International Journal of Environmental Science and Technology (2024) 21:925–938
https://doi.org/10.1007/s13762-023-05202-2

ORIGINAL PAPER

Multi-component volatile organic compounds (VOCs) treatment nexus: High-performance of activated carbon derived from residual agroforestry biomass

K. Isinkaralar[1]

Received: 5 December 2022 / Revised: 9 August 2023 / Accepted: 4 September 2023 / Published online: 28 September 2023

Abstract

Epilobium montanum, agroforestry residue biomass, produced low-cost activated carbon using the acidic chemical activating agent. The aim of this study is to explore the changes that occur in *E. montanum* during activation with H_3PO_4. The microstructures of the formed phosphoric acid-treated fibrous lignocellulosic-derived activated carbon (EM38-AC) are determined by Brunauer, Emmett and Teller, X-ray diffraction analysis, thermogravimetric analysis, scanning electron microscope, and Fourier transformed infrared spectroscopy methods. The EM38-AC with maximum surface area and total pore volume of 835 m^2/g and 0.48 cm^3 as environmentally friendly material were prepared at 700 °C, activation time of 150 min, and H_3PO_4 impregnation ratio of 3:1. The EM38-ACs have tested BTEX adsorption and the equilibrium capacities of benzene, toluene, ethylbenzene, and xylene at 20 °C and 30% RH were 112, 126, 119, and 84 mg/g for multi-system. Multi-component BTEX adsorption capacity decreased significantly with the increasing temperature and humidity. The adsorption of the BTEX mixture on EM38-ACs decreased by 28.5–35.4%, compared to the relative humidity of 30 and 90%. Also, the reusability of EM38-ACs showed good thermal regeneration and fell to 84.55% after seven cycles. Here the direct result revealed that EM38-ACs showed the largest BET surface area and the best adsorption capacity. Finally, utilizing these renewable feedstocks presents us with the avenues to realize sustainable synthesis through the green process and the purpose of a sustainable future in indoor air quality.

Graphical abstract

Keywords Adsorption equilibria · Carbon · Green chemistry · Removal mechanism · Sustainable development goals · Volatile organic compounds

Editorial responsibility: Maryam Shabani.

Extended author information available on the last page of the article

List of symbols

BET	Brunauer, Emmett and Teller
BTEX	Benzene, toluene, ethylbenzene, and xylene
C_i	Inlet BTEX concentration at equilibrium concentration (mg/L)
C_o	Outlet BTEX concentration at equilibrium concentration (mg/L)
DFT	Density functional theory
EM38-AC	Phosphoric acid-treated fibrous lignocellulosic-derived activated carbon
EMB	Precursor for activated carbons
F	Feed flow rate (mL/min)
FTIR	Fourier-transformed infrared
H_3PO_4	Phosphoric acid
q_e	Equilibrium adsorption capacity (mg/g)
S_{BET}	Surface area (m^2/g)
SEM	Scanning electron microscope
TGA	Thermogravimetric analysis
V_{MES}	Mesopore volume (cm^3/g)
V_{MIC}	Micropore volume (cm^3/g)
VOC	Volatile organic compound
V_T	Total pore volume (cm^3/g)
W	Weight of adsorbent
XRD	X-ray diffraction

Introduction

Volatile organic compounds (VOCs) generate a group of chemicals that can present a significant threat to the environment and human health under standard conditions because of a large variety of diffusivity, toxicity, and carcinogenic (USEPA 2012; Paciência et al. 2016). It gives rise to environmental problems and public concerns due to its negative contribution to photochemical smog, the greenhouse effect, and depletion of the stratospheric ozone layer and secondary organic aerosol formation (Berezina et al. 2020; Gómez et al. 2020). It has drastically increased with the rapid urbanization, industrialization, and traffic emissions, which contribute to the human risk such as irritation of the eyes, nose, throat, and lungs, damaged liver, kidney, and central nervous system, long-term exposure to even serious cancer (Jaars et al. 2018; Ghobakhloo et al. 2023; Isinkaralar 2023a) and being emitted into the atmosphere (Alvim et al. 2018; Pan et al. 2023) from vehicles (Song et al. 2020), biomass burning (Amnuaylojaroen et al. 2019), paint coating (Mo et al. 2021), solvents (Pearson 2019), petrochemical industries (Pinthong et al. 2022) and refineries (Roveda et al. 2020).

The harmful effects of pollutants on the ecosystem and environment that arise with their interrelationships must be reduced strictly in recent years. Therefore, the development of VOC removal methods with a practical and environmentally friendly approach has gained momentum worldwide. Among the numerous attentions, adsorption (Isinkaralar 2023b, c, d), absorption (Lhuissier et al. 2018), thermal oxidation (Tomatis et al. 2019), regenerative (Pu et al. 2021), catalytic oxidation (Guo et al. 2021) and biofiltration (Mikkonen et al. 2018) techniques have emerged and are widely used in gaseous VOCs application by researchers. Their effectiveness was investigated adsorption technology came to the fore as a result of its positive and negative aspects. Among its main advantages, mechanisms to increase efficiency, such as low initial investment cost, ease of operation, and easy solution to problems that may arise, have been produced. However, in the purification of VOCs, their fate and ambient conditions emerge as essential operating factors. In industrial usage, other parameters such as temperature, adsorbent, humidity, and reactor type affect system efficiency and operational performance are also critical evidence in VOC treatment (Cheng et al. 2020a; Isinkaralar and Meruyert 2023). Generally, low operating temperature, economic efficiency of the adsorbent, feed rate, and concentration significantly affect the success of adsorption (Le-Minh et al. 2018; Hunter-Sellars et al. 2020). In addition, it may need to be changed frequently depending on the surface area and desorption properties of the adsorbent used as a disadvantage. Despite everything, although adsorption is a more efficient and economic VOC removal mechanism, the desired VOCs can be recovered from gas streams (Pan et al. 2018; Gospodarek et al. 2019; Xie et al. 2019).

One way to selection of adsorbents is significant for applying an effective adsorption method (Zhang et al. 2022). Carbon-based materials such as activated carbon (Isinkaralar et al. 2023), activated carbon fibers (Song et al. 2017), modified activated carbons (Lei et al. 2020), and carbon nanotubes (Bang et al. 2019) are preferred because of the large number of pores and high surface areas (Tang et al. 2020). Generally speaking, activated carbon is an essential member of the carbon family and has been the subject of extensive research in recent years (Bedane et al. 2019; Tavan et al. 2021). In particular, high porosity is observed thanks to the pyrolysis of bio-sorbents obtained from wastes from lignocellulosic and agricultural sources at different temperatures under an inert atmosphere (Hsu et al. 2014; Rodríguez-Félix et al. 2021; 2022a, b). Currently, cost-effective and environmentally friendly adsorbents have been produced with abundant forestry, agricultural, and by-products originating from them (Hu et al. 2017; Wang et al. 2022). Recently, biomass-based precursors have been favored as a low-cost material for AC using thermochemical treatment (Xia et al. 2021; Mahari et al. 2022; Shi et al. 2022; Li et al. 2023). It has been a successful sorbent material, especially in removing

non-polar VOC compounds (Qian et al. 2015). Among the VOCs, benzene, toluene, ethylbenzene, and xylene, defined as BTEX, are a group of pollutants with toxic properties commonly found in the indoor environment (El-Hashemy and Ali 2018). Although the studies on BTEX are quite interesting, their behavior on adsorbents has not been clarified depending on the environment (Mehta et al. 2020). Relatively few studies have focused on the adsorption of gaseous BTEX on lignin-based activated carbon (Li et al. 2020; Tehrani et al. 2020).

One could view the *Epilobium montanum* as a potential sorbent after inexpensive processing about how to cope with the BTEX adsorption. It grows throughout the temperate areas of the northern hemisphere and is native to various temperate to arctic ecosystems. In actuality, this herbaceous perennial plant is often abundant in open spaces, pastures and rapidly colonizes burned-over lands. Biologists have also utilized *E. montanum* in polyploidy studies for the speciation of plants. The adsorption performance of lignin-based activated carbon depends on the sort of raw material used, the activation method, and the pyrolysis conditions. This depends on the physicochemical properties proposed with their specific properties of activated carbon, such as surface area, pore size, pore distribution, and functional groups (Pallarés et al. 2018; Tapia-Hernández et al. 2019). As reported, the adhesion mechanisms of BTEX gases by activated carbon are divided into single and multi-components (Laskar and Hashisho 2020).

In this study, the adsorption process can be simplified as below: This research assessed the efficiency of the excellent adsorbing ability of biomass-derived activated carbon against multi-component BTEX under several conditions. Accordingly, the main reason for the differences in the capacity of BTEX is the variable conditions of the adsorbing mechanism. A batch system has examined process parameters such as initial concentrations, feed gas-mixture feeding rate, temperature, and humidity on BTEX removal performance. Therefore, the primary target of this study is to evaluate the sorption capacity of complex mixture-BTEX on activated carbon from *E. montanum* with chemical activation.

Materials and methods

Epilobium montanum was used in synthesizing the activated carbons as a precursor (EMB), which belongs to the tree group frequently found in forestry. The residues of the *E. montanum* were obtained at random from different plants and dried as biowaste in plastic bags from the local forest during the autumn months of November and October from Kastamonu, Türkiye.

Materials and adsorbents preparation

The EMB was separated, washed, and pretreated at 75 °C for 96 h. After ensuring it's dry, start to ground by reducing the dimensions (2–3 cm). It has been reduced to smaller dimensions by passing it through a blender with steel blades. The EMB was sieved with the powdered particle size of 250 µm and was oven dried at 85 °C for 24 h. Ready for preparation of activated carbon, 100 g EMB was placed in a furnace (Carbolite, CTF 1200) for the pyrolysis process, which was carbonized in a horizontal tubular furnace at 500–900 °C under a nitrogen (N_2) gas flow of 110 mL/min with a heating rate of 5 °C/min and kept at that temperature for 90 and 150 min. They were removed from the carbonization reactor after it was cooled down to room temperature under a constant flow of N_2.

The EMB biomass was activated by a chemical activation method using the activating agent phosphoric acid (H_3PO_4). The impregnation dealing was performed by soaking about 20 g of the precursors with a required ratio of 1:1–2:1–3:1–4:1–5:1 (chemical agent:biomass (*w*/*w*)) phosphoric acid (H_3PO_4 85 wt%) and continuously stirred until sufficient impregnation at a temperature of 120 °C for 2 h. Afterward, the mixture was left at room temperature for one day and was placed in an oven at 105 °C for 24 h. At the end of the activation procedure, the biomass-derived activated carbons were washed with boiling deionized water until the pH of the activated carbons became neutral. Then, they were labeled as in Table 1.

To evaluate removal efficiency, this study used BTEX (benzene, toluene, ethylbenzene, and xylene) as a model adsorbate. Thus, a stock standard solution of BTEX containing volatile compounds each at 2000 mg/mL in methanol was prepared at a concentration of 1 g/L from Sigma-Aldrich (Milwaukee, WI, USA) and stored in glass stoppered bottles in the dark at 4 °C. Stock standards were prepared in methanol and diluted to give a range of standards for spiking. All reagents and N_2 were of chemical grade (purity ≥ 99%).

Materials characterization

The EM-ACs were characterized by chemical composition, functional groups, morphology, and surface area (S_{BET}). The S_{BET} and porosity texture of the EM-ACs were performed by N_2 adsorption/desorption at − 196 °C using Quantachrome-Autosorb-1C. The S_{BET} (m^2/g) and micropore (V_{MIC} cm^3/g), mesopore (V_{MES} cm^3/g), and total pore volume (V_T cm^3/g) of the EM-ACs were determined using the Brunauer–Emmett–Teller (BET) and t-plot method. The pore size distribution (PSD) and the total pore volume (V_T cm^3/g) were estimated using NOVA touch LX4 by the density functional theory (DFT) and the N_2 adsorption at $P/P_0 \geq 0.98$. The difference between the V_T and V_{MIC} determined the V_{MES}. Several functional

Table 1 H_3PO_4 Carbonization and activation condition of TCACs

Impregnation ratio of the weight of the activating agents and precursor	Carbonization time (min)	Carbonization condition (°C)	Activated carbon ID
1:1–2:1–3:1–4:1–5:1	90	500	EM(1–5)-AC
1:1–2:1–3:1–4:1–5:1	90	600	EM(6–10)-AC
1:1–2:1–3:1–4:1–5:1	90	700	EM(11–15)-AC
1:1–2:1–3:1–4:1–5:1	90	800	EM(16–20)-AC
1:1–2:1–3:1–4:1–5:1	90	900	EM(21–25)-AC
1:1–2:1–3:1–4:1–5:1	150	500	EM(26–30)-AC
1:1–2:1–3:1–4:1–5:1	150	600	EM(31–35)-AC
1:1–2:1–3:1–4:1–5:1	150	700	EM(36–40)-AC
1:1–2:1–3:1–4:1–5:1	150	800	EM(41–45)-AC
1:1–2:1–3:1–4:1–5:1	150	900	EM(46–50)-AC

groups on the surface of the EM-ACs were recorded using an FTIR spectrometer (Fourier transform infrared) in the range of 400–4000 cm^{-1} with KBr pellets using Perkin-Elmer TGA 7 FTIR analyzer. X-ray diffractometer by A Bruker D8 Advance (XRD, Bruker AXS, Germany) was performed on the crystal structures using Cu-Kα ($\lambda = 1.54$ Å) radiation, the scanning rate of 0.59°/s, and diffraction angle (2θ) between 10° and 80°.

The weight loss of samples was performed with the thermogravimetric analysis (TGA, STA7300 Hitachi, Japan). The EM-ACs were coated with gold in E-1010 Ion sputter before to scanning electron microscope (SEM), which examined their surface morphology using Quanta FEG 250, and elemental analysis of EMB and EM-ACs was carried out using EuroVector, EA3000 elemental analyzer. Basing on the physicochemical properties, notably the S_{BET}, the best EM-ACs synthesized with the most effective conditions were selected to study the BTEX adsorption onto EM38-AC. Also, the proximate analysis of EMB and EM-ACs was executed through American Standard Test Method (ASTM) test standards, and the findings were given as moisture (E871-82, ASTM 2013a), volatile matter (E872-82, ASTM 2013b), total ash (E1755-01, ASTM 2015) and fixed carbon content. In addition to this, the biochemical component analysis, including cellulose, hemicellulose, lignin, and extractives (benzene and ethanol ratio of 2:1 *v*/*v*) of EMB was performed by subtracting weight (ASTM E1690-08, ASTM 2016).

Adsorption procedure

BTEX was used as adsorbate for the gaseous adsorption. The batch adsorption experiments were conducted with a predetermined amount of EM38-ACs in the range of 0.15 g with 220 mg/m^3 of BTEX initial concentration. The adsorption reactor was tested at a relative humidity of 30, 90% RH, and with temperature control of 20, 25, 30, and 35 °C. To study the effect of contact time, samples with an initial concentration of 220 mg/m^3 were withdrawn at a predefined time and analyzed to determine the residual BTEX concentration. The concentrations of BTEX were measured using the gas chromatography/mass spectrometry detector (GC–MS; Thermo Scientific Trace 1300 and ISQ-QD Thermo Fisher Scientific).

Tenax®-TA single sorbent tubes were used, and the samples were collected through a vacuum pump (AirLite 110–100, SKC, USA) with a 120 mL/min ratio. The breakthrough profile was measured by Markes Unity Series 2 thermal desorber (Markes International Ltd., Llantrisant, U.K.) coupled with GC–MS. TG-624 capillary columns were utilized to determine the amount of benzene, toluene, ethylbenzene, and xylene using US EPA Method TO-17 (USEPA 1999). The following relations were used to determine the equilibrium adsorption capacity as in Eq. (1).

$$q_{(mg/g)} = \left(\frac{F \times C_o \times 10^{-9}}{W}\right)\left[\left(\frac{C_i}{C_o} \times t_s\right) - \left(\int_0^{t_s} \frac{C_i}{C_o} dt\right)\right] \quad (1)$$

where C_i (mg/L) is the inlet BTEX concentration at equilibrium concentration and C_o (mg/L) is the outlet BTEX value, and a feed flow rate (F) of 180 mL/min, along with 0.15 g of EM38-ACs (W), was utilized for each adsorption system. After the BTEX adsorption, $0.05 \pm 0.0.1$ g EM38-AC saturated with BTEX molecules was regenerated using thermal desorption from 10 °C/min to 450 °C under 100 mL/min N_2 conditions. The regenerated process was repeated seven times with the same steps as the adsorption experiment.

Results and discussion

Agroforestry waste is a high-grade feedstock for EM-ACs due to its suitable carbon content. Proximate and ultimate analyses examined that EMB contains a high amount of carbon, thus, ideal as a carbon precursor.

Table 2 Proximate, ultimate, and biochemical component analyses of EMB and EM-ACs

Material	Proximate analysis (w/w %)			
	Moisture	Ash	Volatile matter	Fixed carbon
EMB	6.29	2.46	64.78	26.47
EM38-AC	1.3	7.57	19.33	71.8
	Ultimate analysis (w/w %)			
	C	H	O	N
EMB	33.59	6.5	49.61	0.3
EM38-AC	77.85	4.39	15.48	1.28
	Component analysis (dry basis, wt%)			
	Cellulose	Hemicellulose	Lignin	Extractives
EMB	43.8	25.6	17.9	12.7

Table 3 Characteristics of EM38-AC

Parameter	Value
S_{BET} (m^2/g)	835
V_{MIC} (cm^3/g)	0.376
V_{MIC} (%)	77.1
V_T (cm^3/g)	0.481
V_{MES} (cm^3/g)	0.117
V_{MES} (%)	22.9
D_P (nm)	2.36
Yield (%)	26.4

The basic properties of the adsorbents

Cellulose, hemicellulose, and lignin are the three base components of biomass, affirming the lignocellulosic nature of EMB. Table 2 shows that EMB, a lignocellulosic bio-waste, is a good choice of material to be evaluated as a precursor for producing EM-ACs.

Table 3 displays the pore structure characteristics of EM38-AC, which showed higher S_{BET} than others. The EM38-AC contained high values of S_{BET}, V_{MIC}, V_{MES}, V_T, D_P, and yields were 835 m^2/g, 0.376 cm^3/g, 0.117 cm^3/g, 0.481 cm^3/g, 2.36 nm, and 26.4%. The characteristics of EM38-AC are mainly related to the physicochemical properties of the EMB activation conditions.

The N_2 adsorption/desorption isotherm and the pore size distribution of the EM38-AC are shown in Fig. 1a. Following IUPAC classification, Note that the isotherm of the EM38-AC based on grape marc showed a type IV form (Shoaib et al. 2020). A distinct hysteresis loop was observed in the entire relative pressure range (up to relative pressure of 0.40), the main characteristic of the type IV isotherm that corresponds to a well-developed micro- and mesoporous structure (Ternero-Hidalgo et al. 2016). Also, the isotherm showed an H_4-type hysteresis loop, evidencing the existence of parallel slit-shaped pores in EM38-AC.

Figure 1b presents the thermograms (TG) of EMB and EM38-AC in a N_2 flow with the ratio of 100 mL/min. The weight loss of EMB obtained from the thermogravimetric curves has similar pyrolysis behavior to other lignocellulosic biomasses, including hemicellulose, cellulose, and lignin

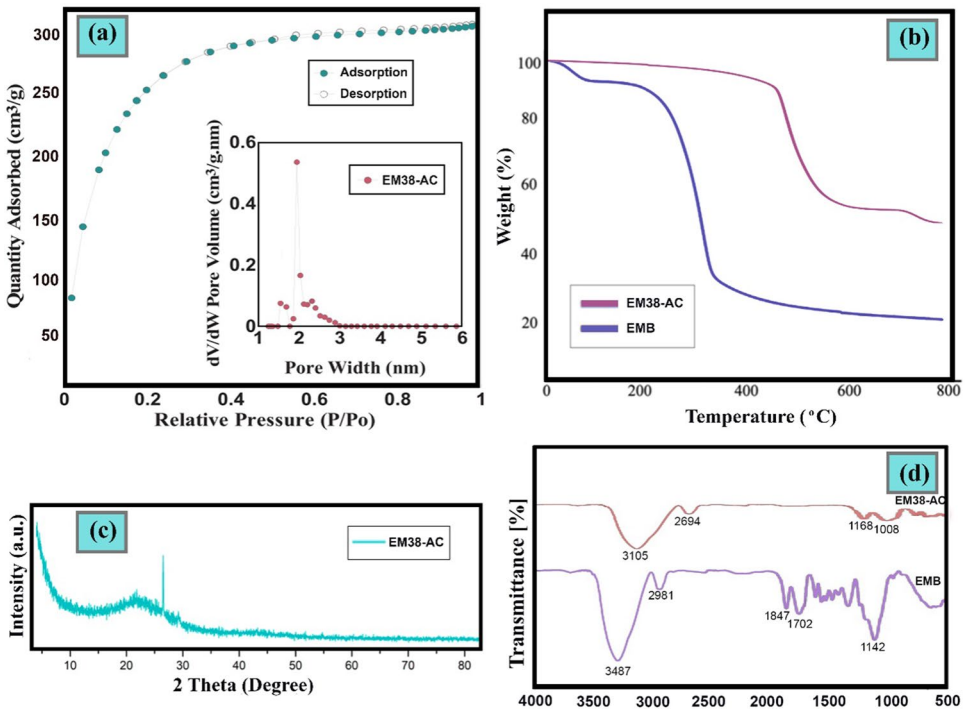


Fig. 1 Basic character, **a** N_2 adsorption–desorption analysis, **b** TGA, **c** XRD profiles, and **d** FTIR spectra of EMB and EM38-AC

(Mamani et al. 2019; Thabede et al. 2023). This thermal profile indicates three stages: dehydration, devolatilization, and solid decomposition; the first weight loss up to 135 °C corresponds to the moisture present in the material. The second weight loss, between 220 and 390 °C may be attributed to the decomposition of hemicellulose and the release of volatile matter in the EMB. The gradual weight loss until 800 °C, may be associated with stable conditions and demonstrate good thermal stability and carbon structure (Vinayagam et al. 2020). The mass degradation of EM38-AC is related to the release of moisture content between 320 and 630 °C, with the reducing volatile matter presence mainly carbon structure. The carbon content of EM38-AC is more than other elements.

Figure 1c indicates the XRD profiles of the EM38-AC, which showed the decrystallinity as in two characteristic peaks at 2θ angle 16.2° and 23.4°. The two peaks imply amorphous carbon; no effective changes happened in the basic crystalline structure. Amorphous cellulose can be hydrolyzed much easier than crystalline cellulose (Shokry et al. 2020). The EM38-AC by H_3PO_4 has lower dehydration ability and affirms the presence of porous and amorphous structure in EM38-AC is an expected feature for BTEX adsorption practices (Salomón et al. 2021).

FTIR analysis was used to determine the functional groups of EMB and EM38-AC in Fig. 1d. The band with a strong, broad vibration at 3487 and a weak peak at 3105 cm^{-1} corresponds to –OH group stretching of the hydroxyl group, which decreased in EM38-AC (Jawad et al. 2019). The other peak at 2981 cm^{-1} is ascribed to the C–H symmetric and asymmetric vibration of methoxyl groups (Chiu and Lin 2019). The two peaks centered between 1847 and 1702 cm^{-1} correspond to the C=C stretching of aromatic carbon groups. Two more weak peaks from 1008 to 1168 cm^{-1} attributed to C–O vibrations in acids, alcohols, phenols, and ethers almost vanished in EM38-AC (Rawal et al. 2018). The strong peak at 1142 cm^{-1} would be C=O bonds in phenols, ethers, esters, and acids. The band intensities at 886 and 704 cm^{-1} are assigned to the C–H out-of-plane (Gouda et al. 2023).

SEM micrograph has depicted the pore structure distribution and morphological difference under different magnifications in Fig. 2. The EM38-AC contained high S_{BET} values directly related to the EMB and H_3PO_4 activation characteristics. This indicates that the morphology of the EMB and EM38-AC shows a surface porosity development. Figure 2a shows that the surface morphology of EMB has observed smooth, tight, and hard pores available on the surface. Nonetheless, Fig. 2b shows that the character of EM38-AC is rough, with many irregular and parallel longitudinal pores and many pores with tunnel shapes and sizes. Similar morphologies have also been reported by Liu et al. (2017) and Beltrame et al. (2018). Vukčević et al. (2015) observed that the surface of raw feedstock and activated hemp fibers have the same heterogeneity appearance as observed for deeply longitudinal cracks and highly interconnected irregular wide spaces in this study.

Operation conditions and adsorbed amount

It is known that the initial concentration, temperature, humidity, and adsorbent structure greatly affect BTEX adsorption. The effects of different concentrations tested under the experimental conditions were clearly demonstrated. In this context, the process was completed with the periodic injection of 220 mg/m^3 value given to the adsorption system 20 times in Fig. 3. In the meantime, the ambient temperatures were stabilized at 20, 25, 30, and 35 °C. Adsorption started with the specified temperatures by keeping the partial humidity constant at 30% and 90%, another vital factor in the study. 112, 94, 91 and 86 mg/g for benzene at 20, 25, 30 and 35 °C + 30% RH; 126, 113, 98, and 91 mg/g for toluene; 119, 103, 92, and 87 mg/g for ethylbenzene; 84, 76, 73, and 68 mg/g for xylene. 91, 82, 74, and

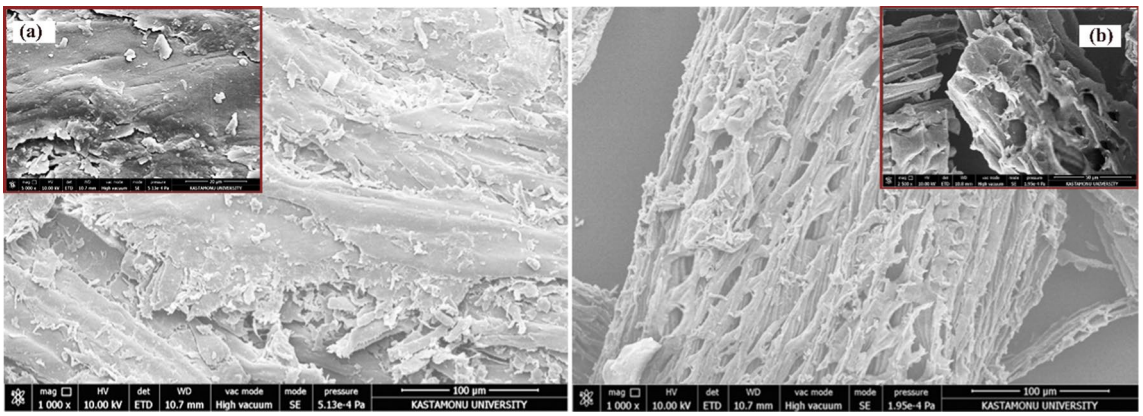


Fig. 2 SEM images of **a** EMB and **b** EM38-AC

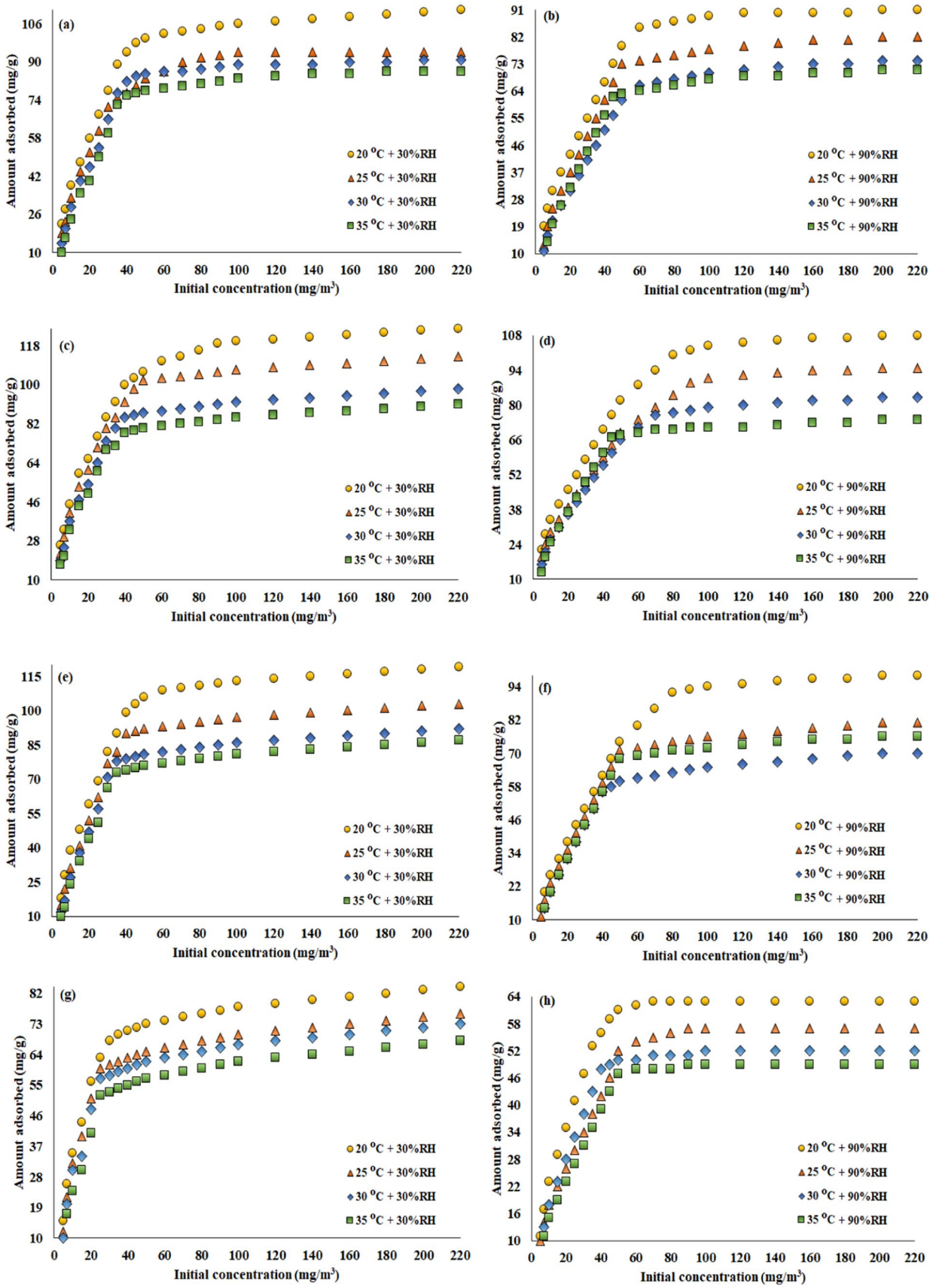
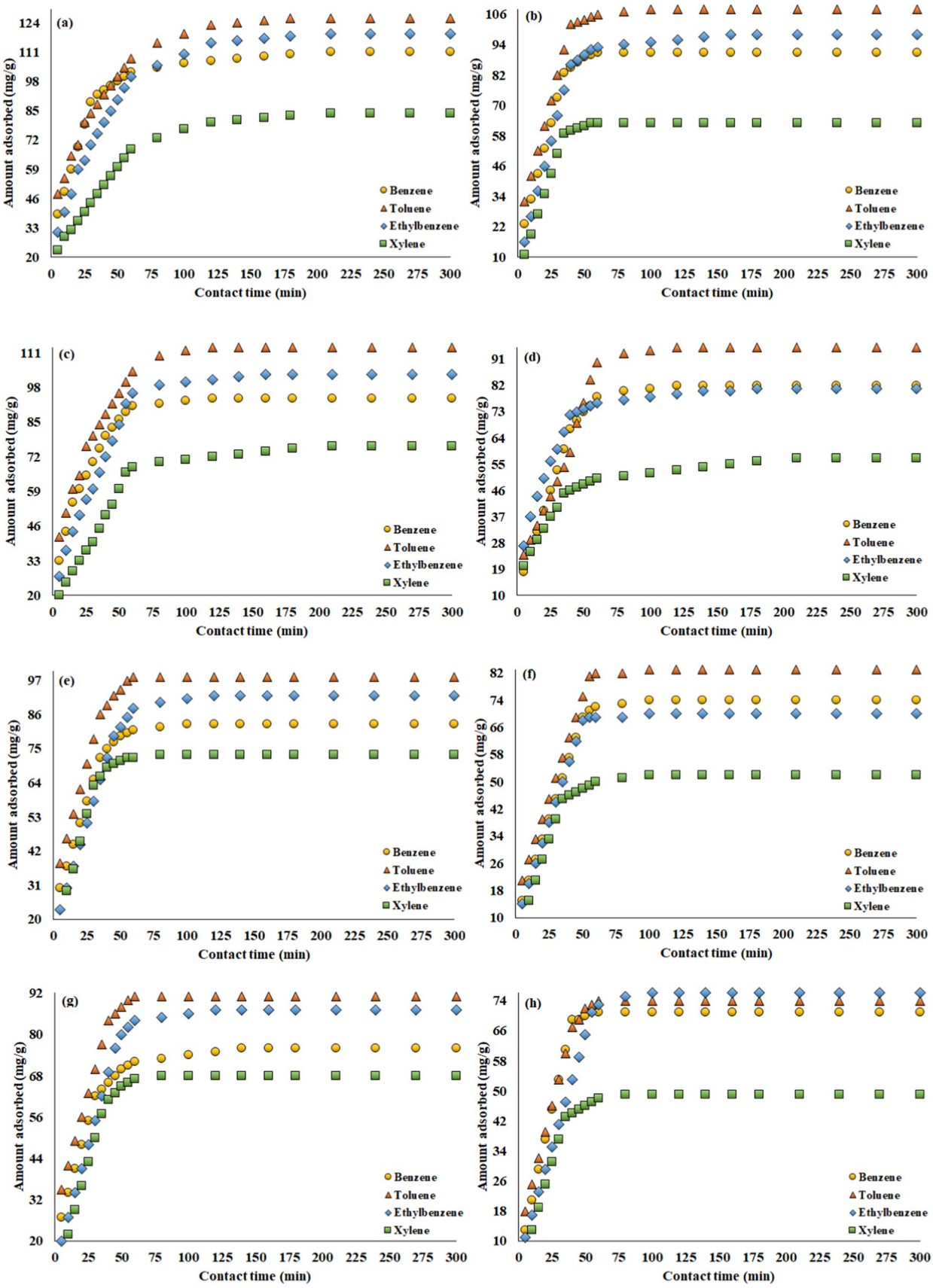


Fig. 3 Relationship between initial concentration and RH of **a**, **b**: benzene; **c**, **d**: toluene; **e**, **f**: ethylbenzene; **g**, **h**: xylene onto EM38-AC


(a)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene
(b)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene
(c)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene
(d)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene
(e)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene
(f)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene
(g)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene
(h)
Amount adsorbed (mg/g)
Contact time (min)
Benzene
Toluene
Ethylbenzene
Xylene

◂**Fig. 4** Relationship between contact time and adsorbate of **a**: 20 °C + 30% RH, **b**: 20 °C + 90% RH, **c**: 25 °C + 30% RH, **d**: 25 °C + 90% RH, **e**: 30 °C + 30% RH, **f**: 30 °C + 90% RH, **g**: 35 °C + 30% RH, and **h**: 35 °C + 90% RH onto EM38-AC

71 mg/g for benzene at 90% RH at the same temperatures; 108, 95, 83, and 74 mg/g for toluene; 98, 81 70, and 66 mg/g for ethylbenzene; 63, 57, 52, and 49 mg/g were found for xylene. As the temperature increased, adsorbing compounds that evaporated more efficiently, such as xylene and benzene, became difficult. Toluene and ethylbenzene had more adhesion than the others. The moisture content of the environment causes a decrease in the adsorptive capacity, and the pores are filled with moisture. BTEX adhesion is observed if the humidity decreases from 90 to 30% and the temperature drops from 35 to 20 °C.

As indicated in the other chart, the time until the EM38-AC stabilized as a result of the loaded BTEX concentration was found to be 300 min in Fig. 4. Adsorption initiation and adsorption saturation points are given. In this context, the efficiency of 0.2 g EM38-AC used in the first 25 min, at 20 °C + 30% RH; 69.23, 66.67, 57.14 and 68.25% were found for benzene, toluene, ethylbenzene, and xylene and, on the contrary, at 20 °C + 90% RH; 61.18, 63.49, 52.94, and 47.62%, respectively. The increase in moisture content caused a decrease in the average adsorption capacity by 28.5–35.4%. The equilibrium state varied depending on the structure of BTEX molecules and environmental conditions. It has been found that incredibly easily volatile substances are more difficult to adhere to than others. The higher the evaporation rate, the lower the reaction rate and the lower the amount of capture. The ease experienced by the substances evaporating at the same temperature when passing to the gas phase negatively correlates with the ease of adhesion to the adsorbent.

Benzene, toluene, ethylbenzene, and xylene are toxic pollutants that can significantly deteriorate indoor air quality due to their carcinogenic effect (Słomińska et al. 2013; Yaghmaien et al. 2019). The BTEX are widely used in environmental applications as sustainability assessment tools, but they cause many problems in treating waste gases (Hosseinzadeh et al. 2018; Moridzadeh et al. 2020; Aghbashlo et al. 2022). It is used in the production of main floor covering (Marć et al. 2017), residential homes (Kozielska et al. 2020), heaters (Alsbou and Omari 2020), printers (Rostami et al. 2021), paints (Zhao et al. 2016), PVC (Chao et al. 2016), wood varnishes (Bari et al. 2015) and many other materials in the indoor environment (Cheng et al. 2020b; Yu et al. 2022). Removal of BTEX, which is so common and can be easily dissolved in indoor air conditions, and released into the environment, is of vital importance. In studies conducted for this purpose, various carbon-based materials as adsorbents in the adsorption process, which are used effectively, are considered successful in the removal of BTEXs due to their high efficiency and stability. However, when compared with the efficiency of using conventional carbon materials, the efficiency after activating lignin-containing activated carbons with chemical agents seems reasonable. The development using green activated carbons and modifications of new carbon materials after activation with acid or base has been tried in BTEX removal (Ferdowsi et al. 2022; Liang et al. 2023). Therefore, the characteristics of green materials should be identified during the production process, and optimum operation conditions should be determined carefully and tested for adsorption application (Konggidinata et al. 2017; de Oliveira Frós et al. 2019). According to the results of this research, adsorbents used to adsorb BTEX emissions in many industrial processes, domestic use, vehicle interiors, air conditioners, and coolers have emerged widely today. In addition, the developed carbon materials present studies showing that they are used in single or multiple BTEX removal indoors.

A large extent of the research on more advanced approaches for the BTEX adsorption method based on agroforestry wastes continues. In this regard, it is understood from the literature that researches continue at full speed due to advantages such as process economy, cost, energy minimization, and convenience (Zou et al. 2019; Bahrami et al. 2021; Ahmadi and Kim 2023). Some development in adsorption materials has been investigated on VOC adsorption, and they summarized and discussed their potential to recover VOCs in recent years. For example, Kraus et al. (2018) performed competitive toluene and water vapor adsorption with 22 different granular zeolites in a packed-bed reactor. The initial toluene concentration was saturated with 216 ppmv at 22 °C, and experimental results represented the hydrophobicity of water and toluene molecules adsorbed at different sites. Toluene molecules on zeolite HiSiv1000 were not affected by water molecules under the present competing terms. Similarly, Blommaerts et al. (2018) used three commercial zeolites and two silica gels to determine selected VOCs' adsorption capacity, including acetone, methanol, isohexane, isopentane, and toluene. The adsorption capacity of zeolites was found to be ZEOflair® 300 > ZEOflair® 110 > ZEOflair® 100 due to their S_{BET} values displaying similar ranks and the same trend. Although silica gels had higher adsorption capacity for the more minor compounds than ZEOflair® zeolites due to they have higher S_{BET} values. Besides, some researchers found that activated carbon for VOCs abatements and adsorption behaviors of performance have been analyzed and compared with other adsorbents (Ushiki et al. 2018; Zhao et al. 2018). For a specific adsorbent, Ghafari and Atkinson (2018) tested 5 ± 0.5 mg of XAD2 and XAD4 on toluene, hexane, and MEK adsorption. The XAD2 and XAD4 modified their characterization to

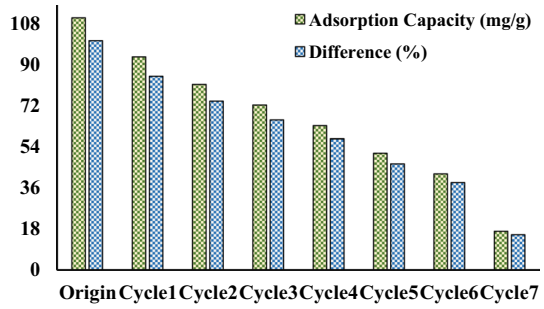


Fig. 5 Reusability of EM38-AC for multi-component BTEX removal

improve VOC capturing ability. XAD4-DCE has higher S_{BET} than others, and the most significant capacity gains found a linear correlation between surface area and pore volume. Ouzzine et al. (2019) considered describing the multi-component VOCs adsorption onto the SACs in a fixed-bed reactor system. The inlet gas rate of the VOC gaseous mixture was set as 100 mL/min, including acetaldehyde, formaldehyde, 2-propenal, 1,3-butadiene, and benzene.

Regeneration

The used adsorbents as hazardous waste can occur as environmental pollutants, so precautions must be taken with economical disposal methods. In this study, the used EM38-AC was regenerated after the BTEX adsorption for the sustainability approach. Figure 5 shows that the adsorption efficiency of the regenerated EM38-AC decreased adsorption performance after 7 cycles with a significant change in the percentage removal of multi-component BTEX. On an economic perspective, due to the pore structure of EM38-AC, they have demonstrated that they obtained disruptions at 84.55% and released BTEX molecules from cavities with reusability.

The benzene adsorption efficiencies were calculated higher than other compounds due to the prominent factors of polarity, boiling point, and molecular size. Numerous research studies in VOCs adsorption mechanisms the carbonaceous material has already been significantly used in non-polar and weakly polar volatile compounds. Xiang et al. (2020) produced biochar from Hickory wood as biomass feedstock for VOCs adsorption, such as acetone, ethanol, chloroform, cyclohexane, and toluene. Among the produced biochars, HWBM600 has increased the largest S_{BET} at 304.84 m^2/g and highest aromaticity, although it had the lowest polarity. The maximum adsorption capacities of HWBM600 for acetone, chloroform, and cyclohexane were 103.4, 87.0, and 72.5 mg/g, respectively. For further insights into the gaseous VOCs adsorption behavior have been previously reported by Dai et al. (2021) and Xiang et al. (2022). BTEX has commonly been detected in indoor air and was desired to remove experimental adsorption with newly carbon-based sorbents as an air purifier filter. As discussed above, in comparison to the adsorption capacity of each compound, dipole moment and boiling point have significant correlations with carbon-derived adsorbents. Therefore adsorbates with higher boiling points are more easily adsorbed due to the superior intermolecular forces. Actually, in this study, results show a similar tendency between VOCs adsorption behaviors and the specific structure of EM38-AC.

Conclusion

The activated carbon materials are prepared from *E. montanum* biomass waste feedstock through H_3PO_4 activation, which has a high surface area and plays an effective and successful role in the removal of multiple BTEX gases. Multi-component BTEX has been treated with EM38-AC under different temperatures and relative humidity. BTEX adsorption on EM38-AC, temperature, and humidity factor in the multiple adsorptions of organic compounds on the surface was investigated. The surface area and porosity of the EM38-AC with different codes due to the differences in the production stage were compared with the BTEX adsorption efficiency. The reactor flow type fixed bed adsorption system used in BTEX adsorption allowed interval sampling. The amount of benzene, toluene, ethylbenzene, and xylene adsorbed on the acid-treated activated carbon is greater than the specified activated carbon. The adsorption performance of EM38-AC and the increase in the amount of BTEX retained on the surface is the influential role of the micropore volumes formed due to the H_3PO_4 activation treatment.

Data availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Conflict of interest There are no competing interests to be declared by the authors.

Ethical approval Not applicable.

References

Aghbashlo M, Hosseinzadeh-Bandbafha H, Shahbeik H, Tabatabaei M (2022) The role of sustainability assessment tools in realizing bioenergy and bioproduct systems. Biofuel Res J 9(3):1697–1706. https://doi.org/10.18331/BRJ2022.9.3.5

Ahmadi Y, Kim KH (2023) Recent progress in the development of hyper-cross-linked polymers for adsorption of gaseous volatile organic compounds. Polym Rev 63(2):365–393. https://doi.org/10.1080/15583724.2022.2082470

Alsbou EM, Omari KW (2020) BTEX indoor air characteristic values in rural areas of Jordan: heaters and health risk assessment consequences in winter season. Environ Pollut 267:115464. https://doi.org/10.1016/j.envpol.2020.115464

Alvim DS, Gatti LV, Corrêa SM, Chiquetto JB, Santos GM, de Souza RC, Pretto A, Rozante JR, Figueroa SN, Pendharkar J, Nobre P (2018) Determining VOCs reactivity for ozone forming potential in the megacity of são paulo. Aerosol Air Qual Res 18:2460–2474. https://doi.org/10.4209/aaqr.2017.10.0361

American Society for Testing and Materials (ASTM) (2013a) E871–82 Standard test method for moisture analysis of particulate wood fuels

American Society for Testing and Materials (ASTM) (2013b) E872–82 Standard test method for volatile matter in the analysis of particulate wood fuels

American Society for Testing and Materials (ASTM) (2015) E1755–01 Standard test method for ash in biomass

American Society for Testing and Materials (ASTM) (2016) E1690–08 Standard test method for determination of ethanol extractives in biomass

Amnuaylojaroen T, Macatangay RC, Khodmanee S (2019) Modeling the effect of VOCs from biomass burning emissions on ozone pollution in upper Southeast Asia. Heliyon 5(10):e02661. https://doi.org/10.1016/j.heliyon.2019.e02661

Bahrami M, Pirmohammadi Z, Bahrami A (2021) A review of new adsorbents for separation of BTEX biomarkers. Biomed Chromatogr 35(9):e5131. https://doi.org/10.1002/bmc.5131

Bang J, You DW, Jang Y, Oh JS, Jung KW (2019) A carbon nanotube sponge as an adsorbent for vapor preconcentration of aromatic volatile organic compounds. J Chromatogr A 1605:460363. https://doi.org/10.1016/j.chroma.2019.460363

Bari MA, Kindzierski WB, Wheeler AJ, Héroux MÈ, Wallace LA (2015) Source apportionment of indoor and outdoor volatile organic compounds at homes in Edmonton, Canada. Build Environ 90:114–124. https://doi.org/10.1016/j.buildenv.2015.03.023

Bedane AH, Guo TX, Eić M, Xiao H (2019) Adsorption of volatile organic compounds on peanut shell activated carbon. Can J Chem Eng 97(1):238–246. https://doi.org/10.1002/cjce.23330

Beltrame KK, Cazetta AL, de Souza PS, Spessato L, Silva TL, Almeida VC (2018) Adsorption of caffeine on mesoporous activated carbon fibers prepared from pineapple plant leaves. Ecotoxicol Environ Saf 147:64–71. https://doi.org/10.1016/j.ecoenv.2017.08.034

Berezina E, Moiseenko K, Skorokhod A, Pankratova NV, Belikov I, Belousov V, Elansky NF (2020) Impact of VOCs and NOx on ozone formation in Moscow. Atmosphere 11(11):1262. https://doi.org/10.3390/atmos11111262

Blommaerts N, Dingenen F, Middelkoop V, Savelkouls J, Goemans M, Tytgat T, Verbruggen SW, Lenaerts S (2018) Ultrafast screening of commercial sorbent materials for VOC adsorption using real-time FTIR spectroscopy. Sep Purif Technol 207:284–290. https://doi.org/10.1016/j.seppur.2018.06.062

Chao KP, Wang P, Wang BH (2016) Determining the permeability of organic solvents through PVC pipes using a direct SPME model. Polym Test 56:110–114. https://doi.org/10.1016/j.polymertesting.2016.09.028

Cheng YH, Lin CC, Lee YT, Lin YC (2020a) The evaluation of BTEX and carbonyls emissions from recycled building materials. Environ Monit Assess 192:1–12. https://doi.org/10.1007/s10661-020-08248-8

Cheng Z, Feng KE, Su Y, Ye J, Chen D, Zhang S, Zhang X, Dionysiou DD (2020) Novel biosorbents synthesized from fungal and bacterial biomass and their applications in the adsorption of volatile organic compounds. Bioresour technol 300:122705. https://doi.org/10.1016/j.biortech.2019.122705

Chiu YH, Lin LY (2019) Effect of activating agents for producing activated carbon using a facile one-step synthesis with waste coffee grounds for symmetric supercapacitors. J Taiwan Inst Chem Eng 101:177–185. https://doi.org/10.1016/j.jtice.2019.04.050

Dai Z, Li D, Ao Z, Wang S, An T (2021) Theoretical exploration of VOCs removal mechanism by carbon nanotubes through persulfate-based advanced oxidation processes: Adsorption and catalytic oxidation. J Hazard Mater 405:124684. https://doi.org/10.1016/j.jhazmat.2020.124684

de Oliveira Frós AC, de Oliveira MA, Soares AAM, Hallwass F, Chojnacki J, Barros BS, Júnior SA, Kulesza J (2019) Selective adsorption of BTEX on calixarene-based molecular coordination network determined by 13C NMR spectroscopy. Inorg Chim Acta 492:161–166. https://doi.org/10.1016/j.ica.2019.04.031

El-Hashemy MA, Ali HM (2018) Characterization of BTEX group of VOCs and inhalation risks in indoor microenvironments at small enterprises. Sci Total Environ 645:974–983. https://doi.org/10.1016/j.scitotenv.2018.07.157

Ferdowsi M, Khabiri B, Buelna G, Jones JP, Heitz M (2022) Air biofilters for a mixture of organic gaseous pollutants: an approach for industrial applications. Crit Rev Biotechnol. https://doi.org/10.1080/07388551.2022.2100735

Ghafari M, Atkinson JD (2018) Impact of styrenic polymer one-step hyper-cross-linking on volatile organic compound adsorption and desorption performance. J Hazard Mater 351:117–123. https://doi.org/10.1016/j.jhazmat.2018.02.051

Ghobakhloo S, Khoshakhlagh AH, Morais S, Mazaheri Tehrani A (2023) Exposure to volatile organic compounds in paint production plants: levels and potential human health risks. Toxics 11(2):111. https://doi.org/10.3390/toxics11020111

Gómez MC, Durana N, García JA, de Blas M, de Cámara ES, García-Ruiz E, Gangoiti G, Torre-Pascual E, Iza J (2020) Long-term measurement of biogenic volatile organic compounds in a rural background area: contribution to ozone formation. Atmos Environ 224:117315. https://doi.org/10.1016/j.atmosenv.2020.117315

Gospodarek M, Rybarczyk P, Szulczyński B, Gębicki J (2019) Comparative evaluation of selected biological methods for the removal of hydrophilic and hydrophobic odorous VOCs from air. Processes 7(4):187. https://doi.org/10.3390/pr7040187

Gouda MS, Shehab M, Helmy S, Soliman M, Salama RS (2023) Nickel and cobalt oxides supported on activated carbon derived from willow catkin for efficient supercapacitor electrode. J Energy Storage 61:106806. https://doi.org/10.1016/j.est.2023.106806

Guo Y, Wen M, Li G, An T (2021) Recent advances in VOC elimination by catalytic oxidation technology onto various nanoparticles catalysts: a critical review. Appl Catal B Environ 281:119447. https://doi.org/10.1016/j.apcatb.2020.119447

Hosseinzadeh A, Najafpoor AA, Jafari AJ, Jazani RK, Baziar M, Bargozin H, Piranloo FG (2018) Application of response surface methodology and artificial neural network modeling to assess non-thermal plasma efficiency in simultaneous removal of BTEX from waste gases: effect of operating parameters and prediction performance. Process Saf Environ Prot 119:261–270. https://doi.org/10.1016/j.psep.2018.08.010

Hsu SH, Huang CS, Chung TW, Gao S (2014) Adsorption of chlorinated volatile organic compounds using activated carbon made from Jatropha curcas seeds. J Taiwan Inst Chem Eng 45(5):2526–2530. https://doi.org/10.1016/j.jtice.2014.05.028

Hu L, Peng Y, Wu F, Peng S, Li J, Liu Z (2017) Tubular activated carbons made from cotton stalk for dynamic adsorption of airborne toluene. J Taiwan Inst Chem Eng 80:399–405. https://doi.org/10.1016/j.jtice.2017.07.029

Hunter-Sellars E, Tee JJ, Parkin IP, Williams DR (2020) Adsorption of volatile organic compounds by industrial porous materials:

impact of relative humidity. Microporous Mesoporous Mater 298:110090. https://doi.org/10.1016/j.micromeso.2020.110090
Isinkaralar K (2023) Experimental evaluation of benzene adsorption in the gas phase using activated carbon from waste biomass. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-023-03979-3
Isinkaralar K (2023b) A Study on the gaseous benzene removal based on adsorption onto the cost-effective and environmentally friendly adsorbent. Molecules 28(8):3453. https://doi.org/10.3390/molecules28083453
Isinkaralar K (2023) Comparison of the gaseous benzene adsorption capacity by activated carbons from *Fraxinus excelsior* L. as a lignocellulosic residual. Chem Papers. https://doi.org/10.1007/s11696-023-02925-x
Isinkaralar K, Meruyert K (2023) Adsorption behavior of multi-component BTEX on the synthesized green adsorbents derived from *Abelmoschus esculentus* L waste residue. Appl Biochem Biotechnol. https://doi.org/10.1007/s12010-023-04556-0
Isinkaralar K, Turkyilmaz A, Lakestani S (2023) Equilibrium study of benzene, toluene, ethylbenzene, and xylene (BTEX) from gas streams by black pine cones-derived activated carbon. Environ Technol Innov. https://doi.org/10.1016/j.eti.2023.103209
Isinkaralar O (2023) Bioclimatic comfort in urban planning and modeling spatial change during 2020–2100 according to climate change scenarios in Kocaeli, Türkiye. Int J Environ Sci Technol. https://doi.org/10.1007/s13762-023-04992-9
Jaars K, Vestenius M, van Zyl PG, Beukes JP, Hellen H, Vakkari V, Venter M, Josipovic M, Hakola H (2018) Receptor modelling and risk assessment of volatile organic compounds measured at a regional background site in South Africa. Atmos Environ 172:133–148. https://doi.org/10.1016/j.atmosenv.2017.10.047
Jawad AH, Ismail K, Ishak MAM, Wilson LD (2019) Conversion of Malaysian low-rank coal to mesoporous activated carbon: structure characterization and adsorption properties. Chin J Chem Eng 27(7):1716–1727. https://doi.org/10.1016/j.cjche.2018.12.006
Konggidinata MI, Chao B, Lian Q, Subramaniam R, Zappi M, Gang DD (2017) Equilibrium, kinetic and thermodynamic studies for adsorption of BTEX onto ordered mesoporous carbon (OMC). J Hazard Mater 336:249–259. https://doi.org/10.1016/j.jhazmat.2017.04.073
Kozielska B, Bragoszewska E, Kaleta D (2020) Investigation of indoor air quality in offices and residential homes in an urban area of Poland. Air Qual Atmos Health 13:131–141. https://doi.org/10.1007/s11869-019-00777-7
Kraus M, Trommler U, Holzer F, Kopinke FD, Roland U (2018) Competing adsorption of toluene and water on various zeolites. Chem Eng J 351:356–363. https://doi.org/10.1016/j.cej.2018.06.128
Laskar II, Hashisho Z (2020) Insights into modeling adsorption equilibria of single and multi-component systems of organic and water vapors. Sep Purif Technol 241:116681. https://doi.org/10.1016/j.seppur.2020.116681
Lei B, Liu B, Zhang H, Yan L, Xie H, Zhou G (2020) CuO-modified activated carbon for the improvement of toluene removal in air. J Environ Sci 88:122–132. https://doi.org/10.1016/j.jes.2019.07.001
Le-Minh N, Sivret EC, Shammay A, Stuetz RM (2018) Factors affecting the adsorption of gaseous environmental odors by activated carbon: a critical review. Crit Rev Environ Sci Technol 48(4):341–375. https://doi.org/10.1080/10643389.2018.1460984
Lhuissier M, Couvert A, Amrane A, Kane A, Audic JL (2018) Characterization and selection of waste oils for the absorption and biodegradation of VOC of different hydrophobicities. Chem Eng Res Des 138:482–489. https://doi.org/10.1016/j.cherd.2018.08.028
Li H, Chen J, Zhang W, Zhan H, He C, Yang Z, Peng H, Leng L (2023) Machine-learning-aided thermochemical treatment of biomass: a review. Biofuel Res J 10(1):1786–1809. https://doi.org/10.18331/BRJ2023.10.1.4
Li S, Song K, Zhao D, Rugarabamu JR, Diao R, Gu Y (2020) Molecular simulation of benzene adsorption on different activated carbon under different temperatures. Microporous Mesoporous Mater 302:110220. https://doi.org/10.1016/j.micromeso.2020.110220
Liang C, Li C, Zhu Y, Du X, Yao C, Ma Y, Zhao J (2023) Recent advances of photocatalytic degradation for BTEX: materials, operation, and mechanism. Chem Eng J 455:140461. https://doi.org/10.1016/j.cej.2022.140461
Liu S, Ge L, Gao S, Zhuang L, Zhu Z, Wang H (2017) Activated carbon derived from bio-waste hemp hurd and retted hemp hurd for CO2 adsorption. Compos Commun 5:27–30. https://doi.org/10.1016/j.coco.2017.06.002
Mahari WAW, Waiho K, Azwar E, Fazhan H, Peng W, Ishak SD, Tabatabaei M, Yek PNY, Almomani F, Aghbashlo M, Lam SS (2022) A state-of-the-art review on producing engineered biochar from shellfish waste and its application in aquaculture wastewater treatment. Chemosphere 288:132559. https://doi.org/10.1016/j.chemosphere.2021.132559
Mamani A, Sardella MF, Gimenez M, Deiana C (2019) Highly microporous carbons from olive tree pruning: optimization of chemical activation conditions. J Environ Chem Eng 7(1):102830. https://doi.org/10.1016/j.jece.2018.102830
Marć M, Namieśnik J, Zabiegała B (2017) The miniaturised emission chamber system and home-made passive flux sampler studies of monoaromatic hydrocarbons emissions from selected commercially-available floor coverings. Build Environ 123:1–13. https://doi.org/10.1016/j.buildenv.2017.06.035
Mehta D, Hazarika N, Srivastava A (2020) Diurnal variation of BTEX at road traffic intersection points in Delhi, India: source, ozone formation potential, and health risk assessment. Environ Sci Pollut Res 27:11093–11104. https://doi.org/10.1007/s11356-019-07495-8
Mikkonen A, Li T, Vesala M, Saarenheimo J, Ahonen V, Kärenlampi S, Blande JD, Tiirola M, Tervahauta A (2018) Biofiltration of airborne VOC s with green wall systems—Microbial and chemical dynamics. Indoor Air 28(5):697–707. https://doi.org/10.1111/ina.12473
Mo Z, Lu S, Shao M (2021) Volatile organic compound (VOC) emissions and health risk assessment in paint and coatings industry in the Yangtze River Delta. China Environ Pollut 269:115740. https://doi.org/10.1016/j.envpol.2020.115740
Moridzadeh M, Dehghani S, Rafiee A, Hassanvand MS, Dehghani M, Hoseini M (2020) Assessing BTEX exposure among workers of the second largest natural gas reserve in the world: a biomonitoring approach. Environ Sci Pollut Res 27:44519–44527. https://doi.org/10.1007/s11356-020-10379-x
Ouzzine M, Romero-Anaya AJ, Lillo-Rodenas MA, Linares-Solano A (2019) Spherical activated carbons for the adsorption of a real multi-component VOC mixture. Carbon 148:214–223. https://doi.org/10.1016/j.carbon.2019.03.075
Paciência I, Madureira J, Rufo J, Moreira A, Fernandes EDO (2016) A systematic review of evidence and implications of spatial and seasonal variations of volatile organic compounds (VOC) in indoor human environments. J Toxicol Environ Health, Part B 19(2):47–64. https://doi.org/10.1080/10937404.2015.1134371
Pallarés J, González-Cencerrado A, Arauzo I (2018) Production and characterization of activated carbon from barley straw by physical activation with carbon dioxide and steam. Biomass Bioenerg 115:64–73. https://doi.org/10.1016/j.biombioe.2018.04.015
Pan KL, Pan GT, Chong S, Chang MB (2018) Removal of VOCs from gas streams with double perovskite-type catalysts. J Environ Sci 69:205–216. https://doi.org/10.1016/j.jes.2017.10.012

Pan Q, Liu QY, Zheng J, Li YH, Xiang S, Sun XJ, He XS (2023) Volatile and semi-volatile organic compounds in landfill gas: composition characteristics and health risks. Environ Int. https://doi.org/10.1016/j.envint.2023.107886

Pearson JK (2019) European solvent VOC emission inventories based on industry-wide information. Atmos Environ 204:118–124. https://doi.org/10.1016/j.atmosenv.2019.02.014

Pinthong N, Thepanondh S, Kondo A (2022) Source identification of VOCs and their environmental health risk in a petrochemical industrial area. Aerosol Air Qual Res 22(2):210064. https://doi.org/10.4209/aaqr.210064

Pu G, Li X, Yuan F (2021) Numerical study on heat transfer efficiency of regenerative thermal oxidizers with three canisters. Processes 9(9):1621. https://doi.org/10.3390/pr9091621

Qian Q, Gong C, Zhang Z, Yuan G (2015) Removal of VOCs by activated carbon microspheres derived from polymer: a comparative study. Adsorption 21:333–341. https://doi.org/10.1007/s10450-015-9673-9

Rawal S, Joshi B, Kumar Y (2018) Synthesis and characterization of activated carbon from the biomass of Saccharum bengalense for electrochemical supercapacitors. J Energy Storage 20:418–426. https://doi.org/10.1016/j.est.2018.10.009

Rodríguez-Félix F, Corte-Tarazón JA, Rochín-Wong S, Fernández-Quiroz JD, Garzón-García AM, Santos-Sauceda I, Plascencia-Martínez DF, Chan-Chan LH, Vásquez-López C, Barreras-Urbina CG, Olguin-Moreno A, Tapia-Hernández JA (2022) Physicochemical, structural, mechanical and antioxidant properties of zein films incorporated with no-ultrafiltered and ultrafiltered betalains extract from the beetroot (*Beta vulgaris*) bagasse with potential application as active food packaging. J Food Eng 334:111153. https://doi.org/10.1016/j.jfoodeng.2022.111153

Rodríguez-Félix F, Graciano-Verdugo AZ, Moreno-Vásquez MJ, Lagarda-Díaz I, Barreras-Urbina CG, Armenta-Villegas L, Olguín-Moreno A, Tapia-Hernández JA (2022b) Trends in sustainable green synthesis of silver nanoparticles using agri-food waste extracts and their applications in health. J Nanomater 2022:1–37. https://doi.org/10.1155/2022/8874003

Rodríguez-Félix F, López-Cota AG, Moreno-Vásquez MJ, Graciano-Verdugo AZ, Quintero-Reyes IE, Del-Toro-Sánchez CL, Tapia-Hernández JA (2021) Sustainable-green synthesis of silver nanoparticles using safflower (*Carthamus tinctorius* L.) waste extract and its antibacterial activity. Heliyon 7(4):e06923. https://doi.org/10.1016/j.heliyon.2021.e06923

Rostami R, Fazlzadeh M, Babaei-Pouya A, Abazari M, Rastgho L, Ghasemi R, Saranjam B (2021) Exposure to BTEX concentration and the related health risk assessment in printing and copying centers. Environ Sci Pollut Res 28:31195–31206. https://doi.org/10.1007/s11356-021-12873-2

Roveda L, Polvara E, Invernizzi M, Capelli L, Sironi S (2020) Definition of an emission factor for VOC emitted from Italian and European refineries. Atmosphere 11(6):564. https://doi.org/10.3390/atmos11060564

Salomón YLDO, Georgin J, Franco DS, Netto MS, Piccilli DG, Foletto EL, Oliveira LFS, Dotto GL (2021) High-performance removal of 2, 4-dichlorophenoxyacetic acid herbicide in water using activated carbon derived from Queen palm fruit endocarp (*Syagrus romanzoffiana*). J Environ Chem Eng 9(1):104911. https://doi.org/10.1016/j.jece.2020.104911

Shi D, Yek PNY, Ge S, Shi Y, Liew RK, Peng W, Sonne C, Tabatabaei M, Aghbashlo M, Lam SS (2022) Production of highly porous biochar via microwave physiochemical activation for dechlorination in water treatment. Chemosphere 309:136624. https://doi.org/10.1016/j.chemosphere.2022.136624

Shoaib AG, El-Sikaily A, El Nemr A, Mohamed AEDA, Hassan AA (2020) Testing the carbonization condition for high surface area preparation of activated carbon following type IV green alga *Ulva lactuca*. Biomass Convers Biorefin 12:3303–3318. https://doi.org/10.1007/s13399-020-00823-w

Shokry H, Elkady M, Salama E (2020) Eco-friendly magnetic activated carbon nano-hybrid for facile oil spills separation. Sci Rep 10(1):10265. https://doi.org/10.1038/s41598-020-67231-y

Słomińska M, Król S, Namieśnik J (2013) Removal of BTEX compounds from waste gases; destruction and recovery techniques. Crit Rev Environ Sci Technol 43(14):1417–1445. https://doi.org/10.1080/10643389.2011.647760

Song C, Liu Y, Sun L, Zhang Q, Mao H (2020) Emissions of volatile organic compounds (VOCs) from gasoline-and liquified natural gas (LNG)-fueled vehicles in tunnel studies. Atmos Environ 234:117626. https://doi.org/10.1016/j.atmosenv.2020.117626

Song M, Zhang W, Chen Y, Luo J, Crittenden JC (2017) The preparation and performance of lignin-based activated carbon fiber adsorbents for treating gaseous streams. Front Chem Sci Eng 11:328–337. https://doi.org/10.1007/s11705-017-1646-y

Tang M, Huang X, Peng Y, Lu S (2020) Hierarchical porous carbon as a highly efficient adsorbent for toluene and benzene. Fuel 270:117478. https://doi.org/10.1016/j.fuel.2020.117478

Tapia-Hernández JA, Del-Toro-Sánchez CL, Cinco-Moroyoqui FJ, Juárez-Onofre JE, Ruiz-Cruz S, Carvajal-Millan E, López-Ahumada GA, Castro-Enriquez DD, Barreras-Urbina CG, Rodríguez-Felix F (2019) Prolamins from cereal by-products: classification, extraction, characterization and its applications in micro-and nanofabrication. Trends Food Sci Technol 90:111–132. https://doi.org/10.1016/j.tifs.2019.06.005

Tavan Y, Azizpour H, Bahmanyar H (2021) Mathematical modeling of volatile organic compounds removal over activated carbon. J Environ Chem Eng 9(1):104777. https://doi.org/10.1016/j.jece.2020.104777

Tehrani NHMH, Alivand MS, Rashidi A, Shamskar KR, Samipoorgiri M, Esrafili MD, Maklavany DM, Shafiei-Alavijeh M (2020) Preparation and characterization of a new waste-derived mesoporous carbon structure for ultrahigh adsorption of benzene and toluene at ambient conditions. J hazard mater 384:121317. https://doi.org/10.1016/j.jhazmat.2019.121317

Ternero-Hidalgo JJ, Rosas JM, Palomo J, Valero-Romero MJ, Rodríguez-Mirasol J, Cordero T (2016) Functionalization of activated carbons by HNO3 treatment: influence of phosphorus surface groups. Carbon 101:409–419. https://doi.org/10.1016/j.carbon.2016.02.015

Thabede PM, Mtunzi F, Nyamukamba P (2023) Sorption behaviour of ibuprofen using activated carbon derived from rose geranium (*Pelargonium graveolens* L.) leaves. Appl Sci 13(8):5133. https://doi.org/10.3390/app13085133

Tomatis M, Moreira MT, Xu H, Deng W, He J, Parvez AM (2019) Removal of VOCs from waste gases using various thermal oxidizers: a comparative study based on life cycle assessment and cost analysis in China. J Clean Prod 233:808–818. https://doi.org/10.1016/j.jclepro.2019.06.131

U.S. Environmental Protection Agency (2012a) Integrated risk information system database for risk assessment. Washington, DC: U.S. EPA

Determination of volatile organic compounds in ambient air using active sampling onto sorbent tubes, compendium of methods for the determination of toxic organic compounds in ambient air, Second Edition Compendium Method TO-17. U.S. Environmental Protection Agency U.S. EPA

Ushiki I, Kikuchi K, Sato Y, Ito Y, Takishima S, Inomata H (2018) Adsorption equilibria of VOCs (n-octane, propylene glycol monomethyl ether, ethanol, and 2-propanol) on activated carbon under supercritical carbon dioxide conditions. Fluid Phase Equilib 462:59–64. https://doi.org/10.1016/j.fluid.2018.01.027

Vinayagam M, Babu RS, Sivasamy A, de Barros ALF (2020) Biomass-derived porous activated carbon from *Syzygium cumini*

fruit shells and *Chrysopogon zizanioides* roots for high-energy density symmetric supercapacitors. Biomass Bioenerg. https://doi.org/10.1016/j.biombioe.2020.105838

Vukčević MM, Kalijadis AM, Vasiljević TM, Babić BM, Laušević ZV, Laušević MD (2015) Production of activated carbon derived from waste hemp (Cannabis sativa) fibers and its performance in pesticide adsorption. Microporous Mesoporous Mater 214:156–165. https://doi.org/10.1016/j.micromeso.2015.05.012

Wang H, Xie H, Cao Q, Li X, Liu B, Gan Z, Zhang H, Gao X, Zhou G (2022) Hierarchical porous activated carbon from waste *Zanthoxylum bungeanum* branches by modified H3PO4 activation for toluene removal in air. Environ Sci Pollut Res 29(23):35443–35458. https://doi.org/10.1007/s11356-022-18706-0

Xia C, Cai L, Zhang H, Zuo L, Shi SQ, Lam SS (2021) A review on the modeling and validation of biomass pyrolysis with a focus on product yield and composition. BRJ. https://doi.org/10.18331/BRJ2021.8.1.2

Xiang W, Zhang X, Cao C, Quan G, Wang M, Zimmerman AR, Gao B (2022) Microwave-assisted pyrolysis derived biochar for volatile organic compounds treatment: characteristics and adsorption performance. Bioresour Technol. https://doi.org/10.1016/j.biortech.2022.127274

Xiang W, Zhang X, Chen K, Fang J, He F, Hu X, Tsang DCW, Ok YS, Gao B (2020) Enhanced adsorption performance and governing mechanisms of ball-milled biochar for the removal of volatile organic compounds (VOCs). Chem Eng J. https://doi.org/10.1016/j.cej.2019.123842

Xie R, Ji J, Guo K, Lei D, Fan Q, Leung DY, Huang H (2019) Wet scrubber coupled with UV/PMS process for efficient removal of gaseous VOCs: Roles of sulfate and hydroxyl radicals. Chem Eng J 356:632–640. https://doi.org/10.1016/j.cej.2018.09.025

Yaghmaien K, Hadei M, Hopke P, Gharibzadeh S, Kermani M, Yarahmadi M, Emam B, Shahsavani A (2019) Comparative health risk assessment of BTEX exposures from landfills, composting units, and leachate treatment plants. Air Qual Atmos Health 12:443–451. https://doi.org/10.1007/s11869-019-00669-w

Yu B, Yuan Z, Yu Z, Xue-song F (2022) BTEX in the environment: an update on sources, fate, distribution, pretreatment, analysis, and removal techniques. Chem Eng J. https://doi.org/10.1016/j.cej.2022.134825

Zhang W, Li G, Yin H, Zhao K, Zhao H, An T (2022) Adsorption and desorption mechanism of aromatic VOCs onto porous carbon adsorbents for emission control and resource recovery: recent progress and challenges. Environ Sci Nano 9(1):81–104. https://doi.org/10.1039/D1EN00929J

Zhao P, Cheng YH, Lin CC, Cheng YL (2016) Effect of resin content and substrate on the emission of BTEX and carbonyls from low-VOC water-based wall paint. Environ Sci Pollut Res 23:3799–3808. https://doi.org/10.1007/s11356-015-5616-y

Zhao X, Zeng X, Qin Y, Li X, Zhu T, Tang X (2018) An experimental and theoretical study of the adsorption removal of toluene and chlorobenzene on coconut shell derived carbon. Chemosphere 206:285–292. https://doi.org/10.1016/j.chemosphere.2018.04.126

Zou W, Gao B, Ok YS, Dong L (2019) Integrated adsorption and photocatalytic degradation of volatile organic compounds (VOCs) using carbon-based nanocomposites: a critical review. Chemosphere 218:845–859. https://doi.org/10.1016/j.chemosphere.2018.11.175

Authors and Affiliations

K. Isinkaralar[1]

✉ K. Isinkaralar
kisinkaralar@kastamonu.edu.tr

[1] Department of Environmental Engineering, Faculty of Engineering and Architecture, Kastamonu University, 37150 Kastamonu, Türkiye