a), the curve obtained under dark conditions showed a 50 % breakthrough ($t_{0,5}$) at about 4 hours and complete saturation after

approximately 6,5 hours. Under simultaneous adsorption and photocatalysis, $t_{0,5}$ was not reached within the 8,3 hours experimental period, and the outlet concentration reached a plateau equivalent to $C/C_0 \approx 0,30$. This clearly indicates that UV irradiation delayed the breakthrough and improved the overall removal performance of the textile. This behavior is attributed to the contribution of photocatalytic degradation on the TiO_2-coated face, where the pollutant fraction not retained by the activated carbon is subsequently degraded. The difference between the two plateaus is due to the catalytic reaction.

For the double-sided configuration (Figure 3b), $t_{0,5}$ increased from 11 hours in adsorption alone to 23 hours under simultaneous adsorption and photocatalysis. In addition, although the dark experiment reached saturation after about 25h, the coupled system still exhibited $C/C_0 = 0,72$ after 75h, indicating that complete saturation was substantially delayed under irradiation. This result confirms the beneficial effect of coupling adsorption and photocatalysis on the long-term performance of the system. Derakhshan-Nejad *et al.*, (2020) reported that TiO_2/ZSM-5 under UV improves ethylbenzene breakthrough time and reduces VOCs release.

It should be noted that the larger intervals between some data points in Figure 3b are related to the long experimental duration (>70 h). Due to manual sampling, measurements were less frequent during nighttime periods.

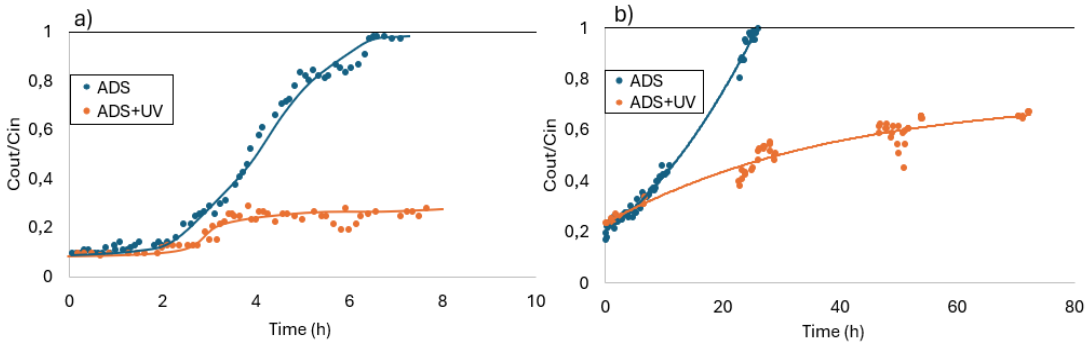

Figure 3: Breakthrough curves of the toluene for (a) the single-sided configuration (m_{AC}= 3.5 g/m²) and (b) the double-sided textile configuration (m_{AC}= 9.7 g/m²), under dark and UV irradiation (Q =0.5 m^3/h, C_0=1.50 mg/m^3 and m_{TiO2}= 30 g/m²).

Even if the activated carbon quantity is higher in the double-sided configuration, under irradiation this configuration did not appear to be the most efficient. Indeed, the single-sided textile achieved a pollutant removal efficiency of about 70 %, whereas the performance of the second configuration decreased to about 33 %. These results suggest that the lower efficiency may be related to the way which activated carbon and TiO_2 were deposited on the same surface. In this configuration (Figure $1_{(ii)}$), the activated carbon may have partially covered TiO_2 particles, thereby reducing light penetration and limiting access to photocatalytic sites. By contrast, in the single sided configuration, the two functions remained separated: the pollutant stream first passed through the activated carbon layer, and the non-adsorbed fraction was then exposed to the illuminated TiO_2 side. These results agree with those reported by Zhang and his co-workers (Zhang et al., 2016), they showed that TiO_2@C photocatalysts gave the highest activity only with very thin carbon layers. While thicker carbon coating reduced the photocatalytic performance because they limited light use and restricted access to the TiO_2 surface.

Although breakthrough times ranging from 11 to 23 h may appear limited for full-scale applications, these results correspond to laboratory-scale operating conditions. For scaling up the process, operational lifetime could be extended by increasing the adsorbent loading, optimizing reactor design, using multiple filtration stages, or implementing periodic regeneration strategies. Furthermore, the coupling of adsorption and photocatalysis may contribute to in situ regeneration of the adsorbent and therefore enhance long-term performance.

4. Conclusions

This study demonstrated the synergistic potential of coupling adsorption and photocatalysis within a single multifunctional optical-fiber textile. By screening five commercial adsorbents, Ecosorb powder (AC3) was identified as the optimal material, offering a strong balance between adsorption capacity and processability for spray-coating. The findings highlight that the spatial distribution of the functional layers is critical for process efficiency. While the double-sided configuration provided longer breakthrough times due to inherently higher carbon retention during coating, the single-sided configuration achieved a superior overall removal efficiency of approximately 70% under UV irradiation. Separating the adsorption and photocatalytic functions prevents the activated carbon from physically masking the TiO_2 layer, thereby maximizing UV light penetration and catalytic

activation. Overall, this approach provides a scalable pathway for compact air purification systems. Future developments will focus on optimizing mass loadings, assessing the impact of humidity, and evaluating long-term *in-situ* regeneration under multi-pollutant conditions.

Acknowledgements

The authors gratefully acknowledge the financial support of ANR under the project TEXAD (ANR-22-CE04-0009 TEXAD)

Nomenclature

VOCs – Volatile organic compounds
AC – Activated carbon
ADS – Adsorption
C_e – Equilibrium concentration, mg/m^3
C_0 – Inlet concentration, mg/m^3
C – outlet concentration, mg/m^3
FID – Flame ionization detection
FFAP– Free fatty acid phase column
GC – Gas Chromatography
K_L – The Langmuir constant, m^3/mg
K_F – The Freundlich constant, -
LEDs – Light-Emitting Diodes
m_{AC} – The mass of activated carbon, g
m_{TiO2} – The mass of titanium dioxide, g/m^2
q_e– The adsorption capacity at equilibrium, gT/g
q_{max} – The maximum monolayer adsorption capacity, gT/g
Q – Flow rate, m^3/h
TiO_2 – Titanium dioxide
UVA – Ultraviolet type A
V – The volume, m^3

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