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Enhanced adsorption of cooking fume pollutants by loofah carbon modified by Fenton reagents

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ABSTRACT

In this study, natural loofah was used as a raw material to adsorb cooking fume pollutants after grinding into a powder (TGS), activation by phosphoric acid to generate activated loofah carbon (TGSC-0), and further modification by Fenton's reagent (TGSC-1). SEM, GC-MS, FT-IR, and X-ray diffraction analyses, in addition to surface area and pore measurements, were used to characterize the adsorption performance of TGS, TGSC-0, and TGSC-1 toward cooking fume pollutants including oils, particulate matter, and non-methane hydrocarbon). TGSC-1 was the best adsorbent when compared against TGS and TGSC-0, and exhibited saturated adsorption capacities for oil, non-methane hydrocarbon (NMHC), PM_{2.5}, and PM₁₀ of 10.367 mg/g, 4.132 mg/g, 5.613 µg/g, and 16.486 µg/g, respectively. Microscopy indicated that the TGSC-1 surface was rougher than that of TGSC-0. In addition, the adsorption properties of TGSC-1 were enhanced due to abundant hydroxyl, carbonyl, and carboxyl groups on the material surfaces, while iron was also present in the amorphous form that was generated on TGSC-1 surfaces from Fenton's reagent. As TGSC-1 mass increased, the adsorption breakthrough time and adsorption capacity for simulated cooking fumes (SCFs) gradually increased. Further, Langmuir models better fit the adsorption process based on the highest R² values being observed for Langmuir model fitting curves of TGSC-1 adsorption of pollutants (i.e., oils, NMHC, PM_{2.5}, and PM₁₀) from SCF, suggesting that adsorption was primarily due to monolayer adsorption and that chemical adsorption plays a major role in this process. This study provides a theoretical basis for the application of TGSC adsorption technology in the treatment of cooking fumes.

Keywords: Loofah carbon; Fenton's reagent; Adsorption; Oil; Particulate matter; Non-methane hydrocarbon.

Graphical Abstract

1. Introduction

Increased economic development and improved living standards have led to a focus on preventing and controlling resultant air pollution for environmental protection (Ma et al. 2020). The Chinese catering industry has rapidly developed in recent years and the associated cooking fumes have become the primary source of indoor air pollution. Cooking fumes represent a unique source of pollution in China and have gradually become the third largest polluting gas in recent years, behind industrial waste gas and automobile exhaust (Alves et al. 2021).

Cooking fumes contain carcinogens, although carcinogens like formaldehyde, acetaldehyde, and benzene are not detected in edible oils and fuels, suggesting that these compounds entirely derive from cooking activities (Yu et al. 2015). High-temperature cooking has become more popular in recent years to disinfect and improve food tastes, but this style of cooking also produces more cooking fumes (Cheng et al. 2016). Cooking fume contains a complex mixture of toxic pollutants including metals, benzene, particulate matter (PM), volatile organic compounds, polycyclic aromatic hydrocarbons (PAHs), quinones, and carbonyl compounds. Consequently, exposure to oil fumes can lead to various health effects including heart and lung diseases (Abdullahi et al. 2013; Wong et al. 2013), diabetes (Wang et al. 2018), brain damage (Naseri et al. 2019), sleep disorders (Fu et al. 2017), female reproductive problems (Zhang et al. 2020), and even diseases in children resulting from contact with mothers during pregnancy (Fang et al. 2020). Cooking fume waste gas is a multiphase aerosol fluid suspended in air that combines gas, liquids, and solids. Waste gas density usually ranges from 1,130 to 11,134 kg/m³ and exhibits characteristic expansibility, fluidity, boundary layer effects, and viscosity (Zhao et al. 2019). Thus, cooking fumes contain a variety of toxic and harmful components that vary with cooking methods, food types, and heating temperatures. In general, cooking fumes comprise mixed gases that form from thermal volatilization, oxidation, pyrolysis, and polymerization of edible oils and ingredients at high temperatures, in addition to their secondary reactants (Zhang et al. 2019). Therefore, cooking fumes represent compound pollutants with complex and variable compositions, and their composition varies with changes in temperature. The current primary monitoring focus of cooking fume pollutants is the examination of gas phase concentrations of cooking fumes and benzene series (Tucki et al. 2019). For example, experimental collection of cooking fume samples from different restaurants have shown that

waste gas from barbecue restaurants primarily comprise alkane olefins, while home-cooked dishes primarily produce isobutane or propylene, and fried dishes primarily produce olefins (Ho et al. 2019). When high-temperature cooking fumes are emitted into the atmosphere, some VOCs can be converted into new particles through homogeneous or heterogeneous reactions (Li et al. 2011; Wang et al. 2015). Therefore, evaluation of cooking fume pollutants should not be limited to gas phase concentrations of cooking fumes, but should also include concentrations of NMHC in addition to particulate matter (PM_{2.5} and PM₁₀) within catering cooking fumes.

Activated carbon is the most common adsorbent and is widely used in various applications due to its porous structure and active groups on its surface (Ho et al. 2021). The adsorption performance of activated carbon is determined by its surface structure and chemical properties. Modification of carbon surfaces by activation can improve their adsorption performance. However, the popularization and application of activated carbon is limited due to its high costs. Thus, studies have focused on identifying low-cost and easily available agricultural waste materials to prepare activated wooden carbon with excellent adsorption effects (Wang et al. 2021; Ali et al. 2021). Activated carbon can be produced from rice straw, fruit shells, and bagasse raw materials, while applied activators are generally KOH, ZnCl₂, and H₃PO₄ (Liu et al. 2021). In addition, phosphoric acid has been widely used as an activator due to its high carbon yield and low energy consumption (Ali. et al. 2020).

Few studies have investigated the use of loofah to prepare activated carbon and no studies have evaluated the modification of materials with Fenton reagents. In this study, natural loofah was investigated as a raw material with phosphoric acid as an activator to prepare loofah carbon. Fenton reagent modification successfully led to the generation of a new type of loofah carbon material that was subsequently characterized using SEM, FT-IR, XRD, and N₂ adsorption-desorption modeling. These new results provide a scientific basis for developing agricultural waste to mitigate cooking fume pollutants.

2. Materials and methods

2.1. Materials

Natural loofah was purchased from Jinan within Shandong, China. Perchloroethylene (purity ≥ 99.0%), 30% hydrogen peroxide, phosphoric acid (purity ≥ 99.0%), iron(II) sulfate heptahydrate (purity ≥ 99.0%), and anhydrous sodium sulfate (purity ≥ 99.0%) were all purchased from the Shanghai Aladdin Biochemical Technology Co., Ltd., China company. Vegetable blend, chili, and zanthoxylum oils were provided by Golden Dragon Fish Food Co., Ltd., China. Condensate waste oil was retrieved from a canteen at the Guilin University of Technology, China.

Sample morphologies were investigated with a JSM-6380LV scanning electron microscope (JEOL, Japan). The skeletons and functional groups within sample compounds were characterized with a ThermoNexus 470 Fourier infrared spectrometer (Nicolet, United States). XRD analysis was conducted using an X' PertPRO X-ray powder diffraction instrument (PANalytical, Netherlands). Nitrogen adsorption and desorption isotherms were measured with a ASAP2020 automatic rapid specific surface area and mesopore / micropore analyzer (Micromeritics, United States). The concentrations of pollutants were determined with a JC-OIL-6A infrared oil meter (Qingdao Juchuang Environmental Protection Co., Ltd., China), a portable SKY2000 non-methane total hydrocarbon meter (Shenzhen Yuante Technology Co., Ltd., China), and a CW-HAT portable particulate matter meter (Background Yashiruifeng Purification Technology Co., Ltd., China).

2.2. Preparation of activated loofah carbon

Natural loofah was washed with distilled water and then dried in an oven at 105°C for 12 h, followed by shearing into fragments and grinding into a powder. The powder was then cleaned with distilled water until reaching a neutral pH, vacuum filtered, and then oven dried at 105°C for 6 h. The dried powder was sieved through a 100 mesh sieve and particulate matter ($\phi=150\ \mu\text{m}$; i.e., the original loofah powder) was identified as the towel-gourd sponge power (TGS). The TGS (20 g) was mixed with a 60% phosphoric acid solution at a material to liquid ratio of 1:5 (w: w) for 24 h. The powder was then vacuum filtered and dried in an oven at 105°C for 6 h. The dried loofah powder mixed with phosphoric acid was placed in a muffle furnace and isolated from oxygen carbonization at 600°C for 2 h, followed by washing with distilled water until reaching a neutral pH, drying, and filtering through a 100-mesh sieve. The resulting loofah charcoal material was identified as TGSC-0. Twenty milliliters of FeSO_4 (0.5 mol/L) were added to the beaker containing the material, and H_2O_2 was added at an H_2O_2 to Fe^{2+} ratio of 10:1. The pH was then adjusted to 3–4 by adding 10 mL of H_2O_2 to configure the Fenton's reagent. The mixture of 5 g TGSC-0 and Fenton's reagent was stand for 24 h, cleaned with distilled water until the pH was neutral, and vacuum filtered. Then, the powder was placed in a drying oven for 6 h at 105°C. The resulting Fenton-modified loofah carbon material was identified as TGSC-1.

2.3. Adsorption of pollutants from cooking fumes

A schematic of the adsorption device is shown in Fig. 1. The self-constructed cooking fume waste gas was used to simulate real-world fume gas. Specifically, 500 mL of blending oil, 20 mL of chili oil, 20 mL of zanthoxylum oil, and 60 mL of condensate waste oil were mixed well in a 1 L three-necked flask. The oil temperature was controlled by an electric stove and heated to 190°C. The air pump passed air into the three-necked flask at a specific pressure and the air was mixed with the cooking fumes produced by heating to form simulated cooking fumes (SCF). A rotameter was used to control the inlet flow rate of flue ($Q=0.12\ \text{m}^3/\text{h}$) in addition to measuring the initial concentration of each pollutant in the cooking fumes at the inlet sampling port. The concentrations of oil, $\text{PM}_{2.5}$, PM_{10} , and NHMC were 100 mg/m^3 , 110 $\mu\text{g}/\text{m}^3$, 240 $\mu\text{g}/\text{m}^3$, and 50 mg/m^3 , respectively. TGS, TGSC-0, and TGSC-1 (5 g) were individually placed in three double-sphere adsorption tubes (DSAT). The cooking fumes were fed to the DSAT, and the SCF pollutants were adsorbed with TGS, TGSC-0, and TGSC-1. In addition, the outlet concentrations of particulate matter ($\text{PM}_{2.5}/\text{PM}_{10}$) and NHMC were measured with portable $\text{PM}_{2.5}/\text{PM}_{10}$ and NHMC instruments, respectively. The outlet SCF samples were suctioned into a 25 mL syringe and then injected into 25 mL colorimetric tubes filled with 15 mL of perchloroethylene, filtered with qualitative filter paper, and dehydrated with anhydrous sodium sulfate, followed by measurements of oils with an infrared oil meter.

Fig. 1. Experimental schematic.

1: air pump, 2: rotameter, 3: electric stove, 4: thermocouple, 5: miscella, 6: three-necked flask, 7: control valve, 8: gas sampling port, 9: sorbent tube, 10: perchloroethylene, 11: infrared oil meter, 12:

portable non-methane total hydrocarbon meter, 13: portable particulate matter meter.

2.4. Experimental methods

2.4.1. Adsorption curve and adsorption capacity calculations

The changes in outlet concentrations of oil, particulate matter (PM10/PM2.5), and NMHC from SCF were used to evaluate adsorption times. Specifically, adsorption times were used as the abscissa and outlet oil concentrations from SCF were used as the ordinates to calculate TGS, TGSC-0, and TGSC-1 adsorption curves for pollutants. A 2.0 mg/m³ maximum allowable emission concentration was set as the breakthrough point of oil concentration according to Chinese catering industry standards. The time corresponding to the outlet concentration/inlet concentration ratio of 0.05 was the breakthrough time for the concentration of particulate matter and NMHC and can be used to calculate the breakthrough adsorption capacity. The time corresponding to the outlet concentration/inlet concentration ratio 0.95 was set as the saturated adsorption time for each pollutant, and the respective saturated adsorption capacity was also calculated.

The adsorption capacity for pollutants from SCF was determined using Eq. (E1).

$$q = \frac{(C_0 \cdot t - S) \cdot Q}{M}, \quad (E1)$$

where q (mg/g) is the adsorption capacity for the unit mass of adsorbent at t , C_0 (mg/L) is the inlet concentration of pollutants, S is the integral area between the breakthrough adsorption curve and the abscissa, t (min) is the adsorption time, and M (g) is the mass of the adsorbent (Zietzschmann. et al. 2016).

2.4.2. Wurof equation calculations

The Wurof equation was used to explain changes of adsorption time and adsorption capacity for adsorbents with different masses to compound pollutants. The equation is as shown in Eq. (E2):

$$\tau = K \cdot L - \tau_0, \quad (E2)$$

where τ (min) is the adsorption breakthrough time, K (min/m) is the adsorption layer protection coefficient, L (m) is the adsorption layer thickness, and τ_0 (min) is the protection time loss. L is calculated according to Eq. (E3)

$$L = \frac{m}{A \cdot \rho_b}, \quad (E3)$$

where m (kg) is the mass of adsorbent, A (m²) is the cross-sectional area of the adsorption layer, and ρ_b (kg/m³) is the bulk density of the adsorbent. The bulk density can be calculated by Eq. (E4):

$$\rho_b = (1 - \varepsilon) \cdot \rho_p, \quad (E4)$$

where ε is the voidage of the adsorption layer and is generally 0.35–0.7, and ρ_p (kg/m³) is the density of the adsorbent.

2.4.3. Adsorption Isotherm Models

Adsorption isotherms were described by Langmuir and Freundlich models that reflect the effects of concentration and temperature on adsorption properties. Langmuir models are often used to describe adsorption forms of monolayers and are suitable for adsorbents with uniform surfaces without interactions between adsorbed molecules. The equation is as follows:

$$q_e = \frac{q_m \cdot K_L \cdot C_e}{1 + K_L \cdot C_e}, \quad (E5)$$

where q_e (mg/g) is the adsorption capacity, q_m (mg/g) is the maximum adsorption capacity, C_e (ppm) is the concentration of gas at saturation, and K_L (ppm⁻¹) is the Langmuir constant (Zhao. et al. 2020).

The Freundlich equation can be used to describe the adsorption isotherm of a heterogeneous surface adsorbent and is an empirical adsorption isotherm that is calculated as follows:

$$q_e = K_F \cdot C_e^{1/n}, \quad (E6)$$

where K_F (mg·g⁻¹ppm^{-1/n}) is the Freundlich constant and $1/n$ is the heterogeneity factor (Novi Sri. et al. 2021).

3. Results and discussion

3.1. Characterization of loofah adsorbents

3.1.1. SEM analysis

SEM was used to characterize the surface microstructures of the TGS, TGSC-0, and TGSC-1 adsorbents (Fig. 2). The outer surfaces of TGSC-0, TGSC-1, and TGS exhibited corrugated structures previously described as "vascular bundle structures" (Liang. et al. 2021). In contrast, the TGS exhibited a rough surface with a large amount of attached pectin layers and an even distribution of Si (Zhang. et al. 2019). The TGSC-0 surface was flat and smooth, exhibiting abundant uniformly-distributed pore structures due to high temperature dehydration (Chen. et al. 2016) that played a role in the adsorption of pollutants from SCF. The TGSC-1 surface was rougher than that of TGSC-0 and exhibited abundant pores in addition to coverage by compounds formed by the Fenton reagent near the pores.

Fig. 2. SEM images of (a) TGS, (b) TGSC-0, and (c) TGSC-1 surfaces.

3.1.2. Fourier infrared spectroscopy

Infrared spectroscopy was conducted to further characterize the TGS, TGSC-0, and TGSC-1 materials (Fig. 3). The FT-IR spectra could be divided into two types of bands: one being the absorption band formed by pore-adsorbed water and -OH groups on the surface, and the other from skeleton vibrations (Cui. et al. 2021). The strong and wide absorption peaks near 3,436 cm⁻¹ and 3,202 cm⁻¹ (Fig. 3) are related to the stretching vibrations of -OH. The absorption peak near 1,615 cm⁻¹ represents the bending vibration peak of the physically-adsorbed water hydroxyl that was caused by the introduction of water molecules into the adsorbed water and interlayer pores on particle surfaces (Song. et al. 2020). The absorption peak near 2,923 cm⁻¹ primarily derives from the asymmetric stretching vibrations of methylene C-H bonds of alkyl groups. A peak near 1,714 cm⁻¹ was also observed that corresponds to the stretching vibration peak of C=O from carboxyl groups (Dai. et al. 2018). The prominent peak near 1,384 cm⁻¹ corresponded to the stretching vibration peak of -NO. The spectral peaks of TGSC-0 and TGSC-1 after activation by phosphoric acid at 1,300-1,100 cm⁻¹ were caused by phosphorus-containing functional groups, while the spectral peaks at 875 cm⁻¹ corresponded to symmetrical vibrations of P-O-P groups in polyphosphates (Shen. et al. 2015). In addition, spectral peaks were observed near 1,036 cm⁻¹ that correspond to SO₄²⁻. A spectral peak near 592 cm⁻¹ was observed that corresponds to the lattice vibrations of cations (Fe³⁺, Al³⁺, and Mg²⁺), consistent with the position of a characteristic stretching

vibration peak for Fe-O (Ramalakshmi. et all. 2021). Thus, these results indicate that the loofah charcoal modified by Fenton reagent comprises a large number of hydroxyl, carbonyl, and carboxyl groups that can effectively improve the adsorption effects of loofah charcoal.

Fenton reactions use Fe^{2+} as a catalyst to react with H_2O_2 at $\text{pH}=2-4$ in order to form $\text{HO}\cdot$ groups with strong oxidation ability. Active groups can be introduced after surface modification of TGSC-0 via $\text{HO}\cdot$ formation mechanisms as follows (Vasilyeva. et all. 2021; Guo. et all. 2021):

Fig. 3. FT-IR spectra of TGS, TGSC-0, and TGSC-1 materials.

3.1.3. X-ray diffraction analysis

XRD analysis was used to investigate the chemical composition of the TGS, TGSC-0, and TGSC-1 materials (Fig. 4). A clear diffraction peak within the TGS spectra corresponded to a carbon diffraction peak at $15-25^\circ$ that could be attributed to an abundance of cellulose, lignin, and pectin on TGS surfaces (Fu. et all. 2018). These components are subject to modification under pyrolysis at high temperatures, leading to decreased diffraction peaks for TGSC-0 and TGSC-1. Comparison to JCPDS standards (No.06-0696) indicated that the peaks at 44.6° and 64.8° belonged to diffraction peaks from body-centered cubic α -Fe. The lack of iron-bearing mineral crystals in the corresponding spectra indicated that the loaded iron exists in an indefinite form and derives from the Fenton reagent reactions during TGSC-0 modification.

Fig. 4. XRD patterns of TGS, TGSC-0, and TGSC-1 materials.

3.1.4. BET analysis

N_2 adsorption-desorption isotherms were evaluated for TGS, TGSC-0, and TGSC-1 (Fig. 5). Based on IUPAC definitions, all three loofah adsorbents exhibited obvious type II adsorption isotherms and clear hysteresis loops. TGS exhibited a H3 hysteresis loop, while TGSC-0 and TGSC-1 exhibited H4 hysteresis loops. The adsorption-desorption curves were not consistent and exhibit obvious hysteresis loops, indicating that mesopores and macropores were present in the adsorption materials (Bardestani. et al. 2019). The curves of the two loofah carbon types indicated that adsorption capacity increased with increasing relative pressure, while adsorption capacity sharply increased at a relative pressure close to 1.0. The primary reason for this observation was that micropores of adsorbents were filled with N_2 at low relative pressure, while adsorption gradually shifted from single-layer to multi-layer dynamics with increasing pressure. Finally, the adsorbent macropores were filled with N_2 , and a capillary agglomeration occurred at high relative pressure (Sinha. et al. 2019). The adsorption capacity of the three adsorbents followed the trend of TGSC-0 > TGSC-1 > TGS (Fig. 5).

Pore size distributions were evaluated for TGS, TGSC-0, and TGSC-1 (Fig. 6) and were uniform for TGSC-0 and TGSC-1 and primarily distributed in the range of 0.5–3.5 nm, while that of TGS was primarily in the range of 1.6–4.0 nm. The pore sizes of TGSC-1 were smaller than those of TGSC-0, primarily due to hydroxyl groups and iron ions that were grafted to the inner surface of the pores after Fenton reagent modification.

The specific surface area and pore structure parameters of TGS, TGSC-0, and TGSC-1 are shown in Table 1. The BET specific surface areas of the three adsorbents followed the trend of: TGSC-0 > TGSC-1 > TGS. After loofah carbon (TGSC-0) surface modification by Fenton's reagent, the pore structures were destroyed and the specific surface areas and pore volumes decreased (Zheng. et al. 2021). The average pore sizes of TGSC-0 and TGSC-1 were 3.963 nm and 2.347 nm, respectively.

Fig. 5. N_2 adsorption-desorption isotherm

Fig. 6. Pore size distribution

Table 1. Specific surface areas and pore structures of loofah carbon materials.

Material	S_{BET} (m ² /g)	V_{total} (cm ³ /g)	D_p (nm)
TGS	5.304	0.032	9.267
TGSC-0	650.904	0.727	3.963
TGSC-1	427.967	0.230	2.347

3.2. Adsorption studies

3.2.1. Comparison of SCF adsorption by different adsorbents

The adsorption properties of the three loofah adsorbents on SCF pollutants (oil, particulate matter, and NMHC) were evaluated. Adsorption breakthrough measurements are widely used direct measurements to evaluate adsorption performance (Zeng, et al. 2020). The adsorption breakthrough curves and adsorption capacities of TGS, TGSC-0, and TGSC-1 for SCF pollutants under dry gas-flue are shown in Figures 7 and 8, respectively. Adsorption performance data are also shown in Table 2. Oils, particulate matter (PM2.5 and PM10), and NMHC exhibited the fastest breakthroughs on TGS, with adsorption capacities of 0.767 mg/g, 0.792 $\mu\text{g/g}$, 1.536 $\mu\text{g/g}$, and 0.533 mg/g, respectively. The adsorption capacities of TGSC-1 were 1.961 mg/g, 1.056 $\mu\text{g/g}$, 2.111 $\mu\text{g/g}$, and 1.092 mg/g, respectively. The adsorption capacity and saturated adsorption capacity values of TGSC-0 were intermediate to those of TGS and TGSC-1. The adsorption capacities of the three adsorbents thus followed the trend of: TGSC-1 > TGSC-0 > TGS. The primary reason for these differences is that TGSC-0 was prepared by dehydrating TGS at high temperature, leading to the pores being dredged and expanded along with increased specific surface areas, and enhanced adsorption capacity. The pore volumes of TGSC-1 were smaller than those of TGSC-0, while abundant hydroxyl, carbonyl, and carboxyl groups were added to its surface that can effectively chemically adsorb SCF composite pollutants, followed by physical adsorption by TGSC-1. Thus, TGSC-1 exhibited the best adsorption performance.

Fig. 7. Adsorption breakthrough curves for different loofah adsorbents and (a) oils, (b) NMHC, (c) PM2.5, and (d) PM10.

Fig. 8. The adsorption capacity of different loofah adsorbents for
(a) oils, (b) NMHC, (c) PM2.5, and (d) PM10.

Table 2. Characteristics of loofah adsorption of SCF pollutants.

Sample	Pollutant	Breakthrough time (min)	Breakthrough adsorption capacity	Saturated adsorption time (min)	Saturated adsorption capacity
TGS	Oil	20	0.767 mg/g	180	7.167 mg/g
	NMHC	28	0.533 mg/g	166	3.293 mg/g
	PM2.5	18	0.792 µg/g	96	4.216 µg/g
	PM10	16	1.536 µg/g	144	13.803 µg/g
TGSC-0	Oil	40	1.559 mg/g	230	9.159 mg/g
	NMHC	46	0.893 mg/g	200	3.973 mg/g
	PM2.5	22	0.968 µg/g	120	5.262 µg/g
	PM10	20	1.921 µg/g	164	15.721 µg/g
TGSC-1	Oil	50	1.961 mg/g	260	10.367 mg/g
	NMHC	56	1.096 mg/g	208	4.132 mg/g
	PM2.5	24	1.056 µg/g	128	5.613 µg/g
	PM10	22	2.111 µg/g	172	16.486 µg/g

3.2.2. Effect of different adsorbent masses on SCF adsorption performance

The effects of different masses of TGSC-1 on SCF adsorption breakthrough curves are shown in Fig. 9. At TGSC-1 masses of 3, 5, 7, 9, and 11 g, TGSC-1 breakthrough times were 20, 50, 60, 70, and 80 min, respectively. In addition, breakthrough times of TGSC-1 for NMHC were 28, 56, 86, 156, and 206, respectively. Lastly, the breakthrough times of TGSC-1 for PM2.5 were 22, 24, 36, 46, and 62, while the breakthrough times of TGSC-1 for PM10 were 20, 22, 32, 42, and 64 min, respectively. Thus, breakthrough times increased with TGSC-1 mass increases.

The effects of different adsorbent masses on SCF adsorption performance is shown in Figure 10. At TGSC-1 masses of 3, 5, 7, 9, and 11 g, the breakthrough adsorptions of TGSC-1 to oil were 0.762, 1.961, 2.452, 3.936, and 5.267 mg/g, respectively, while saturated adsorptions were 8.762, 10.367, 13.952, 19.936, and 21.933 mg/g, respectively. Breakthrough adsorptions of TGSC-1 for NMHC were 0.533, 1.092, 2.115, 5.153, and 10.230 mg/g, respectively, while saturated adsorptions were 3.293, 4.132, 5.765, 8.220, and 14.430 mg/g, respectively. The breakthrough adsorptions of TGSC-1 for PM_{2.5} were 0.790, 1.056, 1.955, 3.340, and 6.770, respectively, while saturated adsorptions were 4.017, 5.613, 7.345, 10.820, and 19.090 µg/g, respectively. The breakthrough adsorptions of TGSC-1 for PM₁₀ were 1.577, 2.111, 3.805, 6.673, and 15.290 µg/g, respectively, while saturated adsorptions were 11.977, 16.486, 23.005, 37.073, and 65.690 µg/g, respectively. Thus, increased TGSC-1 mass was associated with increased adsorption capacity of TGSC-1 to SCF pollutants.

Fig. 9. Effects of different TGSC-1 masses on adsorption breakthrough curves for (a) oils, (b) NMHC, (c) PM_{2.5}, and (d) PM₁₀.

Fig. 10. Effects of different adsorbent masses on adsorption performances for
(a) oils, (b) NMHC, (c) PM2.5, and (d) PM10.

The L - τ fitting line of TGSC-1 adsorption of different pollutants is shown in Fig. 11, which indicates that the breakthrough time for different pollutants varies with the length of TGSC-1 adsorption beds. The parameters of the Wurouf equation to evaluate the adsorption of SCF pollutants by TGSC-1 are shown in Table 3.

Fig. 11. L - τ fitting for TGSC-1 adsorption of SCF pollutants.

Table 3. Wurouf equation parameters for SCF pollutant adsorption by TGSC-1.

Pollutant	Equation	K (min/m)	τ_0 (min)	R^2
Oils	$\tau=1447L-9.35$	1447	13.35	0.995
NMHC	$\tau=3149L-53.29$	3149	53.29	0.983
PM2.5	$\tau=1111L-18.75$	1111	18.75	0.987
PM10	$\tau=1161L-20.62$	1161	20.62	0.992

3.3. Model fitting

The Langmuir and Freundlich model fitting curves are shown in Fig. 12 for the adsorption of SCF pollutants (oils, NMHC, PM2.5, and PM10) by three loofah adsorbents (TGS, TGSC-0, and TGSC-1). The R^2 values (0.99116, 0.99471, and 0.99351, respectively) of the Langmuir model fitting curves were significantly higher than those of the Freundlich model (0.97391, 0.98021, and 0.98953, respectively) for SCF oils. In addition, the R^2 values (0.97814, 0.99448, and 0.99559, respectively) of the Langmuir model fitting curves were significantly higher than those of the Freundlich model (0.97174, 0.99013, and 0.98838, respectively) for NMHC. The R^2 values of the Langmuir and Freundlich model fitting curves were all greater than 0.995, while those of the Langmuir model curve were slightly higher for particulate matter (PM2.5 and PM10). Thus, the Langmuir models better described the adsorption of SCF pollutants by the three loofah adsorbents compared to Freundlich models, indicating that the distribution of adsorption sites on the surfaces of TGS, TGSC-0, and TGSC-1 were generally uniform (Na. et al. 2020).

The Langmuir model is based on the principle of monolayer adsorption that is very suitable for adsorbent surface chemisorption (Alawode. et al. 2019). In contrast, the Freundlich model is more appropriate for non-uniformly distributed adsorption sites on adsorbent surfaces (Na. et al. 2020). The above results suggest that the adsorption of SCF pollutants (oils, NMHC, PM2.5, and PM10) by TGS, TGSC-0, and TGSC-1 was consistent with monolayer adsorption, and that chemical adsorption plays a major role in these processes.

Fig. 12. Langmuir and Freundlich model fitting curves for adsorption of
(a) oils, (b) NMHC, (c) PM2.5, and (d) PM10.

3.4. Adsorption mechanism

TGS is made up of lignin, semi lignin and other plant fibers, and phosphoric acid can quickly penetrate into TGS after dehydration. So, the full pores were distributed into the TGSC-0, which provides a site for the attachment of functional groups and the adsorption of pollutants (Jawad. et al. 2020). Fe^{2+} and Fe^{3+} formed in Fenton reagent have good catalytic effect on the conversion of H_2O_2 to $\text{HO}\cdot$ and $\text{HOO}\cdot$, and $\text{HO}\cdot$ radical has strong addition reaction and oxidation ability because of its lack of electron groups and high potential (Pan. et al. 2008). Therefore, $\text{HO}\cdot$ and $\text{HOO}\cdot$ radicals can react with unsaturated double bonds on the surface of TGSC-0, resulting in the formation of carbonyl and carboxyl

functional groups on the surface of TGSC-1, thus realizing the modification of Fenton reagent.

The stretching vibrations of C-H of methyl, methylene, and aromatic rings were measured by infrared oil meter at 2,930 cm⁻¹, 2,960 cm⁻¹, 3,030 cm⁻¹, respectively, in order to obtain the concentration of oil. C-H has the same polarity as the carbonyl and carboxyl groups on the surface of TGSC-1 (Fig. 3). According to the similar phase solubility principle, TGSC-1 was easier to adsorb C-H, so the adsorption effect of TGSC-1 on oil was better. There was a mesoporous-microporous structure on the surface of TGSC-1, which was dominated by macroporous adsorption when the adsorption pressure increases (Table 1). In addition, TGSC-1 had rough surface, larger specific surface area and larger adsorption area, which can effectively adsorb particulate matter (PM2.5, PM10). In the process of cooking fumes adsorption, the residual Fe³⁺, Fe²⁺, H₂O₂ on the surface of TGSC-1 has strong oxidation (Fig. 4), and these substances can also oxidize and decompose most of NMHC adsorbed on the surface of TGSC-1, thus improving the adsorption performance of TGSC-1.

4. Conclusions

In this study, a natural loofah was successfully prepared as an efficient adsorbent (TGSC-1) of SCF pollutants (oils, particulate matter, and NMHC) and was activated by phosphoric acid and modified by Fenton's reagent. The surface structures and properties of TGSC-1 were characterized by scanning electron microscopy, Fourier transform infrared spectroscopy, X-ray powder diffractometry, and N₂ adsorption-desorption isotherm modeling. The results demonstrated that TGSC-1 was the best adsorbent compared with TGS and TGSC-0 and exhibited saturated adsorption capacities for oil, NMHC, PM2.5, and PM10 of 10.367, 4.132, 5.613, and 16.486 µg/g, respectively. The enhanced adsorption properties of TGSC-1 are due to the large number of hydroxyls, carbonyl, and carboxyl groups in the material, in addition to iron that exists in the amorphous form that is generated on the surface of TGSC-1 from Fenton's reagent reactions. Additional pollutant adsorption experiments were consequently conducted with TGSC-1 and different masses, wherein increased TGSC-1 mass led to increased breakthrough time and adsorption levels. Further, Langmuir models better fit the adsorption dynamics, with most models exhibiting high R² values for TGSC-1 adsorption of SCF pollutants (i.e., oils, NMHC, PM2.5, and PM10). Thus, the adsorption dynamics were consistent with monolayer adsorption, with chemical adsorption playing a major role. These results provide a theoretical basis for the application of TGSC adsorption technology in the treatment of cooking fumes.

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Data availability

All data generated or analyzed during this study are included in this published article.

Author contributions

Conceptualization, Lei Liao and Shengpeng Mo; Data curation, Hongqiang Wang; Formal analysis, Jianwen Wei; Funding acquisition, Lei Liao and Shengpeng Mo; Investigation, Huan Zhang and Peng Zeng; Methodology, Huan Zhang and Lei Liao; Project administration, Huan Zhang; Resources, Huan Zhang; Software, Peng Zeng and Hongquan Liu; Supervision, Hongqiang Wang; Validation, Huan Zhang and Aimiao Qin; Visualization, Huan Zhang; Writing – original draft, Huan Zhang; Writing – review &

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Ethics declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

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