

Salt-templated hierarchical porous activated-carbon films for efficient and regenerable single-pass indoor VOC purification

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ABSTRACT

Activated-carbon adsorption films are promising for indoor VOC purification, but their single-pass performance is often limited by intrafilm mass-diffusion resistance under short gas residence times. To address this issue, salt-templated activated-carbon films were developed for efficient, regenerable VOC capture under ventilation-relevant airflow conditions. Water-soluble salts were dispersed in activated-carbon coatings as removable templates and subsequently leached to construct transport-accessible pore structures. After grinding, the salt-templated coating exhibited a higher BET specific surface area than the planar coating (596.9 vs. 445.9 m²/g), together with an increase in total pore volume from 0.222 to 0.263 cm³/g. At an airflow velocity of 1.0 m/s, the salt-templated film achieved an initial toluene removal efficiency (η_0) of 82.2%, compared with 58.9% for the planar control. Films prepared with NaCl, sea salt, and simulated mixed salts all achieved η_0 values around 80%. The salt-templated films also maintained removal efficiencies above 77% for benzene and tetrachloroethylene and stable performance across 1–10 ppm toluene. STF#3 maintained its performance advantage over the planar control across 0–80% RH, although increasing humidity reduced the absolute efficiency. In situ electrothermal regeneration retained approximately 96% of the initial-cycle efficiency after 15 adsorption–regeneration cycles under dry conditions. This work provides a simple, scalable, and ventilation-oriented strategy for reusable adsorption films in practical indoor VOC control.

1. Introduction

Indoor air pollution remains a major concern for built environments as people spend most of their time in residences, offices, schools, and other enclosed spaces. Volatile organic compounds (VOCs) are among the most common gaseous pollutants in indoor air and are continuously emitted from building materials [1–3], coatings [4], adhesives [5], and cleaning products [6]. Although indoor VOC concentrations are typically much lower than those in industrial exhaust streams, long-term, repeated exposure to VOCs has been associated with adverse health outcomes, including respiratory diseases, neurological symptoms,

cardiovascular effects, and increased cancer risk [7–9]. Therefore, efficient removal of low-concentration VOCs under realistic indoor airflow conditions is essential to improve indoor air quality and reduce the disease burden associated with indoor pollution [10–13].

Adsorption is widely regarded as a practical approach for indoor VOC control [14,15]. It can be readily integrated into compact air-cleaning devices [16], and does not directly produce oxidation by-products [14,17]. Activated carbon is one of the most commonly used adsorbents owing to its developed microporosity, large surface area, and broad affinity toward organic molecules [18–21]. However, high equilibrium adsorption capacity does not necessarily translate into

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high dynamic purification efficiency in ventilation-related applications [22,23]. In practical air-cleaning systems, polluted air usually passes through the adsorbent layer within a short residence time [23,24]. Under such conditions, VOC molecules should rapidly migrate from the bulk airflow to internal adsorption sites [24]. Dense adsorbent layers with poorly connected pore structures will introduce large mass-diffusion resistance [22,23], leaving a substantial fraction of the adsorbent phase underutilized [23]. Therefore, evaluating breakthrough behavior and dynamic adsorption capacity under continuous airflow conditions is essential for understanding whether structured adsorption films can effectively utilize their intrinsic adsorption sites during practical VOC purification. This ineffective use of adsorbents not only lowers purification efficiency [25] but also increases material consumption and energy cost [26,27] during long-term operation.

Improving the accessibility of adsorption sites within structured adsorbent films is therefore essential for enhancing VOC removal under short-contact-time operation [26]. By introducing additional transport pathways, pore engineering can shorten internal diffusion distances [24, 28] and expose pollutants to more active adsorption sites [23]. Several pore-forming strategies have been investigated for structured adsorption materials, including direct ink writing [24,29], gas-forming treatment [25], phase separation [30], and sacrificial template methods [23]. Among these approaches, sacrificial templating is particularly attractive since the size, loading, and distribution of template particles can be used to regulate the pore structure of the final material [31]. Nevertheless, commonly used sacrificial-template materials, such as polymer particles [31,32] and organic pore formers [31], often entail relatively high material costs, high-temperature decomposition [25], or solvent treatment [30]. These requirements may increase fabrication complexity and limit the practical scalability of porous adsorption films for indoor air-cleaning applications [27,33].

Inspired by sacrificial templating methods, water-soluble inorganic salts have the potential to serve as sacrificial templates for the construction of transport-accessible adsorption films [34–36]. Salt particles can be directly dispersed in an adsorbent slurry and subsequently removed by water leaching after coating and drying [37,38]. During coating formation, dispersed salt particles act as sacrificial spacers between activated-carbon and polymer domains. Subsequent water leaching removes these particles, leaving micrometer-scale voids and enlarged interparticle openings [39], thereby shortening intrafilm diffusion paths and improving access to the intrinsic pores of the embedded activated carbon. Unlike salt-assisted carbonization or chemical activation, this process primarily reconstructs the coating architecture under mild conditions [40]. This mild process avoids high-temperature template decomposition [37,41] and can be readily coupled with conventional coating fabrication [42,43]. Moreover, common salts are inexpensive, recyclable, and compatible with large-area film preparation [44,45]. Naturally derived sea salt [46], salt-lake brine salt [47], and salts recovered from industrial brine [48] may also be used as template sources, further improving the practicality and resource flexibility of the material-preparation strategy. Existing salt-based pore-forming studies have mainly focused on salt-assisted carbonization/activation to construct intrinsic pores in newly synthesized carbon materials [38,49], or on water-removable salt porogens to create pores in polymeric and composite matrices [39,50]. However, these studies were not primarily designed for low-concentration gas-phase VOC removal in indoor air purification. In the present work, removable salt particles are introduced into a binder-containing activated-carbon coating and subsequently removed by water leaching. The resulting micrometer-scale pores serve as film-level transport pathways, thereby improving gas-phase VOC access to the pre-existing micro-/mesoporous adsorption sites of activated carbon under short-residence-time single-pass airflow. To the best of our knowledge, few studies have employed salt-derived micrometer-scale pores specifically to improve the dynamic accessibility and utilization of activated-carbon adsorption sites for indoor gas-phase VOC purification.

This distinction motivated the present study on salt-templated activated-carbon films for ventilation-relevant VOC purification.

Therefore, this study focuses on a water-removable salt-templating strategy to construct transport-accessible activated-carbon films for ventilation-relevant VOC purification. Rather than focusing solely on static adsorption capacity, this work emphasizes the dynamic adsorption performance of coating-type activated-carbon films under ventilation-relevant operating conditions, where short gas residence times and transport limitations often govern practical VOC removal efficiency. For this purpose, we regulate the activated-carbon/salt ratio to balance adsorbent loading and pore connectivity, and further examine whether the templating effect can be extended to naturally derived and compositionally complex salt sources. The resulting adsorption films are evaluated under conditions representative of practical indoor air-cleaning operation, including variable airflow velocity, inlet VOC concentration, VOC species, relative humidity, and repeated adsorption–regeneration cycles [51]. This work aims to establish a mechanistic, application-oriented understanding of how salt-templated transport pathways enhance the dynamic utilization, operational robustness, and reusability of activated-carbon adsorption films, thereby advancing the development of durable, resource-efficient materials for indoor VOC control [52].

2. Materials and methods

2.1. Preparation of salt-templated adsorption films

The adsorption film was designed as a structured carbonaceous coating supported on a polyimide–copper (PI–Cu) composite heating substrate. The film layer was prepared by uniformly mixing a porous carbon adsorbent, a polymeric thickening agent, a binder, and removable salt particles as sacrificial templates. The mixed slurry was coated onto the PI–Cu substrate and thermally dried to form a continuous solid film. The solid film was subsequently washed with deionized water to remove the embedded salt particles. This salt-leaching step generated additional transport-accessible pores within the carbonaceous coating.

Within the precursor slurry, activated carbon (5 μm in particle diameter, XFNANO, China) was selected as the primary VOC adsorbent. Sodium polyacrylate (PAAS, Macklin, China) and ethylene–vinyl acetate copolymer (EVA, KAIMING, China) were used as the dispersing/thickening agent and binder, respectively. For the sacrificial template particles, sodium chloride (NaCl, analytical grade, Macklin, China) was primarily used as the model template salt. To further examine the application potential of different salt sources, we used sea salt and simulated mixed salts to prepare additional salt-template films. The raw salts used to formulate the simulated mixed salts included NaCl, Na_2SO_4 , $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, KCl, and $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$. NaCl was purchased from Macklin, China, while all other salts were obtained from Sinopharm Chemical Reagent Co., Ltd., China. All chemicals were of analytical grade.

All salt-templated coating slurries were prepared using the same mixing protocol. As shown in Fig. 1a, 5.0 g of PAAS was dissolved in 10.0 g of deionized water and magnetically stirred at 600 rpm and 80 °C for 1 h to obtain a viscous PAAS solution. Predetermined amounts of activated carbon and template salt were then added to the PAAS solution. The total mass of activated carbon and template salt was fixed at 6.0 g, while their mass ratio was varied as described below. The solution mixture was then stirred for 40 min to disperse the solid particles. Subsequently, 2.5 g of EVA was added as the binder, and the mixture was stirred for another 20 min to form the coating slurry.

The prepared slurry was coated onto the PI–Cu composite heating substrates. A predetermined amount of slurry was drop-cast onto the defined substrate area and spread with a glass rod to form a continuous wet film. The coating load was controlled by adjusting the slurry dosage per unit area. The coated samples were then dried at 80 °C for 20 min to solidify the film layer and improve its adhesion to the substrate. The dried salt-containing films were immersed in 500 mL of deionized water

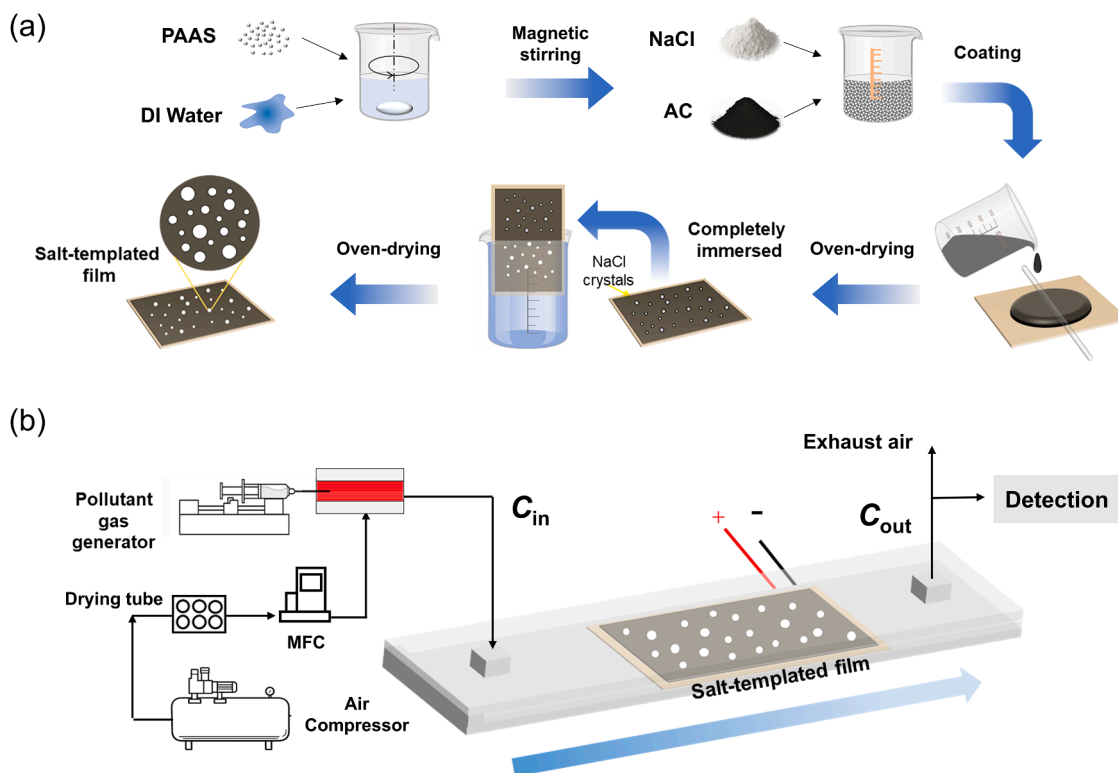


Fig. 1. Schematic illustration of the preparation and testing of salt-templated adsorption films. (a) Preparation process of salt-templated activated-carbon films on PI-Cu composite substrates, including slurry mixing, coating, drying, salt leaching, and final drying. (b) Laboratory-scale single-pass flow system for dynamic VOC purification tests, including gas supply and drying, VOC generation, flow control, adsorption-film module, and inlet/outlet concentration monitoring.

and gently stirred for 1 h to dissolve and remove the embedded salt particles. After salt leaching, the films were removed from the water, gently blotted to remove excess surface water, and dried again at 100 °C for 10 min. This process yielded salt-templated porous adsorption films supported on PI-Cu substrates.

In the main NaCl-templated series, the total mass of activated carbon and NaCl was fixed at 6.0 g, while their mass ratio was systematically varied to tune the adsorbent loading and salt-templated pore structure. Five salt-templated films were prepared and denoted as STF#1–STF#5, corresponding to activated-carbon/NaCl mass ratios of 5:1, 4:2 (2:1), 3:3 (1:1), 2:4 (1:2), and 1:5, respectively. As the corresponding control group, salt-free planar adsorption films were also prepared using the same mixing, coating, and drying procedures, except that no template salt particles were added. The obtained planar films were denoted PF#1–PF#5, and the activated-carbon mass was kept the same as that in the corresponding salt-templated formulations. The PFs were used as comparisons to evaluate the enhancement in VOC adsorption performance induced by salt-templated pore formation. To examine the influence of salt source on pore formation and VOC purification, additional salt-templated films were prepared using naturally derived sea salt and two simulated mixed salts as alternative sacrificial templates, representing high-salinity wastewater from printing and dyeing processes and brines associated with salt-lake lithium extraction. The corresponding films were denoted as SWF, PDSF, and SLSF, respectively, with the activated-carbon mass and total template-salt mass both fixed at 3.0 g. The detailed compositions of the alternative salt-templates are listed in Supplementary Table S1.

2.2. Characterization methods

The morphology and pore structure of the adsorption films were characterized by scanning electron microscopy (SEM) and N₂ adsorption-desorption analysis. The surface morphologies of the films were

observed using SEM (ZEM18, ZEPTOOLS, China). Surface samples were cut directly from the coated film region, while cross-sectional samples were prepared by brittle fracture to expose the internal film structure. Before observation, the samples were sputter-coated with a thin gold conductive layer for 30 s at 15 mA. SEM images were collected at magnifications of 250 × and 2000 × to compare the overall compactness, particle arrangement, surface texture, and pore morphology of the planar and salt-templated films.

The specific surface area and pore-structure parameters were measured by N₂ adsorption-desorption analysis at 77.3 K using a surface area and porosity analyzer (BSD-660T, BSD Instrument, China). The PF#3 and STF#3 coatings were carefully separated from the PI-Cu substrates and ground for 30 min to obtain homogeneous powder samples. Before measurement, the ground coating samples were degassed in situ under vacuum at 300 °C for 240 min to remove physically adsorbed moisture and impurities. The pristine activated carbon and the unground coating samples were also characterized under identical conditions. The Brunauer-Emmett-Teller method was used to calculate the specific surface area [53]. The total pore volume was estimated from the adsorbed amount at a relative pressure of $P/P_0 \approx 0.99$. The micropore surface area and micropore volume were obtained using the t-plot method [54], while the mesopore size distribution was derived from the adsorption branch using the Barrett-Joyner-Halenda method [55]. Salt removal was further evaluated by ICP-OES for bulk Na quantification and XPS for surface Na and Cl analysis.

2.3. Experimental platform for single-pass VOC purification

The dynamic purification performance of the adsorption films was evaluated using a laboratory-scale continuous single-pass flow system. As shown in Fig. 1b, the platform consisted of a gas supply and conditioning unit, a VOC generation and mixing unit, a humidity regulation unit, a rectangular test duct equipped with the adsorption-film module,

and an online VOC monitoring unit. Compressed air was used as the carrier gas. During operation, the carrier gas was sequentially purified, dried, mixed with the target VOC vapor, passed through the adsorption-film module, and finally analyzed at the inlet and outlet sampling ports.

The compressed air first passed through a particulate filter and a silica-gel drying column to remove particles and moisture, producing a dry carrier gas with a relative humidity close to zero. The dried carrier gas was then divided into two branches according to the target humidity condition. One branch passed through a humidification chamber to generate moist air, while the other branch was used to carry and dilute the VOC vapor generated from the VOC evaporation unit. Target VOC vapors were generated using a syringe-pump-assisted evaporation method. Liquid VOCs, including benzene, toluene, and tetrachloroethylene, were loaded into airtight syringes and continuously injected into an upstream micro-evaporation chamber using a syringe pump (LSP01-2A, Longer, China). The evaporation chamber was maintained at 125 °C to ensure stable vaporization. The two branches were subsequently mixed at controlled flow-rate ratios to obtain a pollutant stream with the required relative humidity and a stable VOC inlet concentration of 1–10 ppm. The total gas flow rate was regulated by mass flow controllers to obtain the required superficial airflow velocity in the test duct, which was adjusted within 0.2–1.0 m/s depending on the test condition. The temperature and relative humidity of the gas stream were monitored using a temperature and humidity sensor (COS-03, Shandong Renke Control Technology Co., Ltd., China).

The pollutant stream flowed through a rectangular test duct with dimensions of 500 mm × 85 mm × 2 mm. The adsorption films coated on PI-Cu composite substrates were fixed at a designated position in the duct to maintain consistent gas–solid contact. The effective exposed area of each adsorption film was 15 cm × 7 cm. The thin duct geometry allowed the pollutant stream to pass over the film surface under controlled single-pass conditions. The inlet and outlet VOC concentrations were monitored online using a photoionization detector (PID, PGM7340, RAE Systems, USA). Before the adsorption tests, the PID was calibrated using standard gas cylinders and cross-validated by gas chromatography with flame ionization detection (F70, FULI INSTRUMENTS, China). Sampling ports were arranged upstream and downstream of the adsorption film, and the inlet and outlet streams were alternately measured using a three-way valve. Before each experiment, the system was operated under bypass mode until the inlet VOC concentration reached the target value and remained stable for at least 10 min. The time-dependent single-pass removal efficiency was calculated from the inlet and outlet VOC concentrations. The initial removal efficiency, denoted as η_0 , was defined as the average single-pass removal efficiency during the first 30 min under the tested conditions. The time-dependent single-pass removal efficiency was calculated using Eq. (1):

$$\eta_0 = \left(1 - \frac{C_{out}}{C_{in}}\right) \times 100\% \quad (1)$$

where C_{in} and C_{out} are the inlet and outlet VOC concentrations, respectively, mg/m³.

To further evaluate the practical adsorption performance of the films, the effective adsorption capacity (EAC_{ad} , mg/g) was calculated. The EAC_{ad} parameter represents the cumulative mass of pollutant removed per unit mass of adsorbent during a defined adsorption period. For routine purification tests, the adsorption period was set as 8 h. For the extended breakthrough experiment, the integration period was determined according to the time-resolved outlet concentration profile. In this study, EAC_{ad} was used as a dynamic adsorption metric to quantify adsorbent utilization under single-pass airflow conditions. Therefore, this parameter provides a more application-oriented indicator for assessing whether the adsorption film can continuously maintain indoor pollutant concentrations at a controlled level. EAC_{ad} was calculated according to Eq. (2):

$$EAC_{ad} = \int_{t=0}^{t_e} \frac{G(C_{in} - C_{out})}{M} dt \quad (2)$$

where t_e is the integration time, h; G is the volumetric airflow rate, m³/h; and M is the total dry coating mass, defined as the adsorbent mass in this study, g. For routine purification tests, the integration time was fixed at 8 h; for the extended breakthrough experiment, the integration period was determined from the time-resolved outlet concentration profile. By considering both removal efficiency and adsorbent loading, EAC_{ad} enables a quantitative comparison of the effective pollutant-control capacity of different adsorption films under dynamic single-pass operation.

2.4. Experimental design for dynamic purification and electrothermal regeneration

The effects of film formulation, airflow velocity, salt-template source and composition, inlet VOC concentration, VOC species, and relative humidity on the dynamic single-pass purification performance were systematically investigated. For formulation screening, the NaCl-templated films STF#1–STF#5 and the salt-free planar control films PF#1–PF#5 were first evaluated using toluene as the target pollutant. These tests were conducted at airflow velocities of 0.2, 0.5, and 1.0 m/s to examine the combined effects of activated-carbon loading, salt-template ratio, and gas residence time on dynamic purification performance. The comparison between each STF sample and the corresponding PF sample with the same activated-carbon mass was used to quantify the performance enhancement induced by salt-templated pore formation.

STF#3 was selected as the representative NaCl-templated adsorption film for subsequent operating-condition tests. PF#3 was used as the corresponding salt-free control with the same activated-carbon loading. Before evaluating the effects of operating conditions, the influence of salt source and composition was examined by comparing STF#3 with additional salt-templated films prepared using sea salt and simulated mixed salts. For these salt-source comparison tests, the activated-carbon mass and the total template-salt mass were both fixed at 3.0 g, and only the salt source or salt composition was varied. STF#3, SWF, and PF#3 were used for the representative operating-condition tests. For the concentration-dependent tests, the inlet toluene concentration was set to 1, 2, 5, and 10 ppm to evaluate the stability of single-pass purification performance under different pollutant loading levels. For the VOC-species tests, tetrachloroethylene, toluene, and benzene were selected as representative VOCs, and their inlet concentrations were maintained at 2 ppm. For the humidity-dependent tests, the relative humidity of the pollutant stream was adjusted to 0%, 10%, 20%, 50%, and 80% relative humidity before entering the test duct, while the inlet toluene concentration was maintained at 2 ppm. These experiments were used to evaluate the robustness of the salt-templated adsorption films under varying pollutant concentration, VOC physicochemical properties, and moisture levels. In addition, an extended breakthrough experiment was conducted using STF#3 under representative operating conditions (2 ppm toluene, 1.0 m/s face velocity, 25 °C, and 0% RH) to evaluate the dynamic adsorption behavior and adsorbent utilization during prolonged single-pass operation.

The cyclic adsorption–regeneration performance was evaluated using STF#3 under representative humidity conditions of 0%, 50%, and 80% RH. Each cycle consisted of an 8 h adsorption stage followed by in situ electrothermal regeneration. During the adsorption stage, the toluene-containing pollutant stream was continuously introduced into the test duct at an inlet concentration of 2 ppm and a face velocity of 1.0 m/s under the preset humidity condition. After 8 h of adsorption, VOC generation was stopped, and clean, dry air was introduced as the purge gas at a flow velocity of 0.2 m/s. The PI-Cu substrate was then electrically heated to 80 °C and maintained at that temperature for

20 min to desorb the adsorbed VOCs. After regeneration, heating was stopped, and purging was continued until the film temperature returned to the test range. This adsorption–regeneration sequence was repeated for four consecutive cycles to evaluate the cyclic purification stability and in situ regeneration capability of the salt-templated adsorption film. To assess long-term reusability, an additional 15-cycle adsorption–regeneration test was conducted at 0% RH using the same 8 h adsorption and 80 °C/20 min regeneration protocol. After 15 adsorption–regeneration cycles, the integrity of STF#3 was qualitatively assessed using a bending-and-release procedure.

3. Results and discussion

3.1. Morphology and pore-structure evolution of adsorption films

Since the embedded salt particles in adsorption films could be dissolved and removed during the water-leaching step, salt templating was expected to create additional voids within the film. Such salt-derived pores are expected to shorten internal diffusion pathways and reduce mass-transfer resistance under single-pass flow conditions. Therefore, the representative salt-free planar film containing 3.0 g of activated carbon and no template salt (PF#3 described in Section 2.1) was compared with the NaCl-templated film containing 3.0 g of activated carbon and 3.0 g of NaCl (STF#3 described in Section 2.1). SEM observation and N₂ adsorption–desorption analysis were conducted to characterize the morphology and quantify the accessible pore structure induced by salt templating.

As shown in Fig. 2a, PF#3 exhibited a compact surface, with activated-carbon particles densely embedded in the polymeric matrix and only limited interparticle voids. Based on the SEM scale bars, these

voids were mainly confined to submicrometer-to-few-micrometer gaps between adjacent carbon particles, and no continuous large transport channels were evident. Such a compact arrangement indicates restricted gas-accessible pathways within the composite film, which may limit the dynamic utilization of internal adsorption sites under short gas–solid contact times. By contrast, STF#3 exhibited a more open and heterogeneous morphology after the salt-leaching process (Fig. 2b). The surface SEM image showed abundant salt-derived macroporous features with characteristic sizes ranging from several tens to nearly one hundred micrometers, consistent with the dissolution of embedded salt particles. The high-magnification image further revealed enlarged interparticle openings of several micrometers around the activated-carbon aggregates. These micrometer-scale voids provide direct morphological evidence that sacrificial salt removal reconstructed the film architecture and generated additional gas-transport pathways.

The N₂ adsorption–desorption analysis was further used to quantify the gas-accessible fine-pore structure of the composite films. To minimize the additional N₂-accessibility limitation associated with the intact film geometry, PF#3 and STF#3 were separated from the PI–Cu substrates and ground for 30 min before analysis. As shown in Fig. 2c, STF#3 showed substantially higher N₂ uptake than PF#3 throughout the measured relative-pressure range, indicating that salt templating increased the accessibility of fine pores within the carbonaceous film layer. The more evident separation between the adsorption and desorption branches of STF#3 also suggests the formation of additional nanoscale-to-submicrometer pore connectivity within the composite coating.

The pore-structure parameters and pore-size distribution shown in Fig. 2d provide a quantitative comparison between the two ground coating samples. The BET specific surface area increased from 445.9 m²/

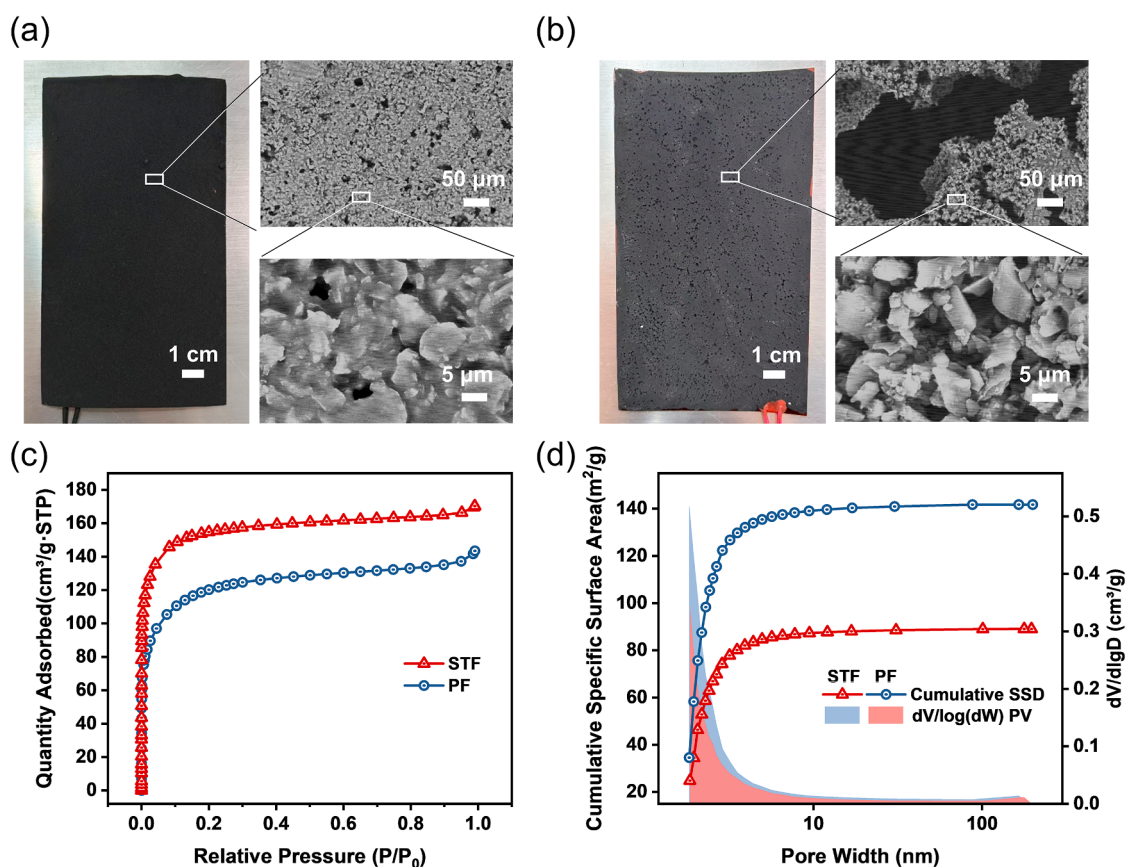


Fig. 2. Morphology and pore-structure characterization of the representative planar and salt-templated adsorption films. (a) Surface morphology of PF#3. (b) Surface morphology of STF#3. (c) N₂ adsorption–desorption isotherms of the ground PF#3 and STF#3 coatings. (d) Pore-size distributions of the ground PF#3 and STF#3 coatings.

g for PF#3 to 596.9 m²/g for STF#3, corresponding to an increase of approximately 34%. The total pore volume increased from 0.222 to 0.263 cm³/g, representing an increase of approximately 18%. The average pore diameters of PF#3 and STF#3 were 1.99 and 1.76 nm, respectively, indicating that both composite coatings retained predominantly microporous structures.

The unground PF#3 and STF#3 coatings showed much lower apparent gas-accessible surface areas than the corresponding ground samples, confirming an additional N₂-accessibility limitation imposed by the intact coating geometry. Because PF#3 and STF#3 contained the same activated-carbon loading and were subjected to identical grinding and degassing procedures, the higher BET surface area and pore volume of ground STF#3 indicate that salt templating improved access to the pre-existing porous structure rather than generating new intrinsic pores within the activated-carbon particles. The textural properties of the pristine activated carbon and the corresponding unground coating samples are provided in Supplementary Section S2 and Table S2.

Elemental analyses provided further evidence of template removal. The bulk Na content decreased from 12.03 ± 0.06 wt% before washing to 2.63 ± 0.04 wt% after washing, corresponding to a 78.1% decrease in the bulk Na weight fraction. Consistently, the Na 1s and Cl 2p signals in the XPS survey spectra decreased after washing. The residual Na signal partly reflects the Na-containing PAAS binder, while a small amount of chloride may remain in poorly accessible regions of the coating (Supplementary Section S3 and Fig. S2).

3.2. Effect of AC/salt ratio on single-pass toluene removal

To evaluate the effect of salt-templated pore formation on dynamic

VOC purification, the single-pass removal performance of different adsorption films was first tested using toluene as the model pollutant at an airflow velocity of 1.0 m/s and an inlet concentration of 2 ppm. The salt-templated films with different activated-carbon/NaCl ratios were compared with the corresponding salt-free planar films to clarify the balance between activated-carbon loading and transport accessibility.

As shown in Fig. 3a, STF#1, STF#3, and STF#5 were selected as representative formulations with progressively decreasing activated-carbon content and increasing NaCl content, corresponding to activated-carbon/NaCl masses of 5.0/1.0, 3.0/3.0, and 1.0/5.0 g, respectively. Their corresponding planar controls, PF#1, PF#3, and PF#5, contained the same activated-carbon masses but no NaCl template. The salt-templated films generally achieved higher removal efficiencies than the corresponding planar films during the 8 h single-pass test. Among the STF series, STF#1 and STF#3 maintained relatively stable removal behavior, with efficiencies decreasing from 81.6% to 68.2% and from 83.3% to 67.7%, respectively. By contrast, STF#5 showed a more pronounced decline from 57.5% to 33.8%, indicating that excessive salt incorporation reduced the effective activated-carbon content and weakened sustained adsorption capacity. The PF series followed a similar declining trend but remained at a lower efficiency level. Specifically, PF#1, PF#3, and PF#5 decreased from 68.5%, 59.8%, and 49.3% to 51.4%, 41.3%, and 28.1%, respectively. These results demonstrate that salt templating enhanced dynamic toluene capture under continuous-flow conditions, whereas excessive replacement of activated carbon with the template salt compromised the available adsorption capacity. At the same activated-carbon loading of 5.0 g, STF#1 remained 19.1%–32.7% higher than PF#1 over the 8 h test, confirming a clear salt-templating effect. Moreover, STF#3

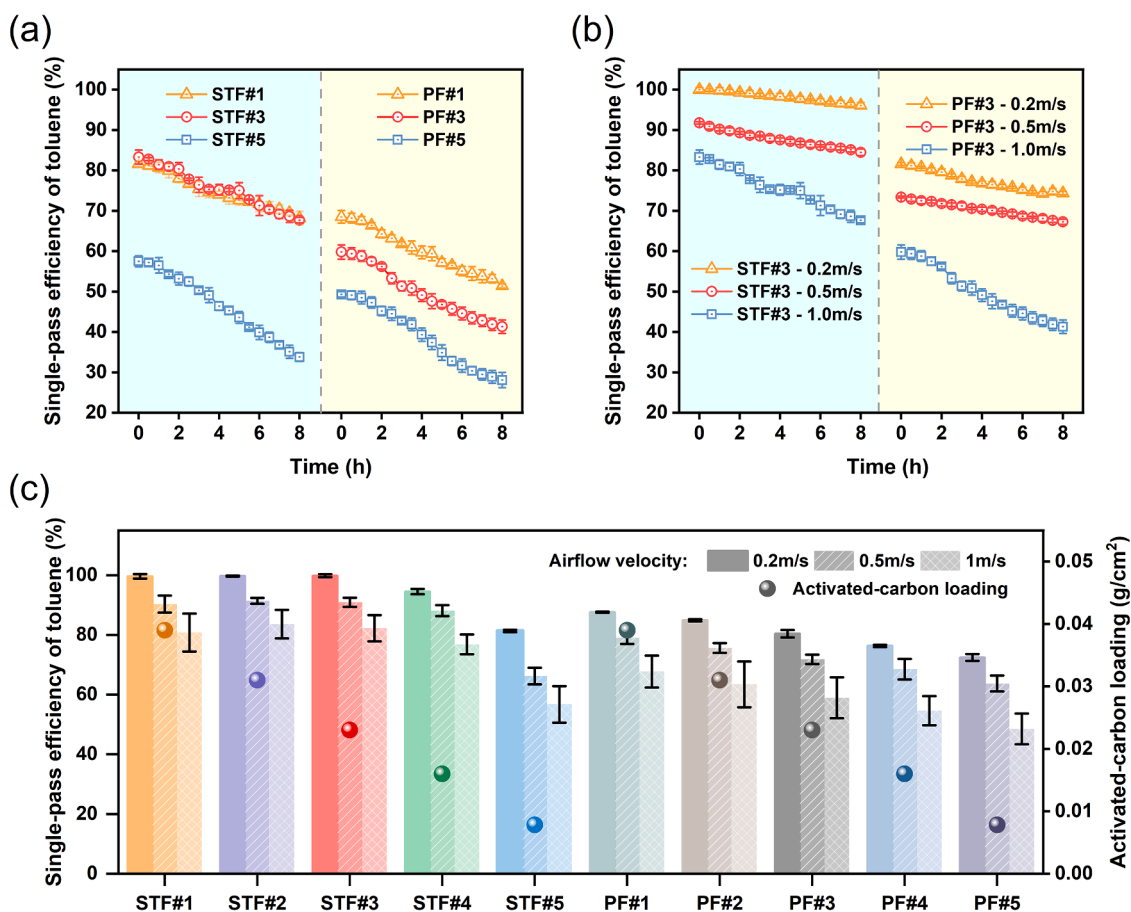


Fig. 3. Effect of AC/NaCl ratio and airflow velocity on the single-pass removal of toluene. (a) Time-dependent toluene removal efficiencies of representative STF and PF films at an airflow velocity of 1.0 m/s. (b) Time-dependent toluene removal efficiencies of STF#3 and PF#3 at different airflow velocities. (c) η_0 values of STF#1–STF#5 and PF#1–PF#5 at airflow velocities of 0.2, 0.5, and 1.0 m/s, with the corresponding activated-carbon loading indicated.

maintained removal performance comparable to STF#1 despite containing 40% less activated carbon, demonstrating improved utilization of the embedded adsorbent.

The effect of airflow velocity was further examined using STF#3 as the representative salt-templated film and PF#3 as the corresponding planar control (Fig. 3b). For both films, the toluene removal efficiency gradually decreased with adsorption time, and the decline became more pronounced as the airflow velocity increased from 0.2 to 1.0 m/s. For STF#3, the initial removal efficiencies remained above 80% at all tested airflow velocities, with the value at 0.2 m/s approaching 100%. After 8 h of operation, STF#3 retained removal efficiencies of 93.3%, 82.2%, and 67.7% at 0.2, 0.5, and 1.0 m/s, respectively. In comparison, PF#3 retained only 70.8%, 61.2%, and 41.3% under the same airflow velocities. This result indicates that increased airflow velocity shortened the gas–solid contact time and accelerated the utilization of readily accessible adsorption sites, while the salt-templated film maintained higher dynamic removal efficiencies.

The formulation-dependent initial removal performance was further summarized using η_0 , defined as the average single-pass removal efficiency over the first 30 min. As shown in Fig. 3c, η_0 values further reveal the balance between pore accessibility and activated-carbon loading. For the STF series, STF#1–STF#3 maintained high and comparable η_0 values despite the activated-carbon loading decreasing from 5.0 to 3.0 g. Their η_0 values were approximately 100%, 90%, and above 80% at airflow velocities of 0.2 m/s, 0.5 m/s, and 1.0 m/s, respectively. Further decreasing the activated-carbon loading to 2.0 and 1.0 g in STF#4 and STF#5 resulted in a clear decline in η_0 , especially at higher airflow velocities. At 1.0 m/s, η_0 decreased from above 80% for STF#1–STF#3 to approximately 75% for STF#4 and below 60% for STF#5. Therefore, STF#3 used much less activated carbon than STF#1 and STF#2 while maintaining similarly high removal efficiencies. These results indicate that a high activated-carbon loading alone did not guarantee the highest single-pass removal efficiency. Rather, sufficient adsorbent mass should be coupled with effective salt-derived transport pathways.

The comparison between the STF and PF series further demonstrates the contribution of salt-templated pore construction. Under the representative 3.0 g activated-carbon formulation, STF#3 reached η_0 values of 99.8%, 90.9%, and 82.2% at 0.2, 0.5, and 1.0 m/s, respectively, whereas PF#3 reached only 80.4%, 71.8%, and 58.9%. This corresponds to relative improvements of approximately 24%, 27%, and 40%, respectively. The larger relative enhancement at 1.0 m/s indicates that salt-derived pores were particularly beneficial under short-contact-time conditions, where intrafilm diffusion and gas-accessibility limitations became more pronounced. This matched-loading comparison demonstrates that the performance enhancement arises from film-level transport restructuring rather than simply from increased activated carbon.

To further clarify the physical origin of this transport restructuring, Supplementary Fig. S3 schematically compares the intrafilm diffusion process in PF and STF. In the compact PF coating, VOC molecules transferred from the air channel must diffuse through a densely packed activated-carbon/polymer layer with limited connected transport voids. This structure is expected to have lower connected porosity, ε_{PF} , and larger diffusion-path tortuosity, τ_{PF} , thereby increasing the intrafilm diffusion resistance, $R_{diff,PF}$. This interpretation is consistent with the relatively low initial toluene removal efficiency of PF#3, which reached only 58.9% at 1.0 m/s despite containing the same 3.0 g activated-carbon loading as STF#3. After salt-templated treatment, salt removal generated enlarged interparticle openings and macroporous transport voids, as observed in Fig. 2a–b. These salt-derived pathways increased the connected porosity of STF, ε_{STF} , and reduced the tortuosity of the diffusion pathways, τ_{STF} , leading to a lower intrafilm diffusion resistance, $R_{diff,STF}$. Consequently, STF#3 achieved a substantially higher initial toluene removal efficiency of 82.2% under the same 1.0 m/s toluene test condition. This comparison supports that the salt-templated architecture improved the dynamic utilization of the intrinsic activated-carbon adsorption sites by enhancing film-level transport accessibility.

3.3. Dynamic adsorption behavior and adsorbent utilization

Although the initial single-pass removal efficiency η_0 provides a direct comparison of purification performance under ventilation-relevant airflow, it does not directly quantify the adsorption capacity or utilization of the embedded activated carbon during prolonged operation. Therefore, an extended breakthrough experiment was conducted using STF#3 to evaluate its dynamic adsorption behavior under continuous-flow conditions. The experiment was performed at a toluene inlet concentration of 2 ppm, a face velocity of 1.0 m/s, 25 °C, and 0% RH, corresponding to the representative operating conditions used for performance evaluation. The complete breakthrough curve is provided in Fig. S4 of the Supplementary Materials.

As shown by the breakthrough profile, the normalized outlet concentration (C_{out}/C_{in}) gradually increased from approximately 0.20 to 0.98 during 122.1 h of continuous adsorption. The initial slow increase indicates rapid toluene uptake at abundant, accessible adsorption sites, whereas the subsequent increase reflects progressive occupation of adsorption sites and the expansion of the mass-transfer zone within the coating. The characteristic breakthrough times further describe the evolution of adsorption behavior. The 50% breakthrough time t_{50} and terminal breakthrough time (defined as $C_{out}/C_{in} \approx 0.98$) were 21.8 h and 122.1 h, respectively, indicating that STF#3 maintained effective VOC capture for an extended period under continuous airflow.

To gain deeper insight into the dynamic breakthrough behavior of different film formulations, we further conducted a model-assisted breakthrough analysis based on the complete STF#3 breakthrough curve and the 8 h time-resolved adsorption data of representative STF and PF films. The one-dimensional gas-to-film mass-transfer model, fitting procedure, and predicted breakthrough descriptors are provided in Supplementary Section S6. STF#3 exhibited a measured t_{50} of 21.8 h and t_{end} of 122.1 h, which were slightly longer than the predicted t_{50} and t_{end} of STF#1, although STF#3 contained only 3.0 g activated carbon compared with 5.0 g in STF#1. This result indicates that increasing activated-carbon loading alone did not necessarily lead to longer dynamic adsorption duration when film-level transport accessibility was limited. In addition, for the same 3.0 g activated-carbon loading, STF#3 showed much longer breakthrough times than the corresponding planar control PF#3, whose predicted t_{50} and t_{end} were only 3.9 h and 61.0 h, respectively. This comparison indicates that the compact planar coating could not fully utilize its embedded activated carbon during dynamic toluene adsorption. By contrast, the salt-templated architecture generated macroporous transport voids and enlarged interparticle openings, thereby improving film-level accessibility and enabling more effective use of intrinsic activated-carbon adsorption sites.

In order to further quantify adsorbent utilization, the dynamic adsorption capacity was calculated by integrating the inlet–outlet concentration difference over the adsorption period. The total captured toluene amount during the breakthrough experiment was 164.6 mg. Based on a measured total dry coating mass of 4.90 g for STF#3, the corresponding effective adsorption capacity (EAC_{ad}) was calculated to be 33.6 mg/g. These results demonstrate that the salt-templated architecture not only enhanced the initial single-pass purification efficiency but also enabled sustained utilization of the embedded activated carbon during prolonged dynamic operation. The detailed breakthrough analysis and mass-balance calculation are provided in Supplementary Sections S5–S6.

3.4. Operating adaptability under ventilation-relevant conditions

To evaluate the operating adaptability of salt-templated adsorption films, their single-pass removal performance was examined under varied salt sources, inlet VOC concentrations, VOC species, and relative humidities. The experiments were all conducted at an airflow velocity of 1.0 m/s. STF#3 and PF#3 were selected as the representative salt-templated film and planar control film, respectively, based on the

formulation-screening results in Section 3.2.

Fig. 4a shows the influence of template-salt source and composition. Under identical single-pass testing conditions, all salt-templated films exhibited substantially higher initial removal efficiencies than the planar control. The η_0 values of the NaCl-templated film (STF#3), sea-salt-templated film (SWF), printing-and-dyeing mixed-salt-templated film (PDSF), and salt-lake mixed-salt-templated film (SLSF) were 81.2%, 78.7%, 82.9%, and 83.4%, respectively, with a narrow variation of only 4.7 percentage points among the salt-templated formulations. By contrast, PF#3 reached an η_0 of only 52.6%. Because the salt-source comparison was conducted as an independent experimental series, the PF#3 value reported here corresponds to the control measured within this test series; the small difference from the formulation-screening result does not affect the within-series comparison. Relative to STF#3, the normalized η_0 values of SWF, PDSF, and SLSF were 0.97, 1.02, and 1.03, respectively. The comparable performance obtained using different sources of salts indicates that the enhancement was primarily associated with the removable-particle templating effect rather than a NaCl-specific contribution. Therefore, diverse salt sources, including naturally derived and compositionally complex salts, can be applied as sacrificial templates to construct transport-accessible porous films for enhanced dynamic VOC capture. This result further suggests a resource-utilization opportunity: abundant sea salt and treatment-demanding saline streams can be converted into functional pore-forming agents for adsorption-film fabrication.

Accordingly, SWF, a porous film prepared from a natural salt source, was selected, along with STF#3 and PF#3, for subsequent comparisons under variable operating conditions. The effect of inlet VOC concentration is presented in Fig. 4b. Over a tenfold increase in inlet toluene concentration from 1 to 10 ppm, STF#3 maintained η_0 values of 80.7%–84.1%, while SWF achieved a comparable range of 79.7%–84.3%. The

variations within the tested concentration range were limited to 3.4 and 4.6 percentage points for STF#3 and SWF, respectively. In comparison, PF#3 remained substantially lower, with η_0 values of 48.7%–50.3%. These results indicate that all three films showed only weak concentration dependence within the tested low-ppm range.

We also evaluated the applicability of salt-templated adsorption films to different VOC species. The results are shown in Fig. 4c. At an inlet concentration of 2 ppm, STF#3 and SWF exhibited high η_0 values for all three tested compounds. For tetrachloroethylene and benzene, SWF exhibited slightly higher η_0 values than STF#3, reaching 85.5% versus 83.8% and 79.7% versus 77.3%, respectively. For toluene, however, STF#3 showed a marginally higher η_0 than SWF, with values of 81.2% and 79.2%, respectively. Notably, the difference between STF#3 and SWF remained within 2.4 percentage points for each VOC species, while both salt-templated films maintained high η_0 values of approximately 80% across the three pollutants. By contrast, PF#3 achieved only 43.2%–48.1%, corresponding to absolute improvements of 35.3–39.5 percentage points after salt templating. These results demonstrate that the salt-templated films provided consistently high single-pass removal efficiencies for representative aromatic and chlorinated VOCs, and that the use of naturally sourced sea salt preserved the broad-spectrum VOC capture capability of the porous film architecture. The slightly higher η_0 of tetrachloroethylene is consistent with its higher molecular mass and lower volatility, as well as its chlorine-rich, readily polarizable structure, which can strengthen dispersion interactions and enhance gas-to-solid partitioning on activated carbon. Because the differences among the three VOCs were modest, pore accessibility and dynamic transport also contribute; selected molecular properties are summarized in Supplementary Table S4.

Relative humidity exerted a pronounced adverse effect on single-pass VOC removal, as shown in Fig. 4d. When the relative humidity increased

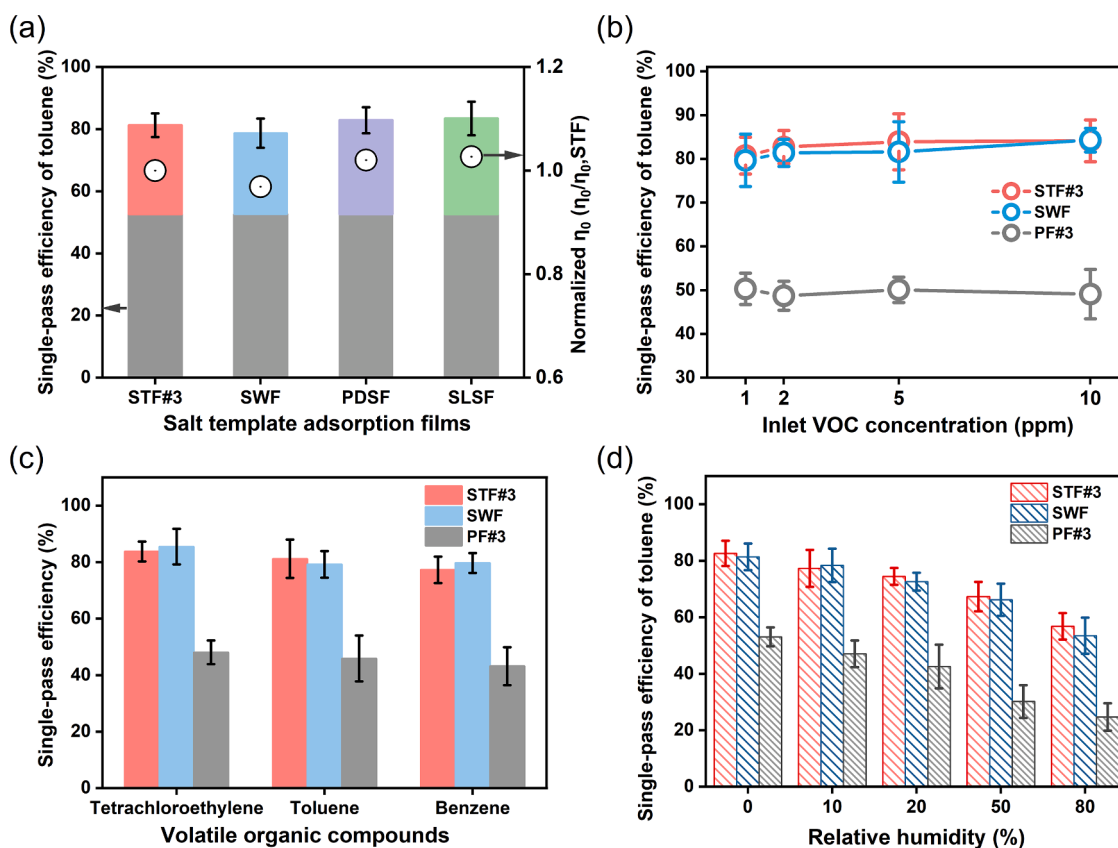


Fig. 4. Operating adaptability of representative adsorption films under variable single-pass purification conditions. (a) Effect of template-salt source and composition on η_0 , including STF#3, SWF, PDSF, SLSF, and PF#3. (b) Effect of inlet toluene concentration on η_0 of STF#3, SWF, and PF#3. (c) η_0 values of STF#3, SWF, and PF#3 for different VOC species at an inlet concentration of 2 ppm. (d) Effect of relative humidity on η_0 of STF#3, SWF, and PF#3.

from 0% to 80%, the η_0 value of STF#3 decreased from 82.6% to 56.8%, while that of SWF decreased from 81.4% to 53.5%. The corresponding η_0 value of PF#3 decreased from 53.1% to 24.7%. Accordingly, at 80% RH, STF#3 and SWF retained approximately 68.8% and 65.7% of their respective dry-condition efficiencies, whereas PF#3 retained only 46.5%. Thus, STF#3 and SWF still exceeded PF#3 by 32.1 and 28.8 percentage points, respectively. The humidity-induced decline is consistent with competitive interference from water vapor on VOC adsorption and reduced accessibility of fine adsorption pores [56,57]. At low-to-moderate relative humidity, water molecules preferentially occupy oxygen-containing and other high-energy polar sites, reducing the number of sites available to toluene through competitive adsorption. At higher relative humidity, hydrogen-bonded water clusters and water films may form, potentially narrowing or obstructing fine-pore entrances, thereby reducing pore accessibility and increasing diffusion resistance. Because toluene is weakly polar and predominantly hydrophobic, both competitive site occupation and water-induced pore obstruction suppress its adsorption. The proposed mechanism is illustrated in Supplementary Fig. S8. Overall, the VOC capture mechanism of salt-templated films involves a hierarchical transport-adsorption process: salt-derived micrometer-scale pathways facilitate convective-diffusive transport through the coating. At the same time, the intrinsic micro- and mesopores of activated carbon provide adsorption sites for VOC retention via physical interactions. Nevertheless, the persistent performance advantage of STF#3 and SWF across the full relative-humidity range indicates that the salt-derived transport architecture remained effective in maintaining gas access to the adsorption layer under moisture interference.

3.5. Cyclic purification performance with in situ electrothermal regeneration

For adsorption-based VOC purification, high initial removal efficiency alone is insufficient for long-term application because progressive occupation of adsorption sites inevitably leads to performance attenuation and material replacement. Integrating the adsorption film with in situ thermal regeneration is expected to provide a means to restore VOC purification performance after each adsorption cycle, thereby reducing adsorbent consumption and replacement costs. Therefore, the cyclic adsorption-regeneration performance of the representative salt-templated film, STF#3, was evaluated under three characteristic moisture regimes relevant to practical operation: an extremely dry baseline condition at 0% RH, a typical indoor humidity condition at 50% RH, and a humid condition at 80% RH.

As shown in Fig. 5a, STF#3 exhibited reproducible adsorption-regeneration behavior over 15 consecutive cycles under dry conditions. Each cycle consisted of an 8 h toluene adsorption stage followed by in situ electrothermal regeneration at 80 °C for 20 min. During each adsorption stage, the single-pass removal efficiency gradually decreased as accessible adsorption sites were occupied, whereas electrothermal regeneration restored it at the start of the subsequent cycle. The initial efficiency remained approximately 83% in cycle #1 and approximately 80% in cycle #15, corresponding to about 96% retention. The end-of-adsorption efficiency similarly remained approximately 68% and 66% in cycles #1 and #15, respectively, corresponding to about 97% retention. After completion of the 15-cycle adsorption-regeneration test, a bending assessment was further conducted to evaluate the mechanical

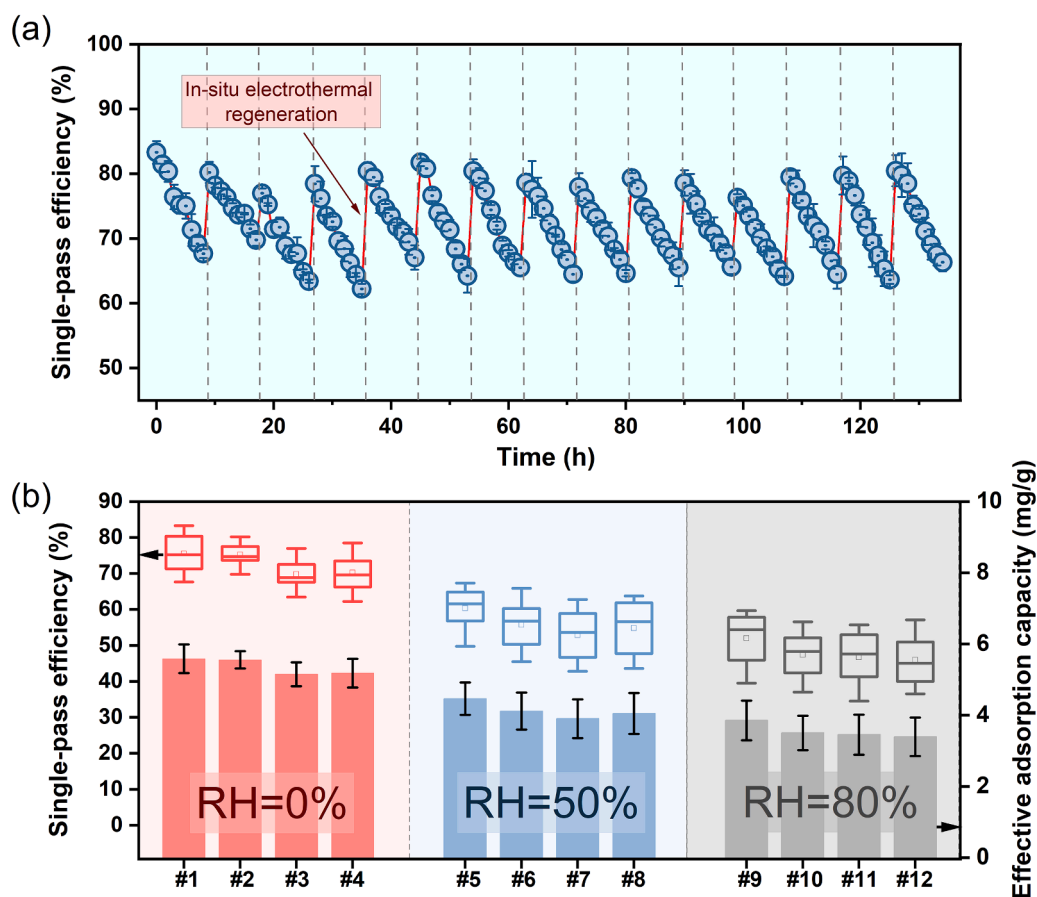


Fig. 5. Cyclic adsorption-regeneration performance of STF#3. (a) Time-dependent single-pass removal efficiency during 15 consecutive cycles under dry conditions (0% RH). (b) Distributions of single-pass removal efficiency and effective adsorption capacity, EAC_{ad} , for four cycles conducted at 0%, 50%, and 80% RH. Three independent four-cycle test series were conducted at 0%, 50%, and 80% RH; for graphical presentation, they are labeled as cycles #1–#4, #5–#8, and #9–#12, respectively. Each adsorption stage lasted 8 h and was followed by in situ electrothermal regeneration at 80 °C for 20 min.

integrity of the film. No visible cracking, large-area delamination, or obvious particle shedding was observed, and the film retained its macroscopic flexibility after repeated electrothermal regeneration. The coating mass changed only slightly from 4.9084 g before the bending assessment to 4.9078 g after the assessment, further indicating negligible material loss during bending (Supplementary Section S9 and Video S1).

Under dry conditions, STF#3 exhibited the highest cyclic removal performance. The initial single-pass removal efficiency was approximately 83% in cycle #1, and it remained above 62.2% throughout the four cycles. Based on the efficiency distributions in Fig. 5b, the average single-pass removal efficiency decreased only from 75.5% in cycle #1 to 70.2% in cycle #4 following the electrothermal regeneration step, corresponding to a performance retention of 93.0% after three regeneration procedures. Consistently, the effective adsorption capacity (EAC_{ad}) remained within 5.2–5.6 mg/g. These results demonstrate that electrothermal regeneration effectively restored the adsorption performance of STF#3 under dry conditions, with only limited cumulative attenuation during repeated operation.

The influence of moisture on cyclic operation was further examined under typical indoor humidity (50% RH) and humid operating conditions (80% RH). As shown in Fig. 5b, increasing relative humidity progressively reduced both the single-pass removal efficiency and the effective adsorption capacity. When the relative humidity increased to 50%, the average efficiency decreased to 52.9%–60.3%, accompanied by a reduction in EAC_{ad} to 3.9–4.5 mg/g. A further increase to 80% RH reduced the average efficiency to 45.9%–52.0% and EAC_{ad} to 3.4–3.9 mg/g. These results quantitatively demonstrate that increasing moisture loading progressively suppresses VOC capture, probably due to competitive adsorption of water molecules and partial blockage of fine transport pathways [56,58]. The corresponding time-dependent adsorption–regeneration profiles under the three humidity conditions are provided in Supplementary Fig. S9.

However, the humidity-induced decrease in absolute purification performance did not eliminate the regenerability of STF#3. Based on the median efficiency distributions in Fig. 5b, the median single-pass efficiency after three electrothermal regeneration procedures retained approximately 92% and 83% of their respective initial-cycle efficiencies at 50% RH and 80% RH, respectively. The lower retention observed at 80% RH may be associated with the substantially increased water-vapor loading in the porous film. Under highly humid conditions, adsorbed water can competitively occupy VOC-accessible adsorption sites and partially obstruct fine-pore transport pathways [59,60]. Nevertheless, the results indicate that the PI–Cu-based electrothermal regeneration method enabled repeated recovery of VOC capture performance across a broad humidity range. A condition-aware comparison with reported VOC adsorbents, including commercial activated carbon benchmarks, was further conducted based on the dynamic adsorption capacity and the clean-air capacity index (Supplementary Section S11). The comparison indicates that the advantage of STF#3 lies not in maximizing the intrinsic equilibrium adsorption capacity, but in improving the utilization of activated carbon under low-concentration, short-contact-time VOC purification conditions. Therefore, the salt-templated film remained functionally regenerable under humid conditions, supporting reduced adsorbent replacement demand and its potential for long-term practical VOC purification.

4. Conclusions

In this study, salt-templated activated-carbon films were developed for efficient single-pass removal of gaseous VOCs under ventilation-relevant conditions. By introducing template salt particles into the activated-carbon coating and subsequently removing them through water leaching, a simple film-structuring strategy was established to improve the accessibility of adsorption sites and reduce mass-transfer limitations in dense planar films. The SEM and BET N_2 adsorption

results confirmed that salt templating effectively reconstructed the film-level pore architecture. The ground STF#3 coating exhibited a 34% higher BET specific surface area and an 18% higher total pore volume than the ground PF#3 coating, confirming improved accessibility of the porous structure within the composite coating. Meanwhile, STF#3 also showed the best balance between pore connectivity and effective activated-carbon loading. At an airflow velocity of 1.0 m/s, STF#3 achieved a single-pass toluene efficiency η_0 of 82.2%, whereas the corresponding planar adsorption film reached only 58.9%, corresponding to a relative improvement of approximately 40%.

The salt-templated films also exhibited broad operating adaptability. Films prepared using NaCl, sea salt, and simulated mixed salts showed comparable η_0 values of 78.7%–83.4%, indicating that naturally derived and compositionally complex salts can also serve as effective sacrificial templates. STF#3 and the sea-salt-templated film SWF maintained stable η_0 values of approximately 80% across inlet toluene concentrations of 1–10 ppm. They also achieved consistently high removal efficiencies of 77.3%–85.5% for representative aromatic and chlorinated VOCs, including benzene, toluene, and tetrachloroethylene. Although elevated relative humidity reduced the absolute removal efficiency because of water-vapor competition, STF#3 maintained its performance advantage over the planar control across 0–80% RH. The salt-templated films exhibited stable regeneration performance via in situ electrothermal desorption: four-cycle tests demonstrated regenerability across 0–80% RH, and long-term cycling stability was observed under dry conditions. Unlike conventional salt-assisted carbonization or activation strategies that primarily regulate intrinsic carbon porosity, the present water-removable salt-templating approach focuses on constructing micrometer-scale transport pathways within binder-containing activated-carbon films, thereby improving the dynamic accessibility and utilization of pre-existing activated-carbon adsorption sites. Overall, the combination of water-removable salt templating provides a scalable strategy for constructing reusable adsorption films with enhanced mass-transfer accessibility and practical potential for ventilation-relevant VOC purification.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at [doi:10.1016/j.buildenv.2026.115192](https://doi.org/10.1016/j.buildenv.2026.115192).

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