



Effect of Humidity on VOC filters for Indoor Air Quality: A Comparative Study of Toluene Sorption by Zeolite 13X and GAC-1240 Under Dry and Humid Conditions

Aamir Hanif¹, Manaswini Acharya¹, Mahesha G R², Majid Naderi¹, Paul Iacomi¹

¹ Surface Measurement Systems Ltd., Unit 5 Wharfside, London, UK

² Particle Characterization Laboratories, Uppal, Hyderabad, Telangana-500039, India

Volatile organic compounds (VOCs) pose significant risks to human health, indoor air quality, and the broader environment. Adsorption-based capture is widely used for VOC removal due to its operational simplicity and effectiveness at low contaminant concentrations. However, adsorbent performance is commonly evaluated under dry conditions that fail to reflect real-world environments where humidity is present. This study presents a systematic evaluation of two prototypical porous materials, Zeolite 13X and granular activated carbon (GAC), which are two widely used commercial adsorbents with contrasting surface chemistries. We use two complementary techniques: DVS (Dynamic Vapor Sorption) analysis for gravimetric vapor uptake measurements and the BTA Frontier for dynamic packed-bed breakthrough analysis. A particular focus is placed on the impact of water vapor on toluene adsorption, demonstrating how humidity conditions critically influence adsorbent selection and performance benchmarking.

Introduction

Volatile organic compounds (VOCs) represent a diverse class of organic chemicals characterized by relatively high vapor pressures at ambient temperature and boiling points typically in the range of 50–260°C [1]. While widely used across industrial processes, their accumulation in indoor and outdoor atmospheres poses serious risks to human health and the environment, including respiratory irritation, fatigue, dizziness, and exacerbation of asthma [2, 3].

Toluene is among the most prevalent VOCs, used extensively in the manufacture of plastics, polyurethane, and nylon, and as a solvent in paints, inks, adhesives, coatings, and cleaning agents [4]. Continuous exposure to toluene even at low ppm concentrations is hazardous: the US Occupational Safety and Health Administration (OSHA) sets a permissible exposure limit of 200 ppm as an 8-hour

time-weighted average, with an immediately dangerous to life or health (IDLH) threshold of 500 ppm [5].

There are a plethora of airborne VOC mitigation strategies, including thermal oxidation, photocatalytic degradation, and ozonation. Adsorption has emerged as one of the most practical approaches due to its operational simplicity and effectiveness at low contaminant concentrations. However, the majority of reported toluene sorption studies have been conducted under dry conditions (0% RH), which do not reflect realistic indoor air environments where humidity levels of usually 40-90 RH% substantially exceed VOC concentrations and can significantly affect adsorption performance [6].



This study addresses this gap by using two complementary techniques of Dynamic Vapor Sorption (DVS) for binary gravimetric uptake measurements and the BreakThrough Analyser (BTA) Frontier for packed-bed breakthrough analysis to systematically evaluate the impact of humid conditions on toluene capture. Two commercially available prototypical adsorbents were selected to represent contrasting surface chemistries: Zeolite 13X as a hydrophilic material and a granular activated carbon (GAC-1240) as a hydrophobic counterpart, enabling a direct assessment of how adsorbent polarity governs performance under realistic humidity conditions.

Methods

Two commercially available adsorbents were selected to represent contrasting surface chemistries: binder-free Zeolite 13X beads of average diameter 0.4 mm (Zeochem) as a hydrophilic material and granular activated carbon (GAC-1240, Norit) as a hydrophobic counterpart.

Gravimetric vapor sorption measurements were performed using the DVS Resolution. This is a dual-vapor gravimetric sorption analyzer uniquely capable of delivering two vapors simultaneously, thereby enabling direct co-adsorption experiments with toluene and water vapor to simulate realistic humid conditions.

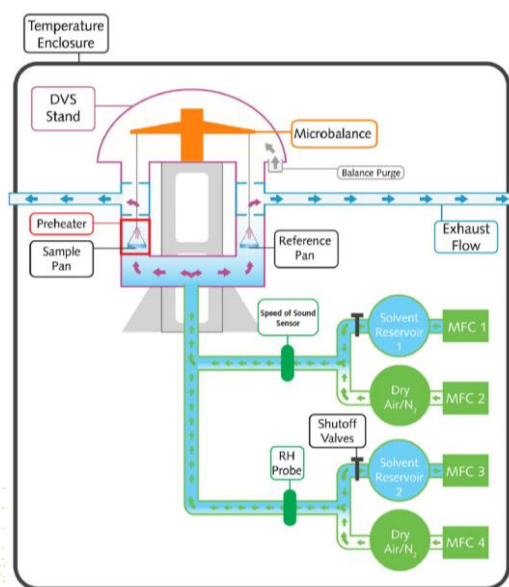


Figure 1. Schematic of the DVS Resolution

At the heart of the instrument, as illustrated in the schematic (Figure 1), is the SMS UltraBalance that records real-time mass changes during adsorption and desorption with a resolution of 0.01 μg , delivering unmatched precision and stability over extended experimental durations. 10-15 mg of the adsorbent was loaded in the sample pan for analysis. Vapor concentration was independently controlled across two channels, each comprising a dedicated solvent reservoir and a pair of mass flow controllers (MFC 1–4) that blend saturated solvent vapor generated by bubbling carrier gas through the respective reservoir with dry nitrogen at precisely defined ratios. Real-time closed-loop feedback was maintained via a patented speed of sound (SoS) sensor for toluene concentration measurements and a secondary capacitive relative humidity (RH) probe, ensuring accurate and stable vapor delivery throughout each experimental cycle. Sample mass changes were recorded continuously as a function of vapor partial pressure. Prior to each sorption measurement, samples were dried in situ at 200 °C for Zeolite 13X and 120 °C for GAC-1240 using the integrated preheater. All experiments were conducted within a temperature-controlled enclosure, maintaining isothermal conditions at 25 °C to prevent condensation and ensure the integrity of vapor-phase composition at the sample surface.

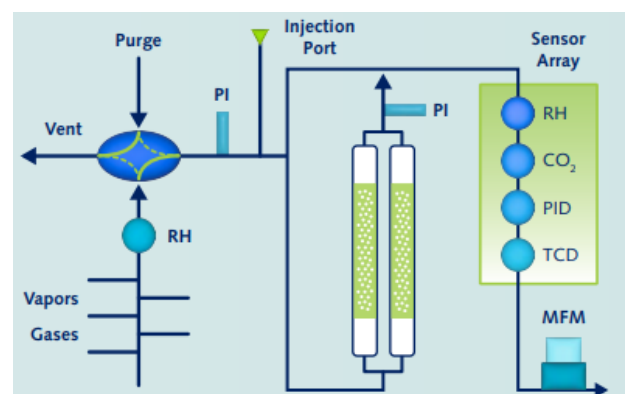


Figure 2. Schematic of the BTA Frontier

The column breakthrough experiments were performed using the BTA Frontier. As illustrated in Figure 2, the instrument operates on a packed-bed chromatographic principle, whereby a precisely blended gas mixture is introduced at the inlet of a sample-packed column, and the effluent concentration is continuously monitored at the



outlet by a dedicated sensor train. Gas and vapor generation are controlled by up to five high-turndown MFCs and up to two solvent reservoirs. The humidity or solvent vapors generated by bubbling a controlled gas fraction through a heated liquid reservoir with saturated wet and dry streams are subsequently blended in a custom manifold to deliver a stable, condensation-free vapor at the target concentration. An upstream switching manifold toggles the column inlet between inert purge and target gas stream, enabling sharp concentration fronts and minimizing dead-volume artefacts particularly critical for small sample masses. Pressure transducers upstream and downstream of the column monitor bed pressure drop to support accurate mass balance calculations. The outlet sensor train comprises of CO₂ NDIR, capacitive RH, photoionization detection (PID) for VOCs, ammonia and H₂S, and a thermal conductivity detector (TCD) for binary mixture analysis, all housed within a temperature-controlled incubator to ensure measurement stability. A dedicated resistive column oven with independent temperature control facilitates in situ sample activation and regeneration prior to each experiment.

For breakthrough experiments, 100-200 mg of adsorbent samples were packed into a silanized glass column between two glass wool plugs. Prior to each run, the sample was activated in situ at 300°C under 200 sccm N₂ for the requisite hold period, then cooled to the analysis temperature of 25°C under the same flow. Breakthrough experiments were initiated by switching the column inlet from pure nitrogen to a blended feed of 775 ppm toluene under dry (0% RH) and humid (30% RH) conditions. Toluene concentration at the outlet was continuously monitored by calibrated PID sensors, with humidity tracked by integrated capacitive sensors. Each experiment was terminated upon near-saturation or after a maximum of 300 minutes. Following the breakthrough, the feed was returned to 200 sccm pure nitrogen and the column temperature ramped to 300 °C for 13X and 120 °C for GAC-1240, held up to 180 minutes to ensure complete desorption, then cooled to 25 °C before

the next run. Blank experiments were conducted under identical conditions using an inert bed in place of the adsorbent to quantify dead-volume contributions and sensor response delays, which were subsequently subtracted from all experimental data. After the final regeneration cycle, the column was reweighed to determine the dry sorbent mass, which was used for all capacity calculations.

Results

Toluene Uptake Under Dry Conditions

Figure 3a presents the DVS time-resolved toluene uptake and Figure 3b isotherms for 13X zeolite and GAC. The majority of toluene uptake occurred during the first dosing step for both materials, indicating rapid occupation of high-affinity adsorption sites at low partial pressures and suggesting strong adsorbate-adsorbent interactions at the onset of exposure. At higher concentration, the incremental uptake was comparatively smaller, consistent with progressive site saturation. Overall, GAC demonstrated a significantly higher toluene uptake capacity, reaching approximately 40 wt.%, compared to 13X zeolite which plateaued near 18 wt.% under equivalent conditions, consistent with GAC's broader pore distribution and higher affinity for non-polar aromatic compounds.

During desorption, uptake at higher concentrations was largely reversible as partial pressure decreased. In contrast, the substantial uptake observed at the initial dosing step showed clear hysteresis and was not fully recovered under the same reduction in partial pressure. This suggests that toluene adsorbed at high-affinity micropore sites is kinetically or energetically hindered from desorbing under the conditions used. These strong interactions require thermal treatment or high vacuum to fully remove the adsorbed toluene.

Three consecutive breakthrough measurements were then conducted at 775 ppm toluene, corresponding to a concentration at the first isotherm data point. The results are presented as normalized breakthrough curves in Figure 3c.

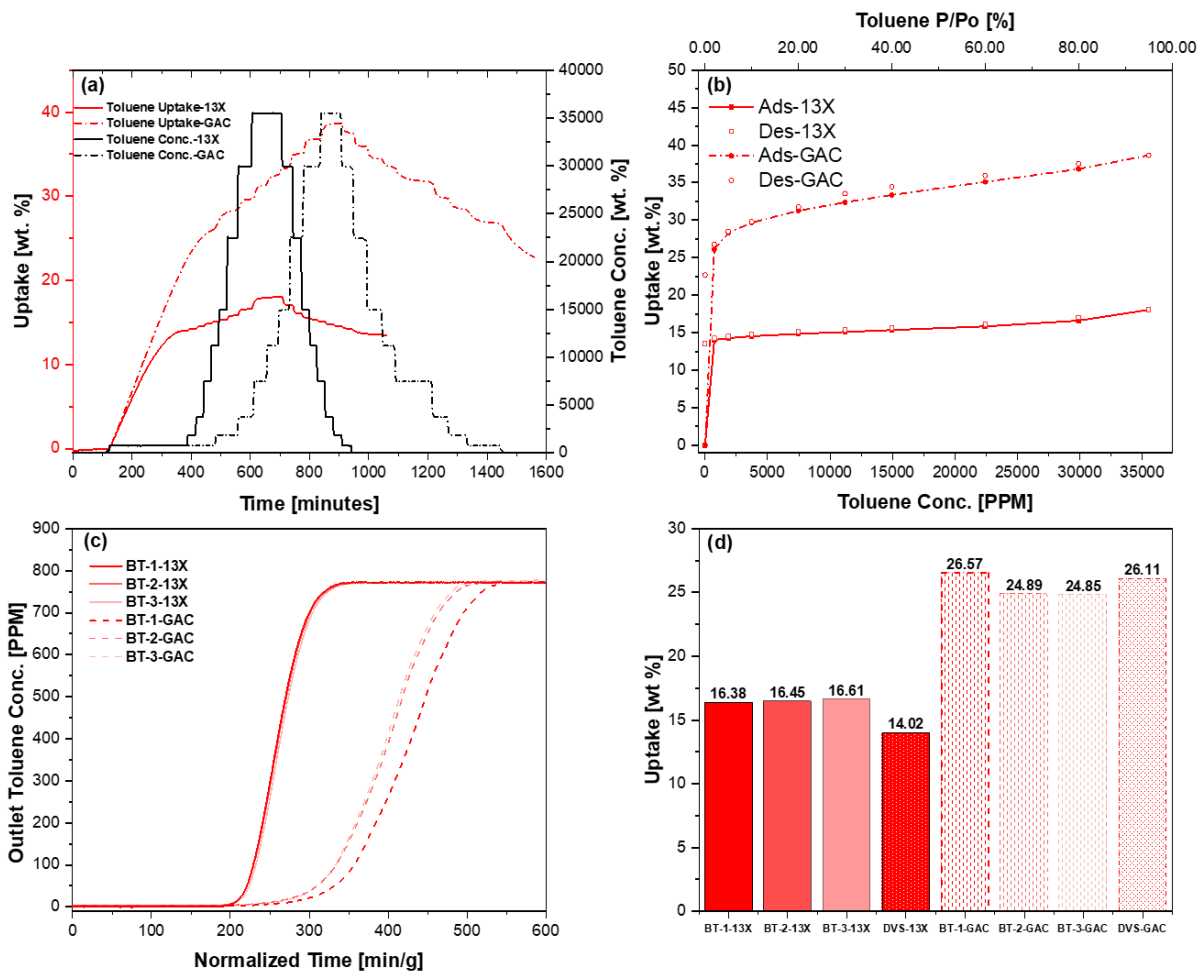


Figure 3. Toluene sorption on 13X zeolite and GAC characterized by DVS and BTA. (a) Time-resolved DVS toluene uptake and concentration profiles for 13X zeolite and GAC recorded during a full sorption–desorption cycle. (b) Respective isotherms for 13X (solid) and GAC (dashed) measured by DVS over 0–35,000 ppm (P/P_0 0–100%); filled symbols denote adsorption and open symbols denote desorption. (c) Normalized breakthrough curves for 13X zeolite (BT-1 to BT-3, solid red shades) and GAC (BT-1 to BT-3, dashed red shades) plotted against normalized time (min/g). (d) Uptake values (wt.%) derived from BTA experiments alongside DVS reference values.

GAC bed reached saturation (outlet concentration ~775 ppm) at normalized times of approximately 400–500 min/g, substantially later than 13X zeolite, which saturated at ~250–300 min/g. This difference is consistent with the markedly higher toluene uptake capacity of GAC relative to 13X zeolite under equivalent conditions.

13X zeolite exhibited excellent inter-run reproducibility, with all three replicate breakthrough curves closely overlapping. This indicates complete regeneration of adsorption capacity during the intervening desorption stage and confirms that the BTA Frontier delivers consistent and reliable results across repeated measurements.

GAC-1240 displayed a marginally longer breakthrough time in the first run compared to the second and third, which then showed stable and closely overlapping profiles. This behavior indicates a reduction in accessible capacity following the initial adsorption cycle, likely attributable to the partial and incomplete desorption of toluene from high-affinity micropore sites during regeneration at 120 °C. After this initial cycle, the adsorbent reaches a stable working capacity that remains consistent across subsequent runs, suggesting a reproducible pseudo-equilibrium state.

Following saturation, the beds were regenerated by heating under flowing nitrogen (200 sccm) to 300 °C for zeolite 13X and 120 °C for GAC-1240. The

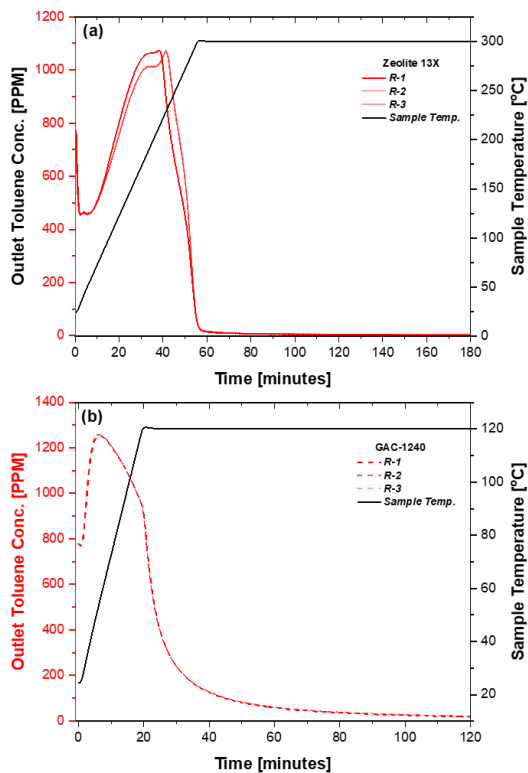


Figure 4. Temperature-programmed desorption of toluene from (a) zeolite 13X during regeneration to 300 °C and (b) GAC-1240 during regeneration to 120 °C, following saturation at approximately 775 ppm toluene under dry nitrogen (200 sccm).

corresponding temperature programmed desorption (TPD) profiles are shown in Figure 4. For zeolite 13X, the first regeneration cycle exhibits a desorption maximum at $T_{\max} \approx 190$ °C, whereas the second and third cycles show two closely spaced maxima at approximately 190 and 210 °C, suggesting a slight change in adsorption-site energetics after the initial cycle. Beyond this, the desorption curves for cycles 2 and 3 are essentially overlapping. The outlet concentration returns to baseline within less than 1 h of holding at 300 °C, indicating efficient regeneration.

In contrast, GAC-1240 shows significant toluene release already from room temperature, reaching a peak outlet concentration at $T_{\max} \approx 54$ °C consistent with somewhat weaker toluene–GAC interactions than for zeolite 13X. The specific amounts desorbed, obtained by integration of the TPD curves, agree well with the corresponding adsorption capacities measured in the preceding saturation step as seen in Figure 5, demonstrating

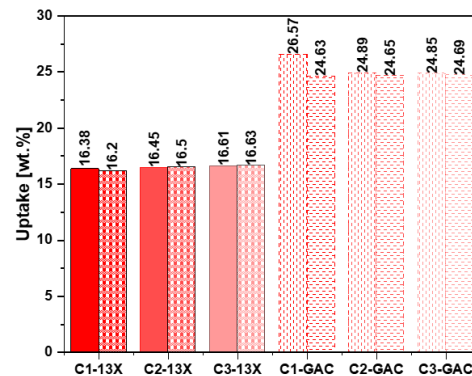


Figure 5. Cyclic toluene capacities for zeolite 13X (C1–C3-13X) and GAC-1240 (C1–C3-GAC). For each cycle the left bar represents adsorption uptake, and right bars show the desorbed amounts from the regeneration step.

essentially complete desorption and good coherence between adsorption and desorption capacities from the BTA Frontier measurements.

Water uptake

Water vapor sorption isotherms of Zeolite 13X and GAC were measured using DVS over an RH range of 0–95%, revealing markedly distinct moisture uptake behaviors that reflect the fundamentally different nature of the two adsorbents. Zeolite 13X exhibits a Type I isotherm profile, characterized by steep and rapid uptake quickly approaching a plateau of approximately 23–25 wt.% a behavior consistent with its strongly hydrophilic aluminosilicate framework. In contrast, GAC displays a sigmoidal Type V isotherm with low moisture uptake below ~40% RH, followed by a sharp pore-filling region that ultimately yields a maximum uptake exceeding 41 wt.% at 95% RH, surpassing that of Zeolite 13X. Notably, GAC also exhibits pronounced hysteresis, a signature of capillary condensation within mesopore networks. These contrasting isotherm profiles carry direct implications for adsorbent selection for VOC remediation. Below 40% RH, GAC adsorbs only a small quantity of water, suggesting it should retain good capacity for toluene uptake within this humidity range. Zeolite 13X, however, adsorbs water strongly even at very low RH levels, meaning that competitive adsorption between water and toluene for the same micropore sites could significantly diminish its toluene uptake capacity under humid conditions.

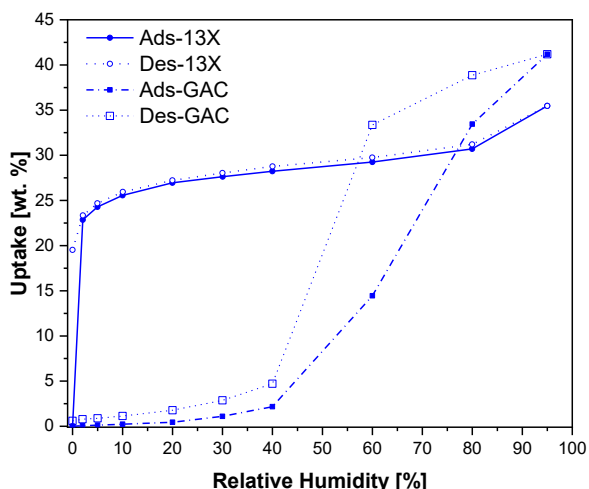


Figure 6. Water vapor sorption isotherms of Zeolite 13X and GAC measured by DVS at 25°C.

Toluene uptake in humid conditions

To clearly evaluate this competitive effect, co-adsorption studies of toluene and water were conducted with DVS and BTA at a background humidity of 30% RH. This lies in a range where Zeolite 13X demonstrated high water loading while GAC exhibited minimal moisture uptake with no expected capillary condensation. The results of these co-adsorption experiments are discussed in the following sections.

DVS co-adsorption measurements were carried out by first exposing the adsorbent to 30 % RH until saturation followed by exposure to 765 ppm Toluene and 30 % RH. The uptake profiles are given in Figure 7. Zeolite 13X rapidly adsorbed water upon its introduction, reaching an equilibrium water loading of 24.45 wt.% within the first stage of the experiment consistent with its strongly hydrophilic character at low humidity levels established in the single-component isotherm data. Upon subsequent toluene introduction, only a marginal additional uptake of 0.09 wt.% was recorded, suggesting that Zeolite 13X was effectively saturated by water prior to toluene exposure and that the two adsorbates compete directly for the same adsorption sites. In contrast, GAC demonstrated a markedly different co-adsorption profile shown in Figure 7b. Consistent with its Type V water vapor isotherm, GAC adsorbed only 1.80 wt.% of water during the 30% RH pre-loading stage.

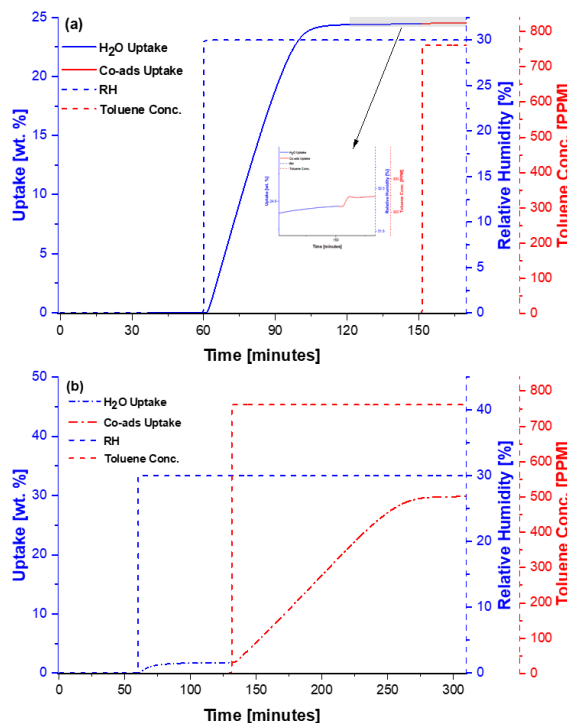


Figure 7. DVS co-adsorption of water vapor and toluene on (a) Zeolite 13X and (b) GAC measured by DVS at 25°C and 30% background relative humidity, showing time-resolved humidity and cumulative uptake (wt.%), target RH (%), and toluene concentration (ppm).

Upon toluene introduction, GAC proceeded to adsorb an additional 28.03 wt.%, yielding a combined total uptake of 29.83 wt.%. These data imply that GAC retains its full toluene adsorption capacity under humid conditions at 30% RH, making it significantly more effective than Zeolite 13X for VOC capture in ambient humidity environments.

While DVS provides valuable time resolved uptake and insight into competitive adsorption behavior through single-component and net co-adsorption uptake measurements. However, directly observing the dynamic interplay between humidity and toluene adsorption and deconvoluting the total uptake to individual components requires a complementary approach. Multicomponent breakthrough analysis using the BTA Frontier translates these indications into an unambiguous, performance-relevant metric by resolving the individual uptake profiles of water vapor and toluene under application-representative conditions.



Figure 8 presents normalized breakthrough curves acquired under simultaneous exposure to 30% RH and ~765 ppm toluene. For Zeolite 13X (Figure 8a), toluene breaks through at approximately 90 min/g, with the outlet concentration rising sharply before exhibiting a pronounced rollup peak of ~1650 ppm at ~145 min/g, more than double the inlet toluene concentration. This rollup is a direct consequence of the competitive displacement mechanism suggested by DVS co-adsorption. As the water breakthrough front propagates through the bed, it displaces previously adsorbed toluene, temporarily driving outlet toluene concentrations well above the inlet level. The cross-hatched area beneath the rollup peak represents the net toluene displaced by water; a confirmation of competitive interaction.

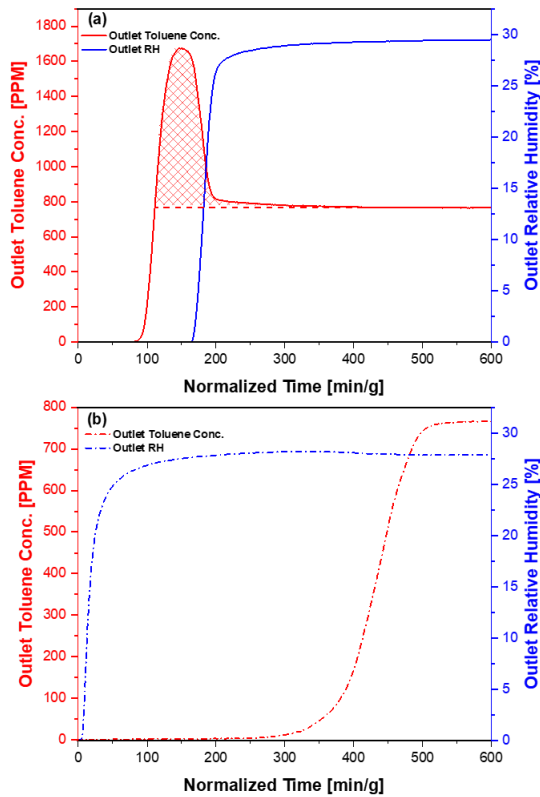


Figure 8. Breakthrough curves of (a) Zeolite 13X and (b) GAC using the BTA Frontier co-exposure to ~765 ppm toluene and 30% RH, showing outlet toluene concentration (ppm, left axis) and outlet RH (%), right axis) as a function of normalized time (min/g). The cross-hatched area in (a) denotes toluene rollup region resulting from competitive displacement by water vapor.

Following the rollup, outlet toluene concentration rapidly declines to the inlet value as the bed reaches saturation with both adsorbates. The toluene rollup followed by water breakthrough confirms that both

species compete for identical adsorption sites within the Zeolite 13X micropore network, severely compromising its practical utility as a VOC adsorbent in humid environments.

GAC (Figure 8b) on the other hand presents a fundamentally different and markedly more favorable breakthrough profile. Water vapor breaks through almost immediately at ~10 min/g consistent with the lower water uptake of GAC at 30% RH. Toluene breakthrough is substantially delayed, commencing only at approximately 300 min/g and following a broad, gradual sigmoidal curve characteristic of the slow mass transfer kinetics within the activated carbon pore network, before reaching the inlet equilibrium concentration beyond 500 min/g. Unlike 13X, no rollup is observed in the GAC toluene breakthrough curve, confirming the absence of competitive displacement between water and toluene. It seems water simply passes through the bed without occupying the toluene adsorption sites. The substantially longer normalized breakthrough time for toluene on GAC compared to Zeolite 13X directly reflects the preserved dynamic toluene capacity under humid conditions, corroborating the equilibrium co-adsorption data obtained by DVS Resolution.

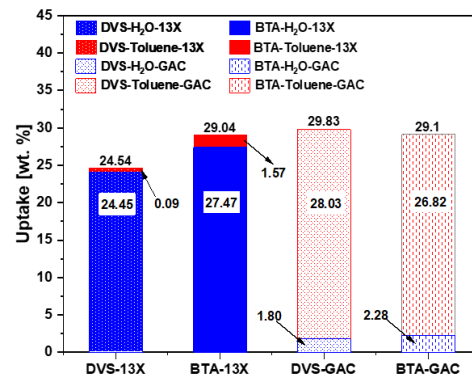


Figure 9. Comparison of DVS and BTA derived adsorption capacities under humid conditions.

A comparison of capacities obtained by DVS Resolution and BTA Frontier under humid conditions shows a close coherence in results obtained by these two independent measurement approaches (Figure 9). A slightly higher BTA capacity for 13X could possibly be due to a higher activation temperature of 13X (300 °C) for BTA versus only 200 °C for DVS.



Conclusions

This study demonstrates the critical importance of evaluating sorbent performance under conditions that reflect real-world operating environments, rather than relying solely on dry-condition benchmarks that can lead to misleading adsorbent selection. Using a systematic, two-instrument characterization workflow, the DVS Resolution for gravimetric co-adsorption measurements and the BTA Frontier for dynamic multicomponent packed-bed breakthrough analysis, the contrasting behaviors of Zeolite 13X and GAC have been rigorously quantified and directly compared across both dry and humid conditions.

In dry conditions, both adsorbents exhibit high toluene uptake, with GAC achieving approximately double the equilibrium capacity of Zeolite 13X (~40 wt.% vs ~18 wt.%), alongside highly reproducible regeneration across three consecutive adsorption-desorption cycles. However, a background of 30% RH reveals a divergence in performance. Zeolite 13X, despite its high intrinsic toluene affinity, is severely compromised by water vapor, as inferred from DVS co-adsorption and confirmed from BTA Frontier breakthrough measurements. This competitive displacement leads to a pronounced toluene rollover in the BTA curves of ~1,650 ppm, more than double the inlet concentration, presenting a direct safety hazard in air purification and respiratory protection applications. GAC, conversely, demonstrated good humidity resilience, with only 1.80 wt.% water uptake at 30% RH. It retained its full toluene adsorption capacity of 28.03 wt.% under co-exposure conditions, and BTA breakthrough experiments unambiguously establishing GAC as the superior adsorbent for VOC capture under studied realistic humid environments.

Critically, the close coherence between capacities derived independently by DVS and BTA Frontier validates both measurement approaches and underscores the power of this combined characterization strategy. Together, these instruments provide a uniquely complete picture of adsorbent behavior.

The DVS Resolution delivers high-sensitivity, sub-microgram gravimetric resolution with independently controlled dual-vapor delivery, enabling precise time-resolved single and co-adsorption kinetic uptake data, and equilibrium isotherm determination, all in a single, automated measurement sequence using a milligram scale adsorbent.

The BTA Frontier deconvolutes the co-adsorption uptake measurements into individual uptakes and other application-relevant performance metrics under packed-bed conditions, with its multi-sensor outlet train (PID, capacitive RH, NDIR, TCD) enabling fully resolved multicomponent breakthrough profiles, accurate capacity quantification, and in situ thermal regeneration thereby directly replicating the conditions encountered in industrial or environmental separation processes.

The workflow demonstrated here from single-component dynamic kinetic and equilibrium uptake through co-adsorption to multicomponent dynamic breakthrough represents a best-practice characterization framework for any application where adsorbent selection under complex, multicomponent gas streams is critical. It is broadly applicable beyond VOC capture to CO₂ removal, ammonia abatement, indoor air quality control, and the development of next-generation functional adsorbents. By bridging the gap between laboratory equilibrium data and real-world packed-bed performance, the DVS Resolution and BTA Frontier together empower researchers to make confident, data-driven decisions thus accelerating the development and deployment of effective adsorption-based solutions.

References

1. WHO/ISO 16000-6: *Indoor air — Part 6: Determination of VOCs in indoor and test chamber air.* <https://www.iso.org/standard/73522.html> Accessed 19th May 2026
2. US EPA (2025). *Technical Overview of Volatile Organic Compounds.* <https://www.epa.gov/indoor-air-quality-iaq/technical-overview-volatile-organic-compounds>
3. Zhou, Xihe, et al. "Environmental and human health impacts of volatile organic compounds: A perspective review." *Chemosphere* 313 (2023): 137489.



4. Kim, Ki-Hyun, et al. "Identifying the best materials for the removal of airborne toluene based on performance metrics-A critical review." *Journal of Cleaner Production* 241 (2019): 118408.
5. OSHA (2025). *Occupational Exposure Limits — Toluene*. 29 CFR 1910.1000 Table Z-2. <https://www.osha.gov/toluene/occupational-exposure-limits>
6. Azmi, Luqman Hakim Mohd, et al. "Fabrication of MIL-101-polydimethylsiloxane composites for environmental toluene abatement from humid air." *Chemical Engineering Journal* 429 (2022): 132304.