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RESEARCH ARTICLE

High-efficiency removal of benzene vapor using activated carbon from *Althaea officinalis* L. biomass as a lignocellulosic precursor

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Abstract

Benzene is a primary air pollutant commonly found widespread in the indoor environment. It has always been a research focus on the environment due to the causes of significant human health concerns. It has been widely utilized in the synthesis of solvent production, which can rarely be found in high concentrations in outdoor air or high amounts in indoor air, depending on its sources. It is aimed to remove different initial benzene concentrations (from 5 to 1500 ppm) with the production of activated carbon as an excellent adsorbent with a high surface area to be used in these situations. Lignocellulosic wastes have great potential for activated carbon for their advantages (abundant, recycled, and low-cost materials, etc.). This study aimed to evaluate biowaste material for activated carbon production from *Althaea officinalis* L. biomass by chemical activation (H_2SO_4, LiOH, and $ZnCl_2$) at temperatures between 500 and 900 °C. Newly developed powdered activated carbons (Ao-ACs) are also tabulated as Ao-AC1-45 for easy reference. Benzene vapor was collected into Tenax TA® tubes by automatic thermal desorption in conjunction with a capillary gas chromatography-mass spectrometry (TD-GC/MS). The significant surface area and production yield of Ao-ACs were obtained at 1424 m^2/g (Ao-AC43) and up to 40.32%, respectively. The maximum gas-phase benzene adsorption capacity was 140 mg/g at 270 min. This research has focused on adsorption gas-phase benzene removal onto Ao-ACs as a low-cost adsorbent from the *Althaea officinalis* L. biomass. Conspicuously, more study is needed to perform the enhanced adsorption of airborne pollutants capacity with inexpensive activated carbon from waste biomass materials.

Keywords Adsorbent · Biomass · Benzene removal · Chemical synthesis · Lignocellulosic precursors

Introduction

Benzene (C_6H_6) is a primary hazardous volatile organic molecule to human health and is higher in the indoor environment (Rao et al. 2007). Remarkably, the benzene gas ratio in petrol stations and the exposures in different age groups have been revealed by studies (Morales Terrés et al. 2010; Hajizadeh et al. 2018). While it can be found in crude oil at up to 4 g/L, it is commonly employed to synthesize 15% of new petroleum-derived goods (Yang et al. 2005). It is carcinogenic to humans and classified by the International Agency for Research on Cancer (IARC) as a Group 1 (IARC 2018). Currently, some electronic devices (e.g., computers, photocopiers, and faxes), wall coverings, textiles, cosmetics, cigarette smoke, insulation materials, chemical-based detergents and stain removers from cooking, agricultural pesticides are primary sources of benzene in indoor air environments (Chen et al. 2021; Zhu et al. 2021). When patients are exposed to gas benzene (especially inhalation) at a daily exposure level of 3.25 mg/m^3 for a month, their hematology is altered. They have a 15% decrease in white blood cells (Huang et al. 2021). As a result, it can be discovered at a high level in closed situations, and it can bring almost several difficulties. Even low dose exposure to benzene can result in various diseases (Lai et al. 2007). Health problems with hematopoietic effects (aplastic anemia, bone marrow disorders, and lymphohematopoietic cancer, and other cancer types based on blood disorders) are seen in people who have been heavily exposed to benzene some ways (Goldstein 2010). In leukemia patients' peripheral blood smear tests,

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exposure to benzene concentrations shows that chromosomal aberrations in lymphocytes, sister-chromatid exchanges, micronuclei increase sparseness, and its genotoxic effect are seen (Cox 2021; Tabatabaei et al. 2021). Paxton et al. (1994) showed 260% times more deaths from leukemia in workers exposed to benzene in a 45-year life span. According to WHO (2010), an increase of 1 g/cm^3 of benzene concentration in indoor air increases the risk of leukemia by 1 in 6,000,000.

The right to breathe clean air was established for the first time with Directive 1980/779/EEC, which was issued in response to the adverse effects of contaminants in indoor air (Ghaffari et al. 2021). Later, the European Union (2008/50/EC) suggested that indoor air concentrations not exceed 5 g/cm^3. Benzene is classified as a Group 1A carcinogen by the International Agency for Research on Cancer (IARC) in several countries, despite the lack of a limit value (Loomis et al. 2017). Indoor air pollutants (IAPs) and their control have been given information about IAPs in the ambient environment. They understood the behavior and characterization of IAPs molecules for active or passive removal methods (Gonçalves et al. 2021). The presence of high benzene indoors can be reduced with different methods for its hydrophobicity. Several ways of dispelling and controlling gas benzene are absorption (Sakhvidi et al. 2022), biofiltration (Saucedo-Lucero and Revah 2018; Siswanto et al. 2020), catalytic oxidation (Derakhshan-Nejad et al. 2020; Gao et al. 2020), condensation (Shokri 2019), photocatalytic oxidation (Gholami et al. 2014; Talaiekhozani et al. 2021), and adsorption (El-Hashemy and Alotaibi, 2021). Besides, IAPs removal methods have been developed because the high cost of using and periodic maintenance of devices that operate continuously has caused them not to be preferred. Therefore, some indoor plants prefer passive removal systems such as adsorption onto activated carbon and biological-based filtration systems (An et al. 2019; Bakar et al. 2021). The mutual point is that they can efficiently adsorb volatile organic compounds (VOCs) such as benzene with minimum cost and a low-level operating system. Literature comparing the gas-phase benzene and its removal methods to high concentrations is rare. Still, activated carbon (especially with high surface area and micropore volume) has been preferred in several research studies to eliminate VOCs at various levels (Shoaib et al. 2020; Jahan et al. 2021). The non-polar nature of pure activated carbon shows a high affinity for non-polar organic benzene (Tham et al. 2011; Le-Minh et al. 2018). Following this purpose, technological developments, the increase in the use of pure chemicals in production, and the increase in the number of materials produced with the developed methods, the success in the removal of pollutants has increased ambient air quality standards for IAPs (Adan-Mas et al. 2021; Medhat et al. 2021). Several reviews have been executed in IAPs for undesirable gases by adsorption over the years. Although there are many adsorption studies, low yields are obtained due to the low production of high efficiency and high quality adsorbents. The increase in efficiency is due to high porosity and multiple gas adsorption (Gao et al. 2021; Naciri et al. 2021; Zhang et al. 2021).

Biowastes have focused on lignin-based organic materials found in nature in abundances, such as decaying terrestrial plants, landscape plants, and agricultural wastes. More recently, many investigations have evaluated its advantages (a high lignocellulosic content) as activated carbons (MacDermid-Watts et al. 2021). The main advantage is a practical and effective application on a large scale. Numerous activated carbons based on biomass precursors are produced from *Tamarix hispida* (Khademi et al. 2015), *Diplotaxis harra* (Tounsadi et al. 2016), *Vitis vinifera* (Fagbayigbo et al. 2017), *Tithonia diversifolia* (Supong et al. 2019), *Sapindus trifoliatus* (Vinayagam et al. 2021), *Aesculus hippocastanum* L. (Isinkaralar et al. 2022) and carbonaceous materials have been employed to manufacture due to their biomass properties (Ipeaiyeda et al. 2020; Momodu et al. 2019; Ma et al. 2021; Ghoma et al. 2022). These materials were synthesized with physical or chemical methods. Physical activation comprises the pyrolysis of materials at high temperatures until 1100 °C by carbon dioxide (CO_2). However, chemical activation generates impregnated with a chemical treatment (sodium hydroxide, phosphoric acid, potassium hydroxide, zinc chloride, etc.) and after pyrolyzed at temperatures between 400 and 900 °C (Xia et al. 2020). The efficiency of activated carbons obtained with the chemical activation process is relatively higher than the activated carbon produced with the physical activation process. The activation method is necessary to gain better porosity (significantly larger micropore volume that provides sufficient benzene adsorption space).

Therefore, this study aims to synthesize adsorbents from *Althaea officinalis* L. (Malvaceae) using chemical activation (H_2SO_4, LiOH, and $ZnCl_2$) to eliminate gas benzene in the indoor air environment. Moreover, activated carbon production was characterized by surface area and pore characteristics, infrared spectroscopy, and elemental analysis. From the study, an extensive and comparative analysis occurs between several production conditions and initial benzene concentrations. It is a prevailing investigation on capturing gas-phase benzene onto the activated carbon from *Althaea officinalis* L. biomass. This paper presented here belongs to enhancement sorbent materials for low and high benzene levels in indoor conditions.

Material and methods

Chemicals and materials

The stems of *Althaea officinalis* L. biomass were obtained as a precursor biowaste material from widely distributed in

Kastamonu, Türkiye. It has a soft structure and can reach a length of two meters and grow abundantly and spontaneously in some locations. Also, it has medicinal features for many ailments for youngsters because it contains polyholosides, phonolic, nitrogenous, sesquiterpenes, steroids, lipids, and minerals. However, if this plant dies after growing in the wild, it is very convenient to use biomass that can be converted into energy. Thus, it was collected when vegetation time was over in its nature. Firstly, it was washed many times with distilled water until neutrality was achieved. It is intended to remove environmental contaminations, and it was dried for two months at room temperature until usage. Next, the lignocellulosic biomass was ball milled, then sieved to the size range 250–500 µm, and was weighed by Adam PW 214 brand. All used chemicals were analytical grade, zinc chloride ($ZnCl_2$, assay 99.5%), lithium hydroxide (LiOH, purity ⩾ 98%), and sulfuric acid (H_2SO_4, purity ⩾ 98%) were purchased from Merck (Darmstadt, Germany), benzene (C_6H_6, purity ⩾ 99.5%) was obtained from Sigma/Aldrich (St. Louis, MO, USA), volatile organic compounds (VOCs) standard solution was procured from Ultra Scientific Inc. (Bologna, Italy), Tenax TA ® tubes were supplied from Markes International (South Wales, UK), Carbopack X 40/60 mesh as multi-sorbent cartridge tubes provided from Supelco (Bellefonte, PA, USA) were used in this test. The purity rate of the chemicals used is high, and they are used without any processing, dilution, or contamination.

Synthesis of Ao-ACs

The synthesis of activated carbons from biomass, based on implemented in five steps, was as follows: (i) mixing the predried of 20 g particles of *Althaea officinalis* L. and 1:0.5, 1:1, and 1:2 for biomass/activation chemical (w/w%) solutions of H_2SO_4, LiOH, and $ZnCl_2$ for 24 h under without interruption agitation at 1000 rpm; (ii) the impregnated sample was dried at 110 °C for 24 h; (iii) reactor (7 cm diameter and 21 cm height) made of high-quality steel that can operate up to 1200 °C without any deformation, embedded within a programmable furnace and was started to pyrolysis at the 500 and 900 °C for 1.5 h under nitrogen (N_2 flow rate of 50 mL/min at a heating rate of 5 °C min^{-1}); (iv) The carbonized samples were washed hot deionized water (80–85 °C) until pH is neutral to dried at 110 °C for 24 h; (v) HCl was boiled approximately 85 °C for removing any remaining chemical and reduce the amount of ash content of the activated carbons. Finally, they were washed with cold distilled water and dried at 110 °C for 24 h. As a result, the activated carbons were prepared and denoted as Ao-AC1-45 according to several production conditions (different temperatures and reagents used). The yield of the Ao-ACs was estimated with Eq. (1).

$$\text{Yield}_{\text{Ao-AC}} = \left(\text{Weight}_{\text{Ao-AC}}/\text{Weight}_{\textit{Althaea officinalis L}}\right) \times 100 \quad (1)$$

Ao-ACs characterization

Nitrogen adsorption–desorption analyses were made at 77 K by Nova Touch LX4 (Quantachrome Instruments, USA), and the porosity test of the Ao-ACs using Brunauer–Emmett–Teller (BET) isotherm. The mesopore volumes were calculated from micropore and total pore volume (V_{meso}:V_{total}—V_{micro}). A PerkinElmer Spectrum 100 Fourier transform infrared spectrometer (FT-IR, PerkinElmer, Waltham, MA, USA) was studied for the functional group surface of the Ao-ACs, their raw material in the region of 400–4000 cm^{-1}. Thermal degradations were conducted with the Perkin Elmer Brand Diamond. The morphology of the Ao-ACs was analyzed by scanning electron microscopy (SEM, FEI Quanta FEG 250). All analyses applied to the produced activated carbon were also applied to the raw material. Proximate analyses of the Ao-ACs were used to identify for volatile matter content determination. The contents of the biomass for volatile matter (VM); E872-85 (2006), moisture (M); E871-82 (2006), and ash (A); E1755-01 (2007) (XRF Xepos II, Spectro) were applied by the American Society for Testing and Materials (ASTM) as international standards. The acid detergent fiber (ADF), neutral detergent fiber (NDF), and Klason lignin (KL) were used to determine the content of raw material (Li et al. 2018). In addition, fixed carbon and oxygen content was calculated with Eq. (2), and Eq. (3), elemental analysis (fixed carbon (FC), carbon (C), hydrogen (H), and nitrogen (N)) was performed by (Euro EA 3000 series, EuroVector, Milano, Italy).

$$\text{FC\%} = 100 - (\text{VM\%} + \text{M\%} + \text{A\%}) \quad (2)$$

$$\text{O\%} = 100 - (\text{C\%} + \text{H\%} + \text{N\%} + \text{M\%} + \text{A\%}) \quad (3)$$

Adsorption experiment

The experiments were performed in a quartz reactor with a volume of nearly 200 cm^3 (diameter of 6 cm and height of 7 cm), and 0.28 g of Ao-ACs was placed in the middle. It was temperature controlled by a thermostatic water bath (Memmert, Germany) for several initial benzene concentrations. Figure 1 depicts the experimental setup in the batch reactor connected to Ao-ACs with N_2 gas flow (50 mL/min), which was run with AirChek XR5000 (SKC, USA) pumps (flow rate of 400 mL/ min) and gas flow meter (regulate the benzene regime into Tenax TA® sorbent in tubes).

Different initial conditions (C_o) of the benzene phase were determined as 5, 50, 150, 500, 1000, and 1500 ppm at 0–270 min contact time. Some parameters are kept constant

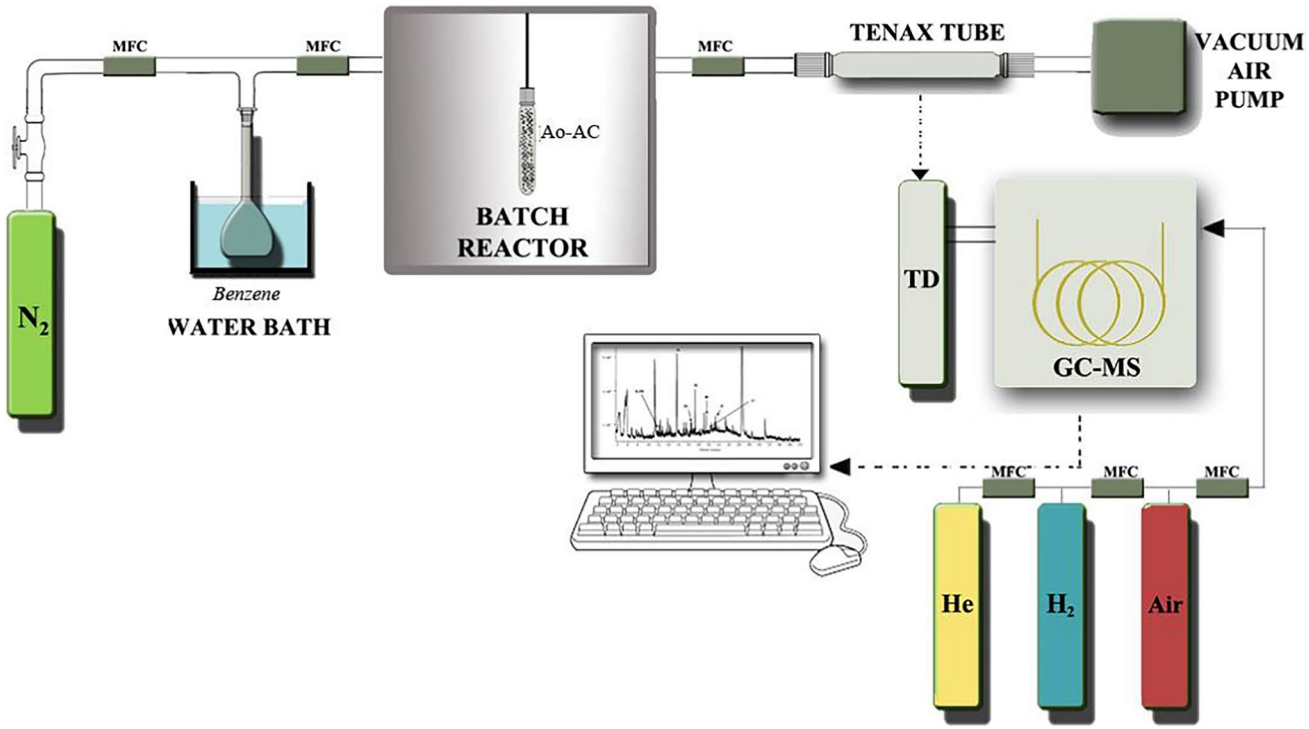

Fig. 1 Schematic diagram of the experimental apparatus

while the system runs, and humidity and temperature conditions are 20% RH and 25 °C. The percentage of gas-phase benzene (removal efficiency %) was calculated by Eq. (4). Where C_o is initial benzene (ppm), C_e is equilibrium benzene concentrations (ppm). The capacity of benzene adsorption onto Ao-ACs was used by Eq. (5). Here, q_t is represented the adsorption capacity at a specific time; m_t is the Ao-ACs weight after benzene adsorption at the time, m_0 is the initial weight of Ao-ACs.

$$\text{Removal of benzene } \% = \left[\left(C_o - C_e\right)/C_o\right] \times 100 \tag{4}$$

$$q_t = \left[\left(m_t - m_0\right)\right]/m_0{}^{*}100 \tag{5}$$

The Ao-ACs production parameters were determined according to temperatures, activation agents, and impregnation ratios given in Table 1.

Benzene analysis in TD-GC/MS

Tenax TA® sorbent tubes were used for benzene sampling by ISO 16000–6 method (ISO 16000–6, 2004), and they have 100 mg Carbopack X (40/60 mesh). Benzene was analyzed using automatic thermal desorption gas chromatography/mass spectrometry (TD-GC/MS, Agilent Technologies 6890 N Network GC System interfaced with an Agilent 5973 Network MSD and using a Unity Series 2 Thermal Desorber). It is detected within a wide range of benzene actively sampled within Tenax TA® (to select its usefulness for adsorbents of VOCs) sorbent tubes by UNE-EN 14,662–1 (UNE-EN 2006). Before beginning the experiments, GC–MS and Thermal Desorber were run as empty for 24 h. All sampling tubes were carried out at 300 °C with He (flow rate 50 mL/min through 10 min) for thermal desorption. Analytes were then injected into the capillary column (DB-1 series 123–1063; 60 m × 0.32 mm × 1 µm by Agilent Technologies, Santa Clara, CA, USA). The injected sample volume was 1 µl, the detector temperature was 250 °C, and the H_2 flow rate of 40 mL/min and the He rate of 20 psi was used as fuel and carrier gases, respectively. At the same time, the system's temperature program is rising from 35° to 300 °C (the rate of 5 °C/min for 30 min). In addition, limits of detection (LOD) and quantification (LOQ) were found at 0.013 mg/m^3 0.047 mg/m^3 for benzene by the standard external method.

Precision and accuracy of data

Before benzene sampling, the reactor and all tools used were cleaned with dry air three times. Then, the precision and accuracy of the obtained data were computed for benzene quality assurance (QA), and quality control (QC) for adsorption experiments were applied with field blanks and triplicate sample measurements. The accuracy was 93.34%

Table 1 Sample labels of Ao-ACs and production conditions

Chemical agents	Sample ID	Impregnation conditions wt%	Carbonization temperature °C	Activation and pyrolysis conditions
$ZnCl_2$	Ao-AC1	0.5:1	500	N_2 flow rate of 50 mL/min; Carbonization time: total retention time 1.5 h as 5 °C/min
	Ao-AC2	0.5:1	600	
	Ao-AC3	0.5:1	700	
	Ao-AC4	0.5:1	800	
	Ao-AC5	0.5:1	900	
	Ao-AC6	1:1	500	
	Ao-AC7	1:1	600	
	Ao-AC8	1:1	700	
	Ao-AC9	1:1	800	
	Ao-AC10	1:1	900	
	Ao-AC11	2:1	500	
	Ao-AC12	2:1	600	
	Ao-AC13	2:1	700	
	Ao-AC14	2:1	800	
	Ao-AC15	2:1	900	
LiOH	Ao-AC16	0.5:1	500	N_2 flow rate of 50 mL/min; Carbonization time: total retention time 1.5 h as 5 °C/min
	Ao-AC17	0.5:1	600	
	Ao-AC18	0.5:1	700	
	Ao-AC19	0.5:1	800	
	Ao-AC20	0.5:1	900	
	Ao-AC21	1:1	500	
	Ao-AC22	1:1	600	
	Ao-AC23	1:1	700	
	Ao-AC24	1:1	800	
	Ao-AC25	1:1	900	
	Ao-AC26	2:1	500	
	Ao-AC27	2:1	600	
	Ao-AC28	2:1	700	
	Ao-AC29	2:1	800	
	Ao-AC30	2:1	900	
H_2SO_4	Ao-AC31	0.5:1	500	N_2 flow rate of 50 mL/min; Carbonization time: total retention time 1.5 h as 5 °C/min
	Ao-AC32	0.5:1	600	
	Ao-AC33	0.5:1	700	
	Ao-AC34	0.5:1	800	
	Ao-AC35	0.5:1	900	
	Ao-AC36	1:1	500	
	Ao-AC37	1:1	600	
	Ao-AC38	1:1	700	
	Ao-AC39	1:1	800	
	Ao-AC40	1:1	900	
	Ao-AC41	2:1	500	
	Ao-AC42	2:1	600	
	Ao-AC43	2:1	700	
	Ao-AC44	2:1	800	
	Ao-AC45	2:1	900	

in replicating analyses of the reference conditions, and the relative standard deviation was 12.29% for all experiments.

Results

The main characteristics of the *Althaea officinalis* L. biomass were determined according to the ASTM standards for volatile matter, moisture, and ash. The raw material's percentage value varies according to the agricultural and climatic conditions in which it is grown. Proximate analysis revealed cellulose, a glucose polymer, 28%, hemicellulose 21.1%, another biopolymer consisting of polysaccharide mixtures, lignin, a polymer of phenylpropane monometric units, randomly non-linearly linked by ester bonds, 23.4%, moisture 9.13%, and ash 2.8%. Also, the main characteristic of the biomass is given in Table 2.

Ao-ACs yield

Experimental results on product yields vary proportionally with the tools used, the purity of the chemicals, and even the person applying it vary. However, some factors directly affect carbonization time, temperature, and system operation without leakage. In addition, several conditions lead to increases or decreases in production yield. To overcome these shortcomings, the modification should be necessary to generate the surface of activated carbon for high levels of targeted gases present in the environment. The activated carbon yield was 33.81 ± 6.51% by weight obtained after the pyrolysis that produced activated carbon has high carbon content in Table 3.

Textural properties

The BET surface areas of the Ao-ACs are proportional to the activation agents undergoing carbonization and optimum temperature ranges. Ao-AC1-15 was prepared with $ZnCl_2$, which exhibited high surface area and increased micropores. Even better results were achieved with H_2SO_4 that the pore width of Ao-AC31-45 has increased the ratio by 2:1. On the other hand, Ao-AC16-30 has the lowest surface area with LiOH impregnated ratios of 0.5:1 w/w%. The issue is even more complicated when microporosity is present as low porosity. As the temperature increases, the pore structure collapses, and smaller micro and macro pores eventually comprise the surface area in Fig. 2.

Table 2 The main characteristic of the *Althaea officinalis* L. biomass

Ultimate analysis	Percentage value (%)
VM	76.51
O	41.25
C	41.16
FC	11.57
H	4.89
N	0.76

Table 3 Elemental analysis of the Ao-ACs

Element	Percentage value (%)
C	78.43
O	17.02
H	1.89
N	2.66

The nitrogen adsorption–desorption isotherm at – 196.15 °C of Ao-ACs is described as Type IV for describing mesoporous materials by the International Union of Pure and Applied Chemistry (IUPAC) classification. The high surface area obtained in the samples produced was activated carbons synthesized with H_2SO_4. Among the examples given in Table 4, Ao-AC43 was chosen to investigate structure due to high pore structure. Although produced Ao-AC14 was obtained in a medium, the BET surface area of 1068.4 m^2/g with $ZnCl_2$, Ao-AC38-45 were prepared by H_2SO_4 between 700 and 900 °C and had high values of surface areas, except for Ao-AC41 due to temperature of 500 °C. Therefore, despite the highest micropore volume, the highest surface area with 1424 m^2/g in Ao-AC43 was 0.298 cm^3/g in Ao-AC44.

SEM micrographs of the *Althaea officinalis* L. biomass and selected Ao-ACs were examined in the surface morphologies by SEM at a magnification scale of 5000x. Figure 3 a shows almost no pores in the untreated state with negligible BET surface area. It had many independent structures and inhomogeneous *Althaea officinalis* L. biomass, needed for easy contact with the inside surfaces. Although Fig. 3 b identified sufficient homogeneous and developed transitional pores, the activation temperature increased from 500 to 900 °C. Significant porosity in the pore structure was observed in its evolution with optimum activation conditions in Ao-AC43. It has a relatively high ash content derived from *Althaea officinalis* L. biomass.

The FT-IR spectra of the *Althaea officinalis* L. biomass and Ao-AC43 were given in Fig. 4, corresponding to the absorption band at 3673, 2979, 1404, 1057, and 615 cm^{-1}. The spectrum possess a small band between 3673 and 3601 cm^{-1} assigned to the hydrogen-bonded –OH groups of alcohols and phenols on the adsorbent surface due to the photocatalytic activity (P-OH groups produced) (Tanaka et al. 2012) in the *Althaea officinalis* L. (lignin, cellulose, and hemicellulose) available in alcohol and acids (Biswas et al., 2017). These bindings and functional groups are constantly interacting between carbon structure and radicals.

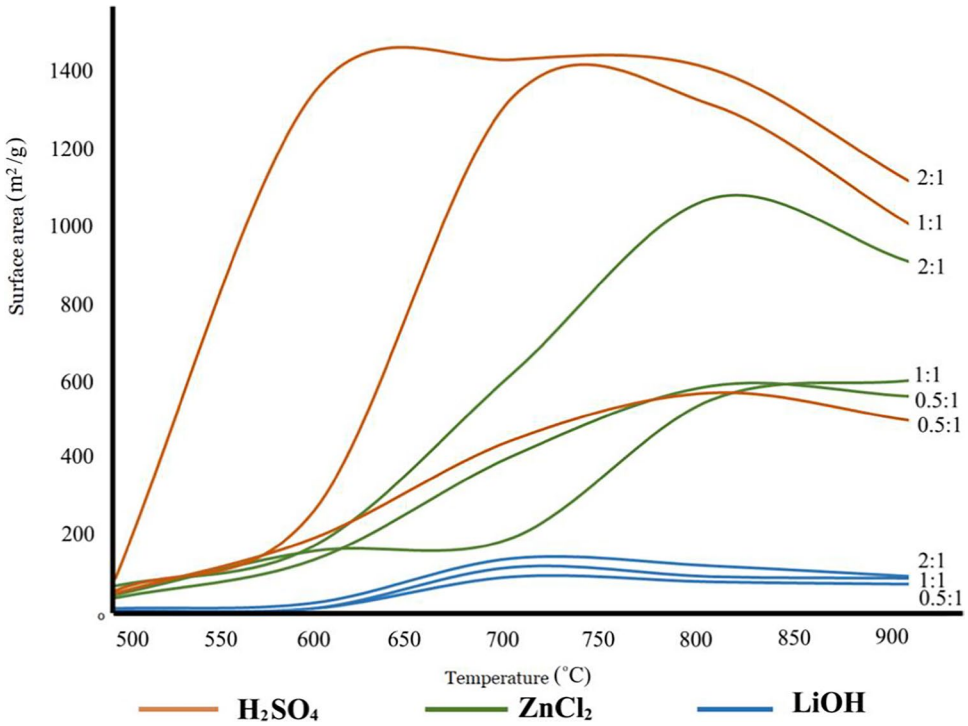

Fig. 2 S_{BET} results of Ao-ACs according to the differences in the production stage

Table 4 The pore structure of selected Ao-ACs and *A. officinalis* biomass

Samples	S_{BET} (m^2/g)	V_{micro} (cm^3/g)	V_{total} (cm^3/g)
Ao-AC14	1068	0.188	0.315
Ao-AC38	1326	0.229	0.337
Ao-AC39	1309	0.227	0.389
Ao-AC40	1003	0.166	0.298
Ao-AC42	1339	0.196	0.328
Ao-AC43	1424	0.223	0.394
Ao-AC44	1401	0.298	0.377
Ao-AC45	1113	0.181	0.269
Althaea officinalis L. biomass	0.0034	0.00087	0.0091

The 2979 cm^{-1} band corresponds to sp^2 C-H and sp^3 C-H stretching, free hydroxyl groups, and C–H interactions within its surfaces (Zawawi et al. 2017). Peak occurring between 1404 and 1125 cm^{-1} is described as aromatic skeletal vibrations and oxygen functionalities such as highly conjugated C-O stretching in carboxylic groups. The band at 1057 cm^{-1} integrates with C-O stretching in acids, alcohols, phenols, ethers, and esters (Puziy et al. 2002). The band between 856 and 478 cm^{-1} was attributed to C-H deformation in structure. Besides, functional groups are vanished mainly due to the corruption of the C–H bonds to form a more stable aromatic C=C bond, which was performed with H_2SO_4 activation.

The thermal behavior of the *Althaea officinalis* L. and Ao-AC43 was observed in the mass loss by TG at 25–800 °C with a heating rate of 10 °C min^{-1} in Fig. 5. The mass loss has occurred in several stages which firstly mass loss for temperatures up to 190 °C to decrease moisture, and then 190–520 °C was observed weight loss difference of sample is a relevant carbonization feature of the *Althaea officinalis* L. biomass due to more significant loss of lignin, cellulose, and hemicellulose. The third stage, between 520 and 630 °C, is relevant to the decomposition of lignin for stable structure, and the final step above 630 °C less loss the mass that the final structure of Ao-AC43 was formed around this temperature.

Effect of benzene adsorption

The benzene adsorption experiments are presented that Ao-AC43 has a superior adsorption ability. Firstly, the adsorption process was worked without the Ao-AC43 until the required stable conditions were achieved in the batch reactor. The maximum benzene efficiency obtained was 87.85% at 50 ppm, although the minimum benzene adsorption performance was acquired by 30.33% at 1500 ppm. The adsorption capacity of an adsorbent is the milligrams of adsorbate per 1 g of Ao-AC43. While the yield was expected to be high at the lowest concentration value, it was 73.98%. The main reason for this is the inability of gases to penetrate sufficiently into the pores in the low concentration activated carbon structure.

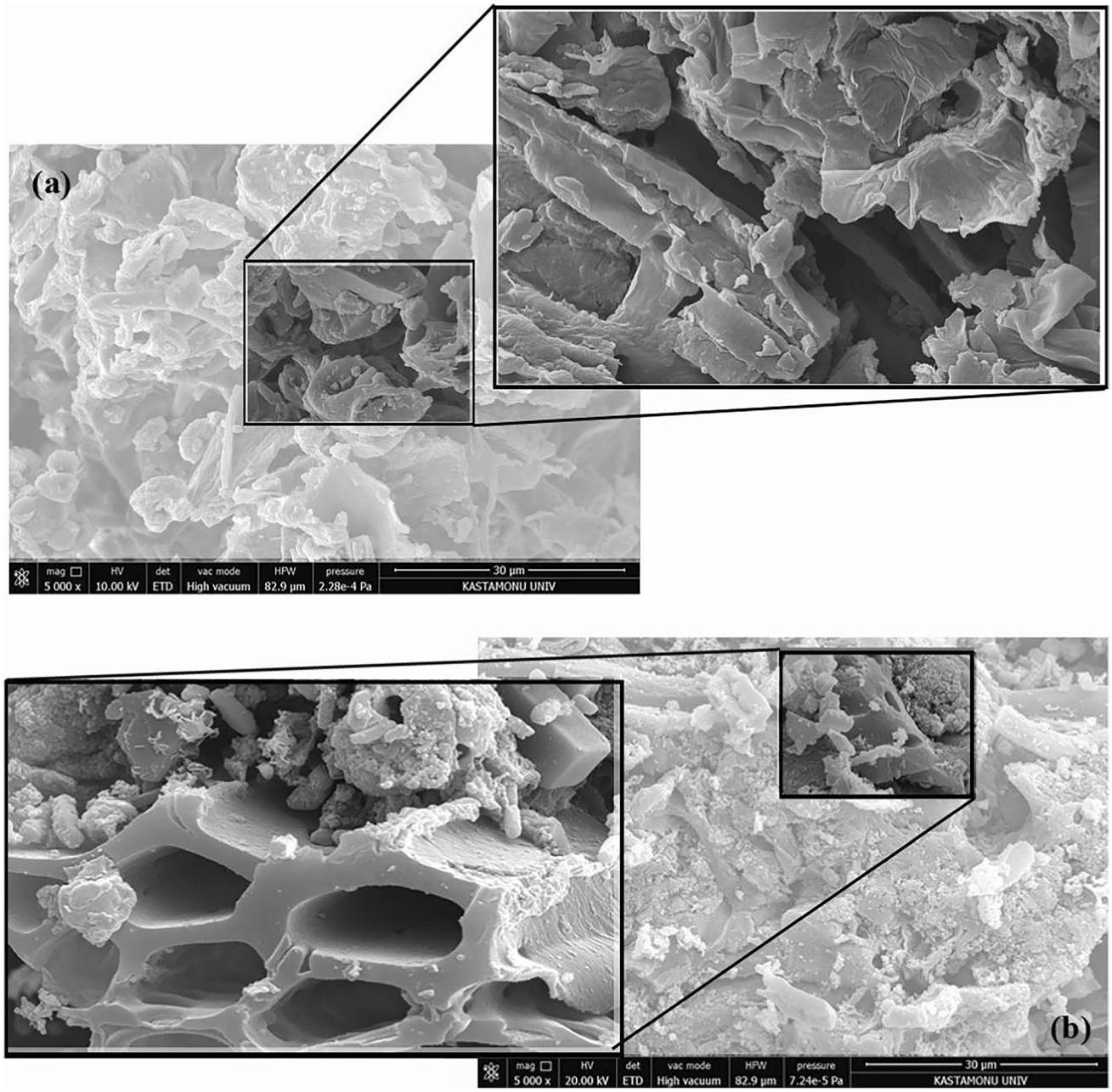

Fig. 3 Scanning electron micrographs of **a** *Althaea officinalis* L. and **b** Ao-AC43 at 30 µm

As the concentration increased, the permeation process took place, and the adsorption capacity increased significantly.

Initial concentration

The several initial gas benzene concentration plays an essential role in the adsorption capacity of Ao-AC43. Therefore, six different initial concentrations were selected as 5, 50, 150, 500, 1000, and 1500 ppm to search for the effect of Ao-AC43. The selection of initial benzene concentrations, commonly found in homes, offices, and indoor environments of various industries, was considered. Meanwhile, other condition parameters were constant (g amount of Ao-AC43, temperature, humidity, etc.). While the lowest value studied was 12.6 mg/g at 5 ppm, 140 mg/g was obtained at 1500 ppm. The initial concentration dramatically increases the total removal efficiency of benzene. Generally, low concentration molecules in the medium have a low adhesion rate and a slower rate of adsorbent in Fig. 6.

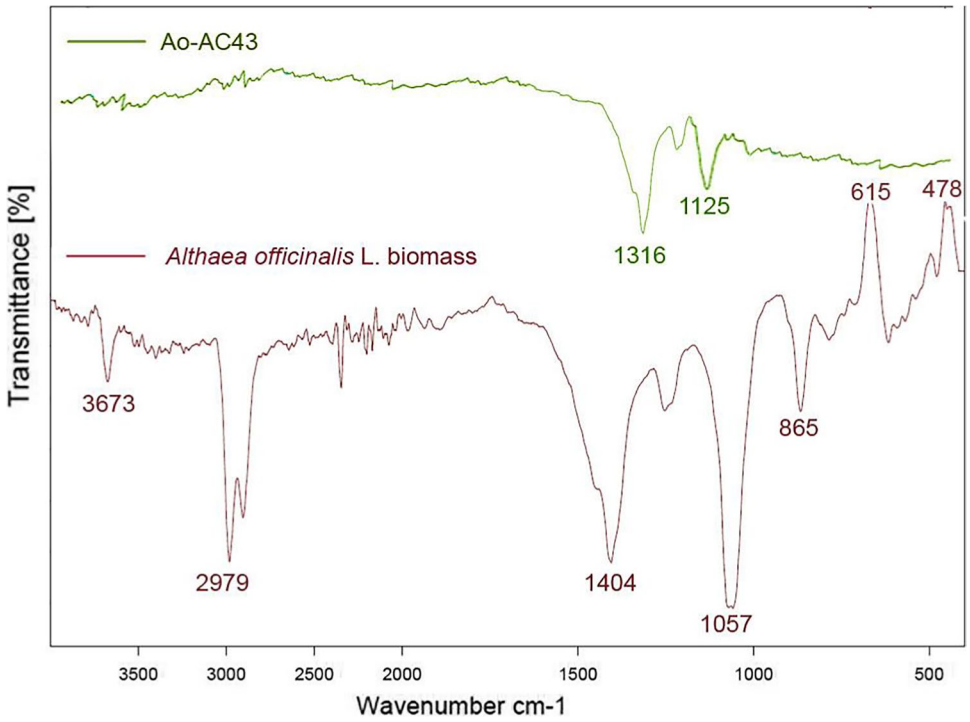

Fig. 4 FT-IR spectrum of the *Althaea officinalis* L. biomass and Ao-AC43

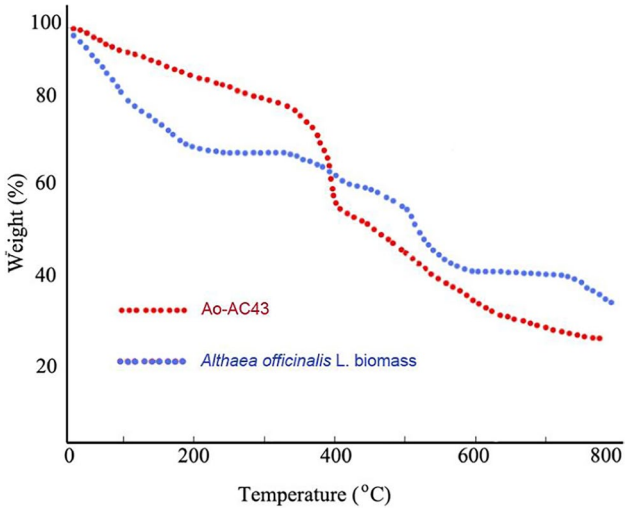

Fig. 5 Thermal behavior curves for the raw material and Ao-AC43

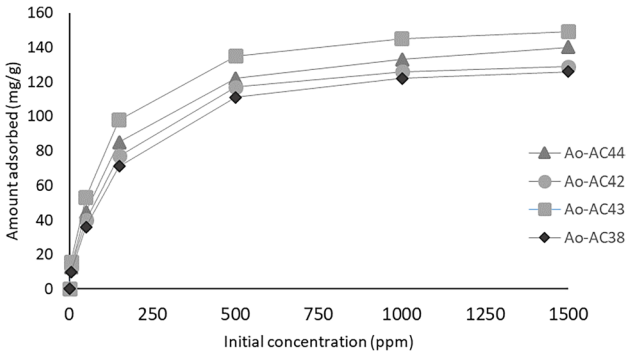

Fig. 6 Effect of initial concentration and amount of adsorbed benzene

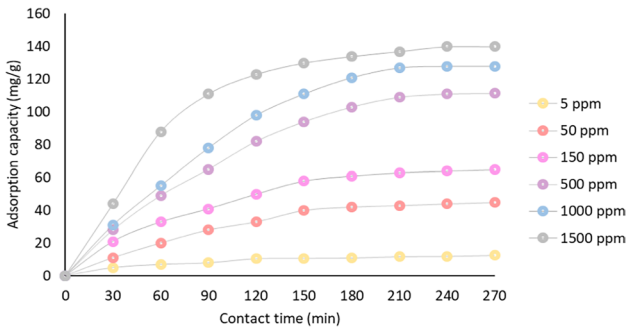

Fig. 7 Effect of the contact time on the removal of gas-phase benzene

Contact time

The study concerning contact time is a vital parameter in all transfer benzene molecules, directly affecting benzene adsorption capacity in Fig. 7. The adsorption capacity of Ao-AC43 was examined until 270 min and slowly increased with the ability of the adsorbent until equilibrium was reached. In the beginning, active sections of Ao-AC43 were empty, and gas molecules of benzene swiftly ensured existence in the cavity of pores. The benzene molecules' adsorption reached equilibrium in 185 min (140 mg/g for

1500 ppm). The optimum contact time for benzene molecules onto Ao-AC43 was observed between 150 and 180 min. It has been observed that the pores were filled slowly at 5 ppm despite the pores quickly uptake benzene at 1500 ppm.

Discussion

Benzene removal has been the subject of investigation for the last years due to its adverse effects on humans at low concentrations. It is known that long-term exposure such as occupational to high benzene levels by uptake of inhalation, which is generally released in indoor spaces, causes carcinogenic effects (Amin et al. 2018; Moridzadeh et al. 2020). There are many ways to remove benzene from indoor air because acute exposure to benzene can be frequently found in the indoor environment (Bedane et al., 2019; Teiri et al. 2021; Jiang et al. 2022). Several adsorbents such as biochar (Gwenzi et al. 2021), clay (Nourmoradi et al. 2012), carbon nanotubes (Abedi et al. 2019), metal–organic frameworks (Santoso et al. 2020), zeolite (Huong et al. 2018), and polymer (Kong et al. 2022) have been reported to reduce VOCs in the literature. The most common adsorbent is activated carbon from dissimilar materials.

Some researchers have tried low and high benzene elimination methods (Ashouri et al. 2021). Further, proximity to success and getting specific adsorbent for benzene molecules. Therefore, many studies have been conducted on a more prosperous and low-cost approach. Ge et al. (2021) reported that cotton-based activated carbon fiber (CACF) was used as a precursor material for removing VOCs. They examined CACF's pore structures on gas benzene adsorption that found intense relation between the pore structure and adsorption ability of the CACF's (CACF-450–650-750). The highest surface area was found at 1568 m^2/g at CACF-650. It reached 828.46 mg/g as the dynamic system had a higher benzene adsorption capacity. Baur et al. (2015) investigated the adsorption of a mixture of toluene and acetaldehyde at low concentrations (80 ppm) onto 0.1 g commercial activated carbon (ACFs) by the transient response method. They showed that the adsorbent could be successfully removed. Sidheswaran et al. (2012) studied an air cleaning system for VOCs with activated carbon fiber. They collected VOCs samples except for formaldehyde onto Tenax (Carbosieve) sorbent tubes and were analyzed by TD-GC/MS. VOCs removal efficiencies were increased when the contact time was decreased to 12 h from 24 h. Laskar et al. (2019) were performed to identify multicomponent adsorption of VOCs (2-propanol, acetone, toluene, n-butanol, and 1,2,4-trimethyl benzene) onto beaded activated carbon (surface area and micropore volume were 1390 m^2/g and 0.51 cm^3/g, respectively) by the Manes method. The experimental result exhibited that adsorption capacity consists of different or non-polar VOCs and polar VOCs. As a result of the adsorption studies with activated carbons, some of them apply the desorption process, although it is not common. In another study, several VOC concentrations (100–900 ppm) were carried out adsorption properties onto fiber-based ACFC by Son et al. (2016). They have also studied the desorption of VOC rate and significantly enhanced the removal rate of adsorbed VOCs. As previous research noted, the adsorption behavior of volatiles rises with the temperature at low concentrations due to the diffusion of the VOC molecules can move much more easily. Limited studies have reported removing high concentration VOCs by activated carbon from different precursors.

Conclusion

Benzene occurs as both a primary and secondary pollutant and has been fastly exhibited due to its smaller molecules. This situation is a vital mechanism that immediately spreads out to ambient air and adversely affects human health. Also, it is frequently emitted by industrial processes, and thus control of benzene in the indoor air is a significant concern to humans for indoor air quality. Although several conventional methods have been tried to remove gas benzene, adsorption onto activated carbon is the best technique for several benzene concentrations. Therefore, activated carbon is becoming increasingly important and is a unique adsorbent for removing VOCs due to its cleaner and more accessible green material. This research targeted significant porosity in produced activated carbon with chemicals by *Althaea officinalis* L. biomass as lignocellulosic precursors. Some substances were compared for better structure of Ao-ACs and were found to be H_2SO_4 as an activating agent, which is relevant to most results in the literature. In conjunction with the development of Ao-AC43 has a large surface area (1424 m^2/g) and high adsorption capacity of gas benzene (140 mg/g). As revealed from the literature, just a few lignocellulosic precursors have been studied to eliminate several initial values of gas benzene for improving indoor air quality. These findings provide important insights into selected Ao-AC43 can also be used as a powerful adsorbent with easy to manufacture, sustainable method, and cost-effective for removal of benzene in the ambient environment. This research struggles with high concentration benzene removal to comply with air quality standards and evaluates the excessive lignocellulosic waste materials. Future work would be worth separating a broader range of benzene concentrations in fundamental indoor areas. Energy cost estimation should be performed to analyze the energy savings obtained from passive adsorption compared to the current active methods that rely entirely on energy.

Author contribution This study is written entirely by Kaan Isinkaralar.

Data availability The data is provided by corresponding author under reasonable requests.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The author declares no competing interests.

References

Abedi Z, Assadi A, Farahmandkia Z, Mehrasebi MR (2019) The effect of natural organic compounds on the adsorption of toluene and ethylene benzene on MWCNT. J Environ Health Sci Eng 17(2):1055–1065. https://doi.org/10.1007/s40201-019-00420-8

Adan-Mas A, Alcaraz L, Arévalo-Cid P, López-Gómez FA, Montemor F (2021) Coffee-derived activated carbon from second biowaste for supercapacitor applications. Waste Manage 120:280–289. https://doi.org/10.1016/j.wasman.2020.11.043

Amin MM, Rafiei N, Poursafa P, Ebrahimpour K, Mozafarian N, Shoshtari-Yeganeh B, Hashemi M, Kelishadi R (2018) Association of benzene exposure with insulin resistance, SOD, and MDA as markers of oxidative stress in children and adolescents. Environ Sci Pollut Res 25(34):34046–34052. https://doi.org/10.1007/s11356-018-3354-7

An Y, Fu Q, Zhang D, Wang Y, Tang Z (2019) Performance evaluation of activated carbon with different pore sizes and functional groups for VOC adsorption by molecular simulation. Chemosphere 227:9–16. https://doi.org/10.1016/j.chemosphere.2019.04.011

Ashouri R, Shirkhanloo H, Rashidi AM, Mirzahosseini SAH, Mansouri N (2021) Dynamic and static removal of benzene from air based on task-specific ionic liquid coated on MWCNTs by sorbent tube-headspace solid-phase extraction procedure. Int J Environ Sci Technol 18(8):2377–2390. https://doi.org/10.1007/s13762-020-02995-4

ASTM Standard E1755–01 (2007) Standard test method for ash in biomass. American Society for Testing and Materials (ASTM), Philadelphia

ASTM Standard E871–82 (2006) Standard test method for moisture analysis of particulate wood fuels. Ameri can Society for Testing and Materials (ASTM), Philadelphia

ASTM Standard E872–85 (2006) Standard test method for volatile matter in the analysis of particulate wood fuels. American Society for Testing and Materials (ASTM), Philadelphia

Bakar NA, Othman N, Yunus ZM, Altowayti WAH, Al-Gheethi A, Asharuddin SM, Tahir M, Fitriani N, Mohd-Salleh SNA (2021) Nipah (Musa Acuminata Balbisiana) banana peel as a lignocellulosic precursor for activated carbon: characterization study after carbonization process with phosphoric acid impregnated activated carbon. Biomass Convers Biorefin, 1-14. https://doi.org/10.1007/s13399-021-01937-5

Baur GB, Beswick O, Spring J, Yuranov I, Kiwi-Minsker L (2015) Activated carbon fibers for efficient VOC removal from diluted streams: the role of surface functionalities. Adsorption 21(4):255–264. https://doi.org/10.1007/s10450-015-9667-7

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

Biswas B, Pandey N, Bisht Y, Singh R, Kumar J, Bhaskar T (2017) Pyrolysis of agricultural biomass residues: comparative study of corn cob, wheat straw, rice straw and rice husk. Biores Technol 237:57–63

Chen R, Li T, Huang C, Yu Y, Zhou L, Hu G, Yang F, Zhang L (2021) Characteristics and health risks of benzene series and halocarbons near a typical chemical industrial park. Environ Pollut 289:117893. https://doi.org/10.1016/j.envpol.2021.117893

Cox LA Jr (2021) Case study: are low concentrations of benzene disproportionately dangerous?. In Quantitative Risk Analysis of Air Pollution Health Effects (pp. 325–353). Springer, Cham. https://doi.org/10.1007/978-3-030-57358-4_12

Derakhshan-Nejad A, Rangkooy HA, Cheraghi M, Yengejeh RJ (2020) Removal of ethyl benzene vapor pollutant from the air using TiO2 nanoparticles immobilized on the ZSM-5 zeolite under UVradiation in lab scale. J Environ Health Sci Eng 18(1):201–209. https://doi.org/10.1007/s40201-020-00453-4

El-Hashemy MAES, Alotaibi NF (2021) Purification of benzene-laden air by static adsorption of benzene onto activated carbon prepared from Diplotaxis acris biomass. Biomass Convers Biorefin. https://doi.org/10.1007/s13399-021-01462-5

Fagbayigbo BO, Opeolu BO, Fatoki OS, Akenga TA, Olatunji OS (2017) Removal of PFOA and PFOS from aqueous solutions using activated carbon produced from Vitis vinifera leaf litter. Environ Sci Pollut Res 24(14):13107–13120. https://doi.org/10.1007/s11356-017-8912-x

Gao Y, Xiao J, Ye J, Huo X, Shen Y (2020) Catalytic oxidation of benzene over alumina-supported Cu-Mn-Ce mixed oxide catalysts. Korean J Chem Eng 37(1):54–64. https://doi.org/10.1007/s11814-019-0428-2

Gao J, Qi X, Zhang D, Matsuoka T, Nakamura Y (2021) Propagation of glowing combustion front in a packed bed of activated carbon particles and the role of CO oxidation. Proc Combust Inst 38(3):5023–5032. https://doi.org/10.1016/j.proci.2020.05.041

Ge Y, Akpinar I, Li Z, Liu S, Hua J, Li W, Zhao T, Hu X (2021) Porous structured cotton-based ACF for the adsorption of benzen. Chemosphere 282:131110. https://doi.org/10.1016/j.chemosphere.2021.131110

Ghaffari HR, Kamari Z, Hassanvand MS, Fazlzadeh M, Heidari M (2021) Level of air BTEX in urban, rural and industrial regions of Bandar Abbas, Iran; indoor-outdoor relationships and probabilistic health risk assessment. Environ Res 200:111745. https://doi.org/10.1016/j.envres.2021.111745

Gholami M, Nassehinia HR, Jonidi-Jafari A, Nasseri S, Esrafili A (2014) Comparison of Benzene & Toluene removal from synthetic polluted air with use of Nano photocatalyticTiO2/ZNO process. J Environ Health Sci Eng 12(1):1–8. https://doi.org/10.1186/2052-336X-12-45

Ghoma W, Sevik H, Isinkaralar K (2022) Using indoor plants as biomonitors for detection of toxic metals by tobacco smoke. Air Qual Atmos Health 15:415–424. https://doi.org/10.1007/s11869-021-01146-z

Goldstein BD (2010) Benzene as a cause of lymphoproliferative disorders. Chem Biol Interact 184(1–2):147–150. https://doi.org/10.1016/j.cbi.2009.12.021

Gonçalves AD, Martins TG, Cassella RJ (2021) Passive sampling of toluene (and benzene) in indoor air using a semipermeable membrane device. Ecotoxicol Environ Saf 208:111707. https://doi.org/10.1016/j.ecoenv.2020.111707

Gwenzi W, Chaukura N, Wenga T, Mtisi M (2021) Biochars as media for air pollution control systems: contaminant removal,

applications and future research directions. Sci Total Environ 753:142249. https://doi.org/10.1016/j.scitotenv.2020.142249
Hajizadeh Y, Mokhtari M, Faraji M, Mohammadi A, Nemati S, Ghanbari R, Abdolahnejad A, Fard RF, Nikoonahad A, Jafari N, Miri M (2018) Trends of BTEX in the central urban area of Iran: a preliminary study of photochemical ozone pollution and health risk assessment. Atmos Pollut Res 9(2):220–229. https://doi.org/10.1016/j.apr.2017.09.005
Huang J, Xu K, Yu L, Pu Y, Wang T, Sun R, Liang G, Yin L, Zhang J, Pu Y (2021) Immunosuppression characterized by increased Treg cell and IL-10 levels in benzene-induced hematopoietic toxicity mouse model. Toxicology 464:152990. https://doi.org/10.1016/j.tox.2021.152990
Huong NT, Phuong VH, Con TH, Son LT, Uyen DT (2018) Removal posibility of benzene vapour in the air by zeolite hy composite. Austrian Journal of Technical and Natural Sciences 1–2:63–71
International Agency for Research on Cancer (2018) IARC monographs on the evaluation of carcinogenic risks to humans. Benzene. Vol 120, Lyon. World Health Organization.
Ipeaiyeda AR, Choudhary MI, Ahmed S (2020) Ammonia and ammonium acetate modifications and characterisation of activated carbons from palm kernel shell and coconut shell. Waste Biomass Valorization 11(3):983–993. https://doi.org/10.1007/s12649-018-0414-7
Isinkaralar K, Gullu G, Turkyilmaz A (2022) Experimental study of formaldehyde and BTEX adsorption onto activated carbon from lignocellulosic biomass. Biomass Conversion and Biorefinery, 1-11. https://doi.org/10.1007/s13399-021-02287-y
Isinkaralar K (2022) Theoretical removal study of gas form BTEX onto activated carbon produced from Digitalis purpurea L. biomass. Biomass Conversion and Biorefinery, 1–11. https://doi.org/10.1007/s13399-022-02558-2
ISO 16000–6 (2004) Indoor Air – Part 6: Determination of volatile organic compounds in indoor and test chamber air by active sampling on Tenax TA sorbent, thermal desorption and gas chromatography using MS/FID.
Jahan K, Singh V, Mehrotra N, Rathore K, Verma V (2021) Development of activated carbon from KOH activation of pre-carbonized chickpea peel residue and its performance for removal of synthetic dye from drinking water. Biomass Convers Biorefin. 1-11. https://doi.org/10.1007/s13399-021-01938-4
Jiang Y, Song J, Zhu A (2022) Gas-phase advanced oxidation (GPAO) for benzene-containing gas by an ultraviolet irradiation/hydrogen peroxide vapour (UV/[H2O2] g) process. Environ Sci Pollut Res 29(11):16418–16426. https://doi.org/10.1007/s11356-021-16920-w
Khademi Z, Ramavandi B, Ghaneian MT (2015) The behaviors and characteristics of a mesoporous activated carbon prepared from Tamarix hispida for Zn (II) adsorption from wastewater. J Environ Chem Eng 3(3):2057–2067. https://doi.org/10.1016/j.jece.2015.07.012
Kong L, Wang Y, Andrews CB, Zheng C (2022) One-step construction of hierarchical porous channels on electrospun MOF/polymer/graphene oxide composite nanofibers for effective arsenate removal from water. Chem Eng J, 134830. https://doi.org/10.1016/j.cej.2022.134830
Lai HK, Jantunen MJ, Künzli N, Kulinskaya E, Colvile R, Nieuwenhuijsen MJ (2007) Determinants of indoor benzene in Europe. Atmos Environ 41(39):9128–9135. https://doi.org/10.1016/j.atmosenv.2007.08.001
Laskar II, Hashisho Z, Phillips JH, Anderson JE, Nichols M (2019) Competitive adsorption equilibrium modeling of volatile organic compound (VOC) and water vapor onto activated carbon. Sep Purif Technol 212:632–640. https://doi.org/10.1016/j.seppur.2018.11.073
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
Li Y, Shuai L, Kim H, Motagamwala AH, Mobley JK, Yue F, Tobimatsu Y, Havkin-Frenkel D, Chen F, Dixon RA, Luterbacher JS, Dumesic JA, Ralph J (2018) An "ideal lignin" facilitates full biomass utilization. Science advances, 4(9), eaau2968. https://doi.org/10.1126/sciadv.aau2968
Loomis D, Guyton KZ, Grosse Y, El Ghissassi F, Bouvard V, Benbrahim-Tallaa L, ... & Straif K (2017) Carcinogenicity of benzene. The Lancet Oncology, 18(12), 1574-1575. https://doi.org/10.1016/S1470-2045(17)30832-X
Ma H, Wang L, Feng X, Chen Y, Wu J, Zhao M, Zhou J (2021) Are activated carbon pore structure parameters linearly positively related to its mass-specific capacitance? J Mater Sci 56(21):12336–12349. https://doi.org/10.1007/s10853-021-06106-
MacDermid-Watts K, Pradhan R, Dutta A (2021) Catalytic hydrothermal carbonization treatment of biomass for enhanced activated carbon: a review. Waste Biomass Valorization 12(5):2171–2186. https://doi.org/10.1007/s12649-020-01134-x
Medhat A, El-Maghrabi HH, Abdelghany A, Menem NMA, Raynaud P, Moustafa YM, Elsayed MA, Nada AA (2021) Efficiently activated carbons from corn cob for methylene blue adsorption. Appl Surf Sci Adv 3:100037. https://doi.org/10.1016/j.apsadv.2020.100037
Momodu D, Okafor C, Manyala N, Bello A, ZebazeKana MG, Ntsoenzok E (2019) Transformation of plant biomass waste into resourceful activated carbon nanostructures for mixed-assembly type electrochemical capacitors. Waste Biomass Valorization 10(6):1741–1753. https://doi.org/10.1007/s12649-017-0165-x
Morales Terrés IM, Miñarro MD, Ferradas EG, Caracena AB, Rico JB (2010) Assessing the impact of petrol stations on their immediate surroundings. J Environ Manage 91(12):2754–2762. https://doi.org/10.1016/j.jenvman.2010.08.009
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(35):44519–44527. https://doi.org/10.1007/s11356-020-10379-x
Naciri Y, Hsini A, Bouziani A, Djellabi R, Ajmal Z, Laabd M, Navio JA, Mills A, Bianchi CL, Li H, Bakiz B, Albourine A (2021) Photocatalytic oxidation of pollutants in gas-phase via Ag3PO4-based semiconductor photocatalysts: recent progress, new trends, and future perspectives. Crit Rev Environ Sci Technol, 1-44. https://doi.org/10.1080/10643389.2021.1877977
Nourmoradi H, Nikaeen M, Khiadani M (2012) Removal of benzene, toluene, ethylbenzene and xylene (BTEX) from aqueous solutions by montmorillonite modified with nonionic surfactant: equilibrium, kinetic and thermodynamic study. Chem Eng J 191:341–348. https://doi.org/10.1016/j.cej.2012.03.029
Paxton MB, Chinchilli VM, Brett SM, Rodricks JV (1994) Leukemia risk associated with benzene exposure in the pliofilm cohort. II. Risk Estimates. Risk Analysis 14(2):155–161. https://doi.org/10.1111/j.1539-6924.1994.tb00040.x
Puziy AM, Poddubnaya OI, Martınez-Alonso A, Suárez-Garcıa F, Tascón JMD (2002) Synthetic carbons activated with phosphoric acid: I. Surface chemistry and ion binding properties. Carbon 40(9):1493–1505. https://doi.org/10.1016/S0008-6223(01)00317-7
Rao PS, Ansari MF, Gavane AG, Pandit VI, Nema P, Devotta S (2007) Seasonal variation of toxic benzene emissions in petroleum refinery. Environ Monit Assess 128(1):323–328. https://doi.org/10.1007/s10661-006-9315-5
Sakhvidi MJZ, Zarei A, Hachesu VR, Zolfaghari A (2022) Evaluating the relationship between the respiratory exposure to the benzene with the primary damages of deoxyribonucleic acid and total antioxidant capacity in one of the oil companies in Iran. Environmental Science and Pollution Research, 1–7.

Santoso SP, Angkawijaya AE, Bundjaja V, Soetaredjo FE, Ismadji S (2020) Metal–organic frameworks and their hybrid composites for adsorption of volatile organic compounds. Applications of Metal–Organic Frameworks and Their Derived Materials, 313-355. https://doi.org/10.1002/9781119651079.ch12

Saucedo-Lucero JO, Revah S (2018) Monitoring key organic indoor pollutants and their elimination in a biotrickling biofilter. Environ Sci Pollut Res 25(10):9806–9816. https://doi.org/10.1007/s11356-018-1274-1

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, 1-16. https://doi.org/10.1007/s13399-020-00823-w

Shokri A (2019) An investigation of corrosion and sedimentation in the air cooler tubes of benzene drying column in linear alkyl benzene production plant. Chem Pap 73:2265–2274. https://doi.org/10.1007/s11696-019-00776-z

Sidheswaran MA, Destaillats H, Sullivan DP, Cohn S, Fisk WJ (2012) Energy efficient indoor VOC air cleaning with activated carbon fiber (ACF) filters. Build Environ 47:357–367. https://doi.org/10.1016/j.buildenv.2011.07.002

Siswanto D, Permana BH, Treesubsuntorn C, Thiravetyan P (2020) Sansevieria trifasciata and Chlorophytum comosum botanical biofilter for cigarette smoke phytoremediation in a pilot-scale experiment—evaluation of multi-pollutant removal efficiency and CO2 emission. Air Qual Atmos Health 13(1):109–117. https://doi.org/10.1007/s11869-019-00775-9

Son HK, Sivakumar S, Rood MJ, Kim BJ (2016) Electrothermal adsorption and desorption of volatile organic compounds on activated carbon fiber cloth. J Hazard Mater 301:27–34. https://doi.org/10.1016/j.jhazmat.2015.08.040

Supong A, Bhomick PC, Baruah M, Pongener C, Sinha UB, Sinha D (2019) Adsorptive removal of Bisphenol A by biomass activated carbon and insights into the adsorption mechanism through density functional theory calculations. Sustainable Chemistry and Pharmacy 13:100159. https://doi.org/10.1016/j.scp.2019.100159

Tabatabaei Z, Baghapour MA, Hoseini M, Fararouei M, Abbasi F, Baghapour M (2021) Assessing BTEX concentrations emitted by hookah smoke in indoor air of residential buildings: health risk assessment for children. J Environ Health Sci Eng 19(2):1653–1665. https://doi.org/10.1007/s40201-021-00721-x

Talaiekhozani A, Rezania S, Kim KH, Sanaye R, Amani AM (2021) Recent advances in photocatalytic removal of organic and inorganic pollutants in air. J Clean Prod 278:123895. https://doi.org/10.1016/j.jclepro.2020.123895

Tanaka H, Tsuda E, Nishikawa H, Fuji M (2012) FTIR studies of adsorption and photocatalytic decomposition under UV irradiation of dimethyl sulfide on calcium hydroxyapatite. Adv Powder Technol 23(1):115–119. https://doi.org/10.1016/j.apt.2011.01.001

Teiri H, Hajizadeh Y, Azhdarpoor A (2021) A review of different phytoremediation methods and critical factors for purification of common indoor air pollutants: an approach with sensitive analysis. Air Qual Atmos Health, 1-19. https://doi.org/10.1007/s11869-021-01118-3

Tham YJ, Latif PA, Abdullah AM, Shamala-Devi A, Taufiq-Yap YH (2011) Performances of toluene removal by activated carbon derived from durian shell. Biores Technol 102(2):724–728. https://doi.org/10.1016/j.biortech.2010.08.068

Tounsadi H, Khalidi A, Abdennouri M, Barka N (2016) Activated carbon from Diplotaxis Harra biomass: optimization of preparation conditions and heavy metal removal. J Taiwan Inst Chem Eng 59:348–358. https://doi.org/10.1016/j.jtice.2015.08.014

UNE-EN 14662–1 (2006) Ambient air quality - standard method for measurement of benzene concentrations - part 1: pumped sampling followed by thermal desorption and gas chromatography.

Union E (2008) Directive 2008/50/EC of the European parliament and of the council of 21 May 2008 on ambient air quality and cleaner air for Europe. Off J Eur Union 152:16e17.

Vinayagam M, Suresh Babu R, Sivasamy A, de Barros ALF (2021) Biomass-derived porous activated carbon nanofibers from Sapindus trifoliatus nut shells for high-performance symmetric supercapacitor applications. Carbon Lett 31(6):1133–1143. https://doi.org/10.1007/s42823-021-00235-4

World Health Organization (2010) Guidelines for indoor air quality: selected pollutants. https://apps.who.int/iris/handle/10665/260127. Accessed 14 Oct 2021

Xia M, Shao X, Sun Z, Xu Z (2020) Conversion of cotton textile wastes into porous carbons by chemical activation with ZnCl2, H3PO4, and FeCl3. Environ Sci Pollut Res 27(20):25186–25196. https://doi.org/10.1007/s11356-020-08873-3

Yang J, Qiao W, Li Z, Cheng L (2005) Effects of branching in hexadecylbenzene sulfonate isomers on interfacial tension behavior in oil/alkali systems. Fuel 84(12–13):1607–1611. https://doi.org/10.1016/j.fuel.2005.01.014

Zawawi NM, Hamzah F, Nasarudin NA, Azman NN (2017) Comparison on the properties of activated carbon derived from rubber seed shell and bamboo. Adv Sci Lett 23:3921–3925

Zhang X, Li Y, Zhang Z, Nie M, Wang L, Zhang H (2021) Adsorption of condensable particulate matter from coal-fired flue gas by activated carbon. Sci Total Environ 778:146245. https://doi.org/10.1016/j.scitotenv.2021.146245

Zhu J, Zhao X, Yang M, Zheng B, Sun C, Zou X, Liu Z, Harada KH (2021) Levels of urinary metabolites of benzene compounds, trichloroethylene, and polycyclic aromatic hydrocarbons and their correlations with socioeconomic, demographic, dietary factors among pregnant women in six cities of China. Environmental Science and Pollution Research, 1-16. https://doi.org/10.1007/s11356-021-16030-7. https://doi.org/10.1166/asl.2017.8267