Characterizations of Activated Carbons from Golden Shower (*Cassia fistula*) upon Different Chemical Activation Methods with Potassium Carbonate

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Abstract

Activated carbons (ACs) were synthesized from golden shower (GS) through chemical activation with K₂CO₃. Two synthesis processes were used: one-stage and two-stage processes. In the one-stage process, GS that was impregnated with K₂CO₃ was directly pyrolyzed (GSAC), and the two-stage process consisted of (1) pyrolytic or hydrolytic carbonization to produce biochar (GSB) or hydrochar (GSH) and (2) subsequent chemical activation was defined as GSBAC and GSHAC, respectively. The characteristics of the ACs and their precursors, including thermal stability and textural, physicochemical, structural, and crystal properties, were thoroughly investigated. Results showed that the characteristics of ACs strongly depend on the method used for their synthesis. The Brunauer–Emmett–Teller surface area followed the order GSAC > GSHAC > GSBAC > GSB > GSH > GS. The existence of acidic groups was determined through Fourier transform infrared spectroscopy and Boehm titration. The excellent adsorptive capacities of the ACs were confirmed from the iodine number (1568–2695 mg/g) and methylene number (143–233 mg/g).

**Keywords:** Activated carbon, chemical activation, hydrochar, biochar, golden shower
1. Introduction

Activated carbons (ACs) with high specific surface areas \( (S_{\text{BET}}) \) play a vital role in adsorbing organic compounds in the water treatment process. According to an industry market research report [1], world demand for AC is estimated to increase 8.1 percent per year to 2.1 million metric tons in 2018. Nevertheless, the high cost of commercial ACs prevents their large-scale use. Lignocellulose materials have been considered as abundant renewable precursors that can be used for manufacturing ACs at lower cost. Typically, ACs can be synthesized through two well-known processes: physical and chemical activation. The chemical activation process can be conducted in one or two stages. In the one-stage process, which is the most common method, raw materials are directly mixed with certain activating reagents and the mixture is pyrolyzed. By contrast, the two-stage process comprises (1) a precarbonization process (i.e., pyrolysis or hydrolysis) and (2) chemical activation. Pyrolysis, a dry carbonization process, is conducted at high temperatures \( (400–1200 \, ^{\circ}\text{C}) \) in an inert atmosphere (i.e., \( \text{N}_2 \) or \( \text{Ar} \) atmosphere), under vacuum conditions, or under oxygen-limited conditions for producing biochar. In hydrolysis, a wet carbonization process, the raw materials are dispersed in an autoclave containing a given solution (i.e., \( \text{H}_2\text{O} \), or \( \text{H}_3\text{PO}_4 \)). Subsequently, the autoclave temperature is controlled \( (150–350 \, ^{\circ}\text{C}) \) for 2–24 h at a specific pressure for producing hydrochar [2].

Many previous investigations have shown that ACs prepared through the two-stage chemical activation process have a larger surface area and higher adsorption capacity than those prepared using the one-stage chemical activation process. For example, Basta et al. [3] prepared ACs from rice straw by using the one-stage and two-stage processes. Their results
showed that two-stage KOH activation through prepyrolysis carbonization was more efficient in producing ACs with high $S_{\text{BET}}$ and high adsorption capacity for methylene blue (MB). A similar result was reported by other investigators [4, 5]. For hydrothermal carbonization, Fernandez et al. [6] reported that $S_{\text{BET}}$ of orange-peel-derived ACs produced from hydrochar in water was twice that of orange-peel-derived ACs in H$_3$PO$_4$ acid solution. ACs with extremely high $S_{\text{BET}}$, synthesized from commercial organic precursors (i.e., furfural, glucose starch, cellulose, eucalyptus sawdust, and saccharides), have been precarbonized through a hydrothermal process [7, 8]. However, very few studies have compared the characteristics of ACs prepared from the three chemical activation methods.

Notably, activating reagents have a strong effect on AC characteristics. ACs activated by K$_2$CO$_3$ show the highest $S_{\text{BET}}$, nearly 2000 m$^2$/g, compared with those activated by Na$_2$CO$_3$, KOH, NaOH, ZnCl$_2$, and H$_3$PO$_4$ [9]. In another comparison study on the efficiency of chemical agents (i.e., K$_2$CO$_3$ and KOH) in the synthesis of ACs [10], ACs activated by K$_2$CO$_3$ and KOH through the optimal carbonization process exhibited similar yields, $S_{\text{BET}}$, and micropore volumes. Furthermore, environmentally friendly chemical agents play a major role in industrial and environmental applications. In particular, K$_2$CO$_3$ is not a deleterious chemical, and it is frequently used in food additives. Therefore, K$_2$CO$_3$ was used as an activating agent in the current study.

*Cassia fistula* (commonly known as golden shower) is a very popular ornamental plant in tropical and subtropical regions, and it can be used as a lignocellulose precursor for synthesizing ACs because it is relatively abundant, a renewable resource, and costs less. Hanif et al. [11] investigated the biosorption of Ni(II) in industrial wastewater by various GS
The results demonstrated that GS was an excellent biosorbent for Ni(II) removal from industrial effluents. Later, the biosorption of chromium(III) and chromium(VI) in aqueous solutions by untreated and pretreated GS biomass was studied by Abbas et al. [12]. Although GS has been used as a biosorbent for removing heavy metal ions, its characteristics have not been reported.

In this study, golden shower (GS) was used as a lignocellulose precursor for synthesizing ACs through various chemical activation methods by using K$_2$CO$_3$. The characteristics of the ACs, comprising thermal, physiochemical, textural, morphological, and crystal properties, surface functional groups, and adsorption capacities for iodine and MB, were thoroughly investigated. In this paper, the characteristics of the ACs’ precursors are also discussed.

### 2. Materials and Methods

#### 2.1. Preparation of feedstock, biochar, hydrochar, and their ACs

Pods of GS were collected from Taipei in Taiwan, and the seeds were removed. The materials shown in Figure S1 were washed with tap water at least thrice and then with deionized distilled (DD) water to remove any adhering dirt or impurity. They were then placed in an oven at 80 °C for 24 h. The dried GS was ground and sieved to obtain particles in the size range from 0.106 to 0.250 mm.

Approximately 50 g of the powdered GS was taken in a porcelain crucible covered with a lid. The crucible was placed in a muffle furnace (Deng Yng DF 40, Taiwan) in a limited-oxygen atmosphere at 800 °C for 4 h for obtaining biochar (GSB). Hydrochar (GSH) was prepared
through a hydrothermal carbonization process. Approximately 30 g of the powdered GS was mixed with 120 mL of DD water in a 200 mL Teflon-lined autoclave at 190 °C for 24h. ACs were synthesized through chemical activation processes with K$_2$CO$_3$. The samples were immersed in K$_2$CO$_3$ solution with a weight ratio of 1:1 (K$_2$CO$_3$/precursors), and this was followed by pyrolysis in limited-oxygen conditions at 800 °C for 4 h (Figure 1). Chemically activated GS, GSB, and GSH are referred to by the abbreviations GSAC, GSBAC, and GSHAC, respectively, and GSAC, GSBAC, GSHAC, and GSB were porous carbon materials. After carbonization, the samples were thoroughly washed with 0.1 M HCl for dissolving ash and inorganic salts. Finally, DD water was used to wash the samples until the pH of the filtrates reached a constant value. The samples were then dried and sieved, and they were stored in brown bottles until use.

2.2. Characteristics of feedstock, biochar, hydrochar, and their ACs

2.2.1. Thermal characteristics

The thermal stability of ACs and their precursors was measured by thermo-gravimetric analysis (TGA; DuPont TA Q50, USA) under air atmosphere. The experiment was carried out from room temperature to 900 °C at a heating rate of 10 °C/min.

2.2.2. Physicochemical characterization
Proximate analysis was performed by following an international standard procedure (ASTM). The bulk (apparent) density and hardness (abrasion) number were obtained from the literature [13].

2.2.3. Textural properties

N₂ adsorption–desorption isotherms were measured using a Micromeritics ASAP 2020 sorptometer at 77 K. The Brunauer–Emmett–Teller (BET) method was employed to compute the specific surface areas ($S_{\text{BET}}$). Furthermore, the micropore surface area ($S_{\text{micro}}$) and micropore volume ($V_{\text{micro}}$) were determined using De Boer’s t-plot (statistical thickness) method. The external (nonmicropore) surface area ($S_{\text{external}}$) was calculated as the difference between $S_{\text{BET}}$ and $S_{\text{micro}}$. The total pore volume ($V_{\text{total}}$) was estimated in terms of the amount of adsorption at a relative pressure ($P/P_0$) of 0.98 by using the Horvath–Kawazoe method. Pore size distributions were measured using Brunauer’s MP method, and the nonmicropore volume ($V_{\text{non-micro}}$) was computed by subtracting the micropore volume from the total pore volume.

2.2.4. Morphological and crystal properties

The morphology of the adsorbents was obtained using scanning electron microscopy (SEM; Hitachi S-4800, Japan). To identify possible crystalline structures, adsorbents were analyzed using X-ray diffraction (XRD; PANalytical PW3040/60 X’Pert Pro) with Cu Kα radiation ($\lambda = 0.154$ nm). The scan angle $2\theta$ covered the range $5^\circ < 2\theta < 60^\circ$ and the scan speed was $3^\circ$/min.

2.2.5. Surface chemistry
The functional groups present on the adsorbent surface were detected using Fourier transform infrared spectroscopy (FTIR; FT/IR-6600 JASCO); the adsorbent particles were pelleted using KBr. The spectra were scanned from 4000 to 650 cm\(^{-1}\). The pH value of the adsorbents at the point of zero charge (pH\(_{\text{PZC}}\)) was determined using the solid addition method, which is analogous to the drift method [14].

The acidic groups and basic sites on the adsorbent surfaces were determined through Boehm titration by following the standardization protocol proposed by Goertzen et al. [15]. The total numbers of acidic (i.e., carboxylic, phenolic, and lactonic, as shown in Figure S2) and carboxylic groups on the adsorbents were computed as the numbers of moles neutralized by NaOH and NaHCO\(_3\), respectively. The number of phenolic groups was assumed to be the difference between the number of moles neutralized by NaOH and Na\(_2\)CO\(_3\), and the number of lactonic groups was assumed as the difference between the moles neutralized by Na\(_2\)CO\(_3\) and NaHCO\(_3\). Furthermore, the total number of basic sites of adsorbents was calculated as the number of moles neutralized by HCl. The numbers of moles of adsorbent surface functionalities (n\(\text{ASF}\), mmol/g) neutralized by NaOH (pKa = 15.74), Na\(_2\)CO\(_3\) (pKa = 10.25), NaHCO\(_3\) (pKa = 6.37), and HCl were determined from the following equations:

\[
\begin{align*}
\text{n}_{\text{ASF (NaOH)}} &= \frac{2V_0\left[V_aC_0 - \frac{V_{HC}C_{HC} - V_{f(NaOH)}C_{f(NaOH)}}{2}\right]}{mV_a} \quad (1) \\
\text{n}_{\text{ASF (NaOHNaHCO\(_3\))}} &= \frac{V_0\left[V_aC_0 - \left(V_{HC}C_{HC} - V_{f(NaOH)}C_{f(NaOH)}\right)\right]}{mV_a} \quad (2) \\
\text{n}_{\text{ASF (HCl)}} &= \frac{V_0\left(V_aC_0 - V_{f(NaOH)}C_{f(NaOH)}\right)}{mV_a} \quad (3)
\end{align*}
\]
where $V_o$ (in millimeter) is the volume of NaOH/Na$_2$CO$_3$/NaHCO$_3$/HCl solution added initially; $C_o$ (in molarity) is the concentration of NaOH/Na$_2$CO$_3$/NaHCO$_3$/HCl when $V_o$ is extracted; $V_{HCl}$ (in milliliter) and $C_{HCl}$ (in molarity) are the volume and concentration of HCl solution added to aliquots taken from $V_o$, respectively; $V_a$ (in milliliter) is the volume of aliquot taken from $V_o$; $m$ (in gram) is the mass of adsorbents; and $V_{t(NaOH)}$ (in milliliter) and $C_{t(NaOH)}$ (in molarity) are the concentration and volume of the titrant in the back titration, respectively.

2.2.6. Adsorption properties

The iodine number (ASTM D4607-14) is the amount of iodine adsorbed (milligram) by 1.0 g of carbon. Three weighed carbon doses were transferred into three Erlenmeyer flasks, and to each flask, 10 mL of 5% (by weight) HCl solution was added. The mixture was boiled for 1.0 min to remove any trace of sulfur and then cooled to room temperature. Subsequently, 50 mL of 0.1 N iodine solution was added to each flask. The flasks were immediately stoppered, shaken vigorously for 30 s, and immediately filtrated. A 25-mL aliquot of each filtrate was directly titrated with a standardized 0.1 N sodium thiosulfate solution ($Na_2S_2O_3\cdot5H_2O$) until the solution became pale yellow. The endpoint was determined by adding 2 mL of starch until the solution turned colorless. The titration experiment was conducted in duplicate, and mean values were considered. It was ensured that filtrate normalities ($C$) determined from eq. (4) were not within the range of 0.08 to 0.04 N. The amount of iodine adsorbed per gram of carbon ($X/M$; milligram per gram) was calculated using eq. (5). The iodine number is the value of $X/M$ at the residual iodine concentration ($C$) of 0.02 N.
where \( N_1 \) is the normality of sodium thiosulfate (in equivalent per liter); \( F \) is the amount of filtrate (in milliliter); and \( S \) is the amount of sodium thiosulfate (in milliliter). Furthermore, we have

\[
A = 0.1 \times 12693.0; \quad B = N_1 \times 126.93; \quad \text{and} \quad DF = (I + H)/F, \quad \text{where} \quad DF \quad \text{denotes the dilution factor,} \quad I \quad \text{represents the amount of iodine (in milliliter), and} \quad H \quad \text{is the amount of 5\% HCl used (in milliliter).}
\]

MB number was defined as the amount (in milligram) of MB adsorbed by 1.0 g of carbon, and Barton’s method [16] was used for determining it. Approximately 0.1 g of the carbon samples was added to Erlenmeyer flasks containing 25 mL at a MB concentration of 1000 mg/L. The flasks were covered with a parafilm and shaken using an orbital shaking incubator (S300R-Firstek) with 150 rpm at 25°C for 24h. The MB concentration was determined using a Genesys 10 UV-Vis spectrophotometer (Thermo Scientific, USA) at maximum wavelength of 665 nm. The amount of MB uptake at equilibrium, \( q_e \) (mg/g), was calculated using the mass balance equation:

\[
q_e = \frac{(C_0 - C_e)V}{m}
\]

where \( C_0 \) is the initial MB concentration (in milligram per liter), \( C_e \) is the equilibrium concentration of MB (in milligram per liter), \( m \) (in gram) is the mass of the adsorbent, and \( V \)
(in liter) is the volume of the solution. All the chemicals used were of analytical reagent grade,
and DD water was used in all the experiments.

3. Results and Discussion

3.1. Thermal characteristics

The pyrolytic characteristics of raw GS were determined using the thermogravimetric analyzer,
and they are presented in Figure 2a. Four overlapping peaks for the maximum weight loss are
visible in the thermogravimetric curve. The weight loss temperature ($T_{\text{max}}$) at 56.2°C was
assigned to the vaporization of moisture (≈4.11%), and the thermal decomposition peaks at
$T_{\text{max}}$ of 307, 332, and 451°C were attributed to the thermal degradation of hemicellulose
(19.37%), cellulose (38.95%), and lignin (37.57%) in GS, respectively. Yang et al. [17] noted
that the pyrolysis of pure hemicellulose and cellulose occurred rapidly and that the weight loss
of pure hemicellulose occurred at 220–315 °C ($T_{\text{max}} = 268$ °C) whereas that of pure cellulose
occurred at 315–400 °C ($T_{\text{max}} = 355$ °C). It is noteworthy that the weight of the residue
remains virtually constant from 500–900 °C, suggesting that complete carbonization of GS
requires a minimum temperature of 500 °C.

For the GSH material, the disappearance of the peak corresponding to the decomposition of
hemicellulose is evident in Figure 2c, indicating that the hydrothermal process at 190 °C can
completely decompose the hemicellulose component of raw GS. However, cellulose and
lignin in GS might not be decomposed during the hydrothermal process, and this possibility is
supported by a previous report [17].
The onset and endset temperatures of the adsorbents are extrapolated on the basis of the intersection of two tangents to the TG curves. As expected, the onset temperatures, which denote the temperatures at which weight loss begins, show an appreciable shift. Furthermore, the endset temperatures of the adsorbents (Figure 2) also show a considerable change and follow the order of GSBAC > GSAC ≈ GSHAC > GSB > GSH > GS. Therefore, it can be concluded that the ACs are thermally more stable than their precursors.

Figure 2

3.2. Physicochemical characterization

Table 1 shows that the porous carbon materials had a relatively low percentage of moisture, total ash, and volatility. These analysis results are in accord with the TGA readings in Figure 2. Generally, a low percentage of ash and moisture indicate high quality of AC, and the low volatile content reflects high potential for industrial applications. Notably, the hardness numbers of the (a measure of ACs’ resistance to attrition) are strongly dependent on those of the precursors of the ACs. The hardness numbers follow the order of GSBAC > GSHAC > GSAC for ACs and GSB > GSH > GS for their precursors (Table 1). The results indicate that precursors with higher hardness numbers can be used to obtain ACs with higher hardness.

In Table 1, the elements containing C and O are the primary composites. The O/C molar ratio has been used as a reference for surface hydrophilicity because it is indicative of polar-group content, with the polar groups most likely to have been derived from carbohydrates. Moreover, the H/C molar ratio has been used as an indicator of the degree of aromatization and carbonization [18]. The H/C molar ratio of GSAC (0.10), GSBAC (0.03), and GSHAC (0.06)
decreased rapidly compared with their precursors—GS (1.37), GSB (0.19), and GSH (0.62), respectively, implying that the ACs had higher aromaticity and were thermally more stable. The analogous results of TGA analysis also indicated that the ACs showed higher thermal stability than their precursors. The relatively higher H/C molar ratio of GSH indicates that original organic plant residues, such as cellulose and lignin (Figure 2), remained in hydrochar. The porous carbon samples (i.e., GSAC, GSBAC, GSHAC, and GSB) had similar O/C molar ratios, suggesting that they shared similar affinity for water.

The GSBAC yield (84.16%) was greater than the GSHAC (63.77) and GSAC yields (57.67). This might result from the complete degradation of hemicellulose, cellulose, and lignin in GS during the previous pyrolysis process for producing GSB (Figure 2). The greater GSHAC yield compared with the GSAC yield was attributed to the hemicellulose in GS that was decomposed by the hydrothermal process to produce GSH (Figure 2).

Table 1

3.3. Textural properties

The adsorption/desorption isotherms of the ACs and their precursors are presented in Figure S4. Clearly, the adsorption isotherms of all the ACs and biochar sample belong to Type I of the International Union of Pure and Applied Chemistry (IUPAC) classification, and the Type I isotherm is a typical characteristic of micropores with a small external surface area [19]. Furthermore, a wide knee (hysteresis loop) is present in the adsorption/desorption isotherms of the porous carbon materials. Hysteresis appearing in the multilayer range of physical adsorption isotherms is usually related to the adsorbent with micropore or mesopore structures.
According to the IUPAC nomenclature, porous carbon materials exhibit the H4-type hysteresis loop, which is associated with narrow slit-like pores.

Table 2 lists the textural parameters of the ACs and their precursors. Both the raw material (GS) and hydrothermal treated material (GSH) had low $S_{\text{BET}}$ and pore volume. Nevertheless, after the chemical activation process, the $S_{\text{BET}}$ values of the ACs increased sharply in comparison with those of their precursors, with the order being GSAC (8.14–1413 m$^2$/g) > GSHAC (24.8–1238 m$^2$/g) > GSBAC (597.8–811.9 m$^2$/g). The micropore volume accounted for a major part of the total pore volume, and its share in the total pore volume decreased in the order: GSAC > GSHAC > GSAC > GSB. A higher percentage of micropore volume might result in higher adsorption capacity of small molecules. Surprisingly, the GSB produced by slow pyrolysis at 800 °C also exhibited favorable textural characteristics, indicating its potential for use as an adsorbent.

Table 2

From a practical and economical perspective, because the yield is as important as the surface area, the product $S_{\text{BET}} \times$ total yield can be considered as a performance criterion for any porous carbon preparation process [20]. Although the total GSAC yield was the lowest (see Table 1), the product of $S_{\text{BET}} \times$ total yield was the highest (814.8 m$^2$/g) for this material; the product values were 789.75 m$^2$/g, 683.24 m$^2$/g, and 137.37 m$^2$/g for GSHAC, GSBAC, and GSB, respectively. Clearly, GSAC is economically beneficial.

3.4. Morphological and crystal properties
Figure 3 shows the morphology of the synthesized ACs and their precursors. The raw GS and hydrothermal material had low porosities and fairly rough surfaces. These observations matched with their low $S_{\text{BET}}$ and total pore volume (Table 2). The microspheres in GSH, which are visible in Figure 2, were formed from the high cellulose fraction in GS during hydrothermal carbonization [7]. However, the high lignin content (Figure 2) might prohibit the formation of a pathway from the high number of carbon spheres in the GSH sample. Furthermore, the poorly developed pores of GSH might result from the weak decomposition of cellulose and lignin during the hydrothermal process. A marked change can be observed in the morphology of GSB when the lignocellulose material is pyrolyzed at a high temperature. The surface morphology of GSB shows well-developed pores and fairly high surface area ($S_{\text{BET}} \approx 598 \text{ m}^2/\text{g}$), and therefore, GSB can be considered as a green adsorbent for use in wastewater treatment processes.

Notably, the synthesized AC samples were characterized by irregular and heterogeneous surface morphology with sponge-like structures. The formation of well-developed pores of various sizes and shapes in the ACs during pyrolysis resulted from the evaporation of K$_2$CO$_3$ [21]. Okada et al. [22] highlighted the high $S_{\text{BET}}$ of ACs prepared from waste newspaper through K$_2$CO$_3$ activation, which may intercalate and expand the interlayers of adjacent hexagonal network planes. The planes consist of C atoms, and pore formation is enhanced because of poorly developed hexagonal planes, which are similar to poorly developed planes in graphite. Another reason for enhanced pore formation might be the diffusion of K$_2$CO$_3$ molecules into the rudimentary pores created during pyrolysis and the consequent acceleration of the K$_2$CO$_3$–C reaction [23]. Pore development in the char during pyrolysis plays a crucial
role in improving $S_{\text{BET}}$ and the total pore volume. Therefore, it can be inferred that the surface morphology of the ACs and biochar strongly depended on their preparation method.

**Figure 3**

XRD patterns of the crystallinities of the six adsorbents are presented in Figure 4. The XRD patterns of raw GS and GSH show high crystallinity, with two sharp peaks at $2\theta$ values of approximately 15° and 22°. These peaks are characteristic of crystalline cellulosic materials [24]. The other adsorbents show weak crystallinity. Cellulose in the GS and GSH with a parallel alignment and a crystalline structure resulted from hydrogen bond interactions and van der Waal’s forces between adjacent molecules [25]. Hemicellulose and lignin are amorphous in nature [24]. The XRD spectra of GSB and AC samples showed the absence of the observed peaks for the adsorbents, suggesting that (1) the structure of GSB and ACs is predominantly amorphous and (2) cellulose and lignin in GS and GSH are completely decomposed at the pyrolysis temperature of 800 °C.

**Figure 4**

3.5. Surface chemistry

Qualitative information on functional groups present on the adsorbent surfaces and their spectroscopic assignments is provided in Figure 5. The spectrum of GS is typical of lignocellulose materials [7, 26]. The bands at 3700–3000 cm$^{-1}$ are assigned to (O–H) stretching vibrations in hydroxyl groups in hemicellulose, cellulose, and lignin [27]. Furthermore, the bands observed in the range of 3000–2800 cm$^{-1}$ are related to asymmetric
and symmetric C–H stretching vibrations of the methyl (–CH3–) and methylene (–CH2=) groups, which are expected to be present in hemicellulose, cellulose, and lignin. The TGA results of GSH (see Figure 2c) confirm that hemicellulose in GS was decomposed during the hydrothermal process. Consequently, the peak at 2924 cm$^{-1}$ in the GSH spectrum reflects aliphatic C–H stretching in the methyl and methylene groups in cellulose and lignin. The intense bands observed for aliphatic CH$_n$ nearly disappeared in the spectra of porous carbon materials, indicating the complete loss of labile aliphatic compounds, and a marked decrease in the nonpolar group content in the carbonization process [28]. The presence of a carbon-carbon triple bond (C≡C) in disubstituted alkynes can be inferred from the bands in the region of 2450–2150 cm$^{-1}$. The C≡C vibrations in alkyne groups of biochar and the three ACs were more intense than those in raw GS, because of the release of volatile matter [26].

The characteristics of carboxylic and lactonic groups (C=O) are evident from the bands at 1800–1650 cm$^{-1}$. The decrease in the most insensitive peaks at 1800–1650 cm$^{-1}$ for the porous carbon materials indicated that C=O groups were decomposed at the high carbonization temperature, and thermal decomposition can be evaluated using [29]. This inference matches with the results of Boehm titration. The amount of carboxylic and lactonic groups present on the porous carbon materials decreased sharply by approximately 93%–97% and 78%–92% compared with raw GS, respectively (Table 3).

Similarly, the bands around the region from 1650 to 1480 cm$^{-1}$ can be attributed to the C=C double bonds in aromatic rings. The presence of aromatic benzene rings can also be recognized from the bands in the 970–730 cm$^{-1}$ region, which belong to the aromatic C–H
out-of-plane bending mode. Finally, the observed band between approximately 1290 and 970 cm$^{-1}$ corresponds to stretching C–O groups [26].

**Figure 5**

The electrical state of the adsorbent surfaces in solutions was characterized by the point of zero charge (PZC). The pH value at which the net (external and internal) surface charge of an adsorbent is zero is defined as pH$_{\text{PZC}}$ [30]. Figure S3 and Table 3 show a plot and pH$_{\text{PZC}}$ values of adsorbent samples, obtained using the pH drift method. Obviously, the pH$_{\text{PZC}}$ values of the ACs were strongly dependent on the chemical activation method used (pH$_{\text{PZC}}$ of GSAC > GSBAC > GSHAC).

**Table 3**

Table 3 presents quantitative information on the acidic and basic groups on the adsorbent surfaces; the information was obtained through Boehm titration. Generally, any adsorbent typically coexists with both acidic and basic properties in solutions. However, the dominant concentration of the total acidic groups or total basic groups is strongly dependent on the pH$_{\text{PZC}}$ values. When pH$_{\text{PZC}}$ < 7.0, the total amount of acidic groups should dominate; otherwise, the total amount of basic groups should dominate. Clearly, the changes in the pH$_{\text{PZC}}$ values are in accordance with the change in the total acidic groups and total basic groups.

**3.6. Adsorption properties**
The adsorption properties of the ACs and biochar were evaluated on the basis of the iodine number and MB number. Iodine molecules ($\approx 0.27$ nm) can be adsorbed into micropores (pore width $> 1$ nm) of porous materials [31], whereas MB molecules with a minimal molecular cross section of approximately 0.8 nm require the minimal pore size distribution to be 1.33 nm [32].

The iodine number of commercial AC is typically 900 mg/g, with the iodine values being greater than 1000 mg/g for high grades of AC. The adsorption capacities of the materials for iodine are listed in Table 4, and a linear correlation between the iodine number and micropore parameters (i.e., volume and surface area) is presented in Figure S5. As expected, the ACs show a high iodine number in the following order: GSHAC (2695 mg/g) $>$ GSAC (2604 mg/g) $>$ GSBAC (1568 mg/g). These iodine values are relatively higher than those of commercial ACs. Several previous investigations have reported that ACs produced from lignocellulose and asphalt materials exhibited a high iodine number, exceeding 2000 mg/g. Nowicki et al. [33] synthesized ACs from walnut shells through chemical activation with KOH, and they claimed that the iodine numbers of ACs were 2160 mg/g at a pyrolysis temperature of 700 °C, and approximately 2000 mg/g at 800 °C. Similar high iodine numbers (2208 mg/g) have been noted in other studies too [34]. Furthermore, Kandah et al. [35] reported that asphalt-derived AC showed an iodine number that was approximately thrice that of commercial AC.

The adsorption capacities of MB with a concentration of 1000 mg/L on biochar and ACs are displayed in Table 4. The adsorption capacity (in milligram per gram) and removal efficiency (in percentage) of MB at 24 h decreased in the order of GSBAC (233.6 mg/g; 94.7%) $>$
GSAC (210.2 mg/g; 85.5%) > GSHAC (143.1 mg/g; 57.8%) > GSB (32.6 mg/g; 13.5%).

Graham (1955) investigated the nominal limiting pore diameter for adsorption of MB by the five commercial ACs and concluded that the average nominal limiting pore diameter for MB adsorption was approximately 1.3 nm. The adsorption amounts of MB on GSB and ACs are related to the adsorption capacities of organic compounds with high molecular weight on the adsorbents. Because organic compounds with high molecular weight cannot enter micropores, the adsorption capacities of porous carbon materials for MB are not proportional to their $S_{BET}$. Both $S_{BET}$ and the pore size are the factors that determine the highest adsorption capacity.

**Table 4**

Table S1 presents a comparison of the textural properties, total yield, and $S_{BET} \times$ total yield of the ACs synthesized in this study with those of ACs prepared in previous investigations. Clearly, the yield of AC synthesized under oxygen-limited conditions was considerably higher than that of AC prepared in an inert nitrogen atmosphere. The values of the specific surface area and total pore volume of both GSAC and GSHAC were in accordance with the values presented in the literature; however, the values for GSBAC did not agree with literature values. This might be attributed to GSBAC being produced with a lower impregnation ratio of the activating reagent/precursor.

3. Conclusions

The characteristics of ACs synthesized from GS indicated the $S_{BET}$ values followed the order of GSAC > GSHAC > GSBAC > GSB > GSH > GS. Micropore volumes of the ACs were 83% for GSAC, 73% for GSHAC, and 68% for GSBAC. Typical acidic functional groups present
on the surface of ACs were accurately identified through FTIR and Boehm titration. Excellent adsorption properties of the ACs were confirmed from the high iodine numbers and the MB index. On the basis of favorable characteristics, GS can be considered an excellent precursor for synthesizing ACs through chemical activation.

Acknowledgements

This current work was financially supported by Chung Yuan Christian University (CYCU) in Taiwan. First author would like to thank CYCU for the Distinguished International Graduate Students (DIGS) scholarship to pursue his doctoral studies.

References


FIGURE CAPTIONS

Figure 1. Schematic illustration of the preparation procedure for GS, GSB, GSH, and their activated carbons (GSAC, GSBAC, and GSHAC)

Figure 2. Thermo-gravimetric analysis of the ACs and their precursors

Figure 3. Scanning electron microscopy (SEM) of the ACs (d-f) and their precursors (a-c)

Figure 4. The X-ray diffraction spectra of the ACs and their precursors

Figure 5. FTIR spectra of activated carbons and their precursors

TABLE CAPTIONS

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Table 2. Textural parameters of the ACs and their precursors

Table 3. Surface chemistry of the ACs and their precursors

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Table 1. Physical and chemical characteristics of ACs and their precursors

<table>
<thead>
<tr>
<th></th>
<th>GS</th>
<th>GSB</th>
<th>GSH</th>
<th>GSAC</th>
<th>GSBAC</th>
<th>GSHAC</th>
</tr>
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<tbody>
<tr>
<td><strong>Ultimate analysis</strong></td>
<td></td>
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<tr>
<td>C (wt %)</td>
<td>53.39</td>
<td>77.29</td>
<td>60.64</td>
<td>71.04</td>
<td>76.31</td>
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<tr>
<td>H (wt %)</td>
<td>6.14</td>
<td>1.26</td>
<td>3.15</td>
<td>0.59</td>
<td>0.19</td>
<td>0.35</td>
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<tr>
<td>N (wt %)</td>
<td>0.84</td>
<td>0.56</td>
<td>1.05</td>
<td>0.60</td>
<td>0.65</td>
<td>1.20</td>
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<tr>
<td>O (wt %)</td>
<td>39.63</td>
<td>20.89</td>
<td>35.16</td>
<td>27.77</td>
<td>22.85</td>
<td>22.84</td>
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<tr>
<td>H/C</td>
<td>1.37</td>
<td>0.19</td>
<td>0.62</td>
<td>0.10</td>
<td>0.03</td>
<td>0.06</td>
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<tr>
<td>O/C</td>
<td>0.56</td>
<td>0.20</td>
<td>0.44</td>
<td>0.29</td>
<td>0.22</td>
<td>0.23</td>
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<tr>
<td><strong>Proximate analysis</strong></td>
<td></td>
<td></td>
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<tr>
<td>Moisture (wt %)</td>
<td>1.80±0.28</td>
<td>2.23±0.29</td>
<td>3.12±0.18</td>
<td>4.86±0.25</td>
<td>3.13±0.72</td>
<td>5.30±0.79</td>
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<td>Volatile (wt %)</td>
<td>76.23±0.53</td>
<td>14.33±3.87</td>
<td>63.11±0.85</td>
<td>13.10±2.33</td>
<td>14.24±3.81</td>
<td>15.43±2.02</td>
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<tr>
<td>Total ash (wt %)</td>
<td>1.17±0.30</td>
<td>0.89±0.08</td>
<td>0.45±0.10</td>
<td>0.93±0.04</td>
<td>0.60±0.15</td>
<td>0.85±0.68</td>
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<tr>
<td>Fixed carbon (wt %)</td>
<td>20.93±0.78</td>
<td>84.73±3.77</td>
<td>33.31±0.95</td>
<td>81.11±2.31</td>
<td>82.03±2.98</td>
<td>78.41±2.53</td>
</tr>
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<td><strong>Physicochemical properties</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Total yield (%)</td>
<td>-</td>
<td>22.97±3.14</td>
<td>-</td>
<td>57.67±3.20</td>
<td>84.16±1.46</td>
<td>63.77±1.38</td>
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<td>Hardness (%)</td>
<td>49.07±2.00</td>
<td>83.05±2.32</td>
<td>77.78±1.70</td>
<td>58.01±3.18</td>
<td>80.89±0.63</td>
<td>76.04±4.26</td>
</tr>
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<td>Bulk density (g/cm³)</td>
<td>0.66±0.022</td>
<td>0.40±0.007</td>
<td>0.32±0.001</td>
<td>0.11±0.002</td>
<td>0.37±0.020</td>
<td>0.17±0.002</td>
</tr>
<tr>
<td>pH (1:20) before washed</td>
<td>5.43±0.33</td>
<td>10.58±0.03</td>
<td>4.83±0.02</td>
<td>11.45±0.05</td>
<td>12.65±0.05</td>
<td>11.37±0.23</td>
</tr>
<tr>
<td>pH (1:20) after washed</td>
<td>-</td>
<td>8.46±0.27</td>
<td>4.20±0.17</td>
<td>8.15±0.20</td>
<td>9.71±0.03</td>
<td>8.81±0.33</td>
</tr>
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</table>

*Calculated by difference; \(^{b}\)atomic ratio; mean values ± standard deviation.
**Table 2. Textural parameters of ACs and their precursors**

<table>
<thead>
<tr>
<th></th>
<th>GS</th>
<th>GSB</th>
<th>GSH</th>
<th>GSAC</th>
<th>GSBAC</th>
<th>GSHAC</th>
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<tbody>
<tr>
<td>BET surface area (m²/g)</td>
<td>8.14</td>
<td>598</td>
<td>24.80</td>
<td>1,413</td>
<td>812</td>
<td>1,238</td>
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<tr>
<td>Langmuir surface area (m²/g)</td>
<td>17.93</td>
<td>772</td>
<td>37.74</td>
<td>1,846</td>
<td>1,030</td>
<td>1,685</td>
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<tr>
<td>External surface area (m²/g)</td>
<td>-</td>
<td>160</td>
<td>-</td>
<td>101</td>
<td>128</td>
<td>109</td>
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<tr>
<td>Micropore surface area (m²/g)</td>
<td>-</td>
<td>438</td>
<td>-</td>
<td>1,302</td>
<td>684</td>
<td>1,130</td>
</tr>
<tr>
<td>Total pore volume (cm³/g)</td>
<td>0.01</td>
<td>0.30</td>
<td>0.08</td>
<td>0.66</td>
<td>0.38</td>
<td>0.68</td>
</tr>
<tr>
<td>Micropore volume (cm³/g)</td>
<td>-</td>
<td>0.16</td>
<td>-</td>
<td>0.55</td>
<td>0.26</td>
<td>0.50</td>
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<tr>
<td>Non-micropore volume (cm³/g)</td>
<td>-</td>
<td>0.14</td>
<td>-</td>
<td>0.11</td>
<td>0.12</td>
<td>0.18</td>
</tr>
<tr>
<td>Micropore/total pore volume (%)</td>
<td>-</td>
<td>53.97</td>
<td>-</td>
<td>83.22</td>
<td>68.60</td>
<td>73.10</td>
</tr>
<tr>
<td>Average pore diameter (nm)</td>
<td>-</td>
<td>3.08</td>
<td>-</td>
<td>2.92</td>
<td>3.73</td>
<td>4.44</td>
</tr>
<tr>
<td>Median pore width (nm)</td>
<td>-</td>
<td>0.63</td>
<td>-</td>
<td>0.65</td>
<td>0.65</td>
<td>0.67</td>
</tr>
<tr>
<td>Total yield x S_BET (m²/g)</td>
<td>-</td>
<td>137.34</td>
<td>-</td>
<td>814.84</td>
<td>683.24</td>
<td>789.75</td>
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</table>
Table 3. Surface chemistry of ACs and their precursors

<table>
<thead>
<tr>
<th></th>
<th>GS</th>
<th>GSB</th>
<th>GSH</th>
<th>GSAC</th>
<th>GSBAC</th>
<th>GSHAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total acidic groups (mmol/g)</td>
<td>8.74±0.21</td>
<td>0.72±0.03</td>
<td>2.12±0.01</td>
<td>0.77±0.07</td>
<td>0.55±0.10</td>
<td>1.20±0.05</td>
</tr>
<tr>
<td>+ Phenolic</td>
<td>0.37±0.38</td>
<td>0.05±0.04</td>
<td>0.53±0.08</td>
<td>0.19±0.09</td>
<td>0.22±0.16</td>
<td>0.39±0.15</td>
</tr>
<tr>
<td>+ Lactonic</td>
<td>1.75±0.21</td>
<td>0.25±0.07</td>
<td>0.83±0.05</td>
<td>0.34±0.13</td>
<td>0.13±0.09</td>
<td>0.37±0.08</td>
</tr>
<tr>
<td>+ Carboxylic</td>
<td>6.61±0.14</td>
<td>0.41±0.04</td>
<td>0.76±0.04</td>
<td>0.25±0.02</td>
<td>0.20±0.03</td>
<td>0.43±0.03</td>
</tr>
<tr>
<td>Total basic sites (mmol/g)</td>
<td>0.12±0.03</td>
<td>0.33±0.08</td>
<td>0.10±0.05</td>
<td>1.56±0.02</td>
<td>0.60±0.06</td>
<td>0.99±1.31</td>
</tr>
<tr>
<td>Total groups (mmol/g)</td>
<td>8.86</td>
<td>1.05</td>
<td>2.21</td>
<td>2.34</td>
<td>1.15</td>
<td>2.18</td>
</tr>
<tr>
<td>Density of acidity(a) (C/m(^2))</td>
<td>-</td>
<td>0.12</td>
<td>-</td>
<td>0.05</td>
<td>0.07</td>
<td>0.09</td>
</tr>
<tr>
<td>Density of total groups(b) (C/m(^2))</td>
<td>-</td>
<td>0.17</td>
<td>-</td>
<td>0.16</td>
<td>0.14</td>
<td>0.17</td>
</tr>
<tr>
<td>pH(_{PZC})</td>
<td>3.75±0.35</td>
<td>6.65±0.21</td>
<td>4.30±0.14</td>
<td>8.55±0.07</td>
<td>7.75±0.07</td>
<td>5.25±0.21</td>
</tr>
</tbody>
</table>

\(a\)Density of acidity = (total acidic groups in mmol/g x Faraday's constant of 96.5 in C/mmol)/S\(_{BET}\) in m\(^2\)/g; \(b\)Density of total groups calculated similarly to density of acidity; mean values ± standard deviation.
Table 4. Iodine number and Methylene number of ACs and biochar

<table>
<thead>
<tr>
<th></th>
<th>GSB</th>
<th>GSAC</th>
<th>GSBAC</th>
<th>GSHAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iodine number (mg/g)</td>
<td>794±6.16</td>
<td>2604±2.26</td>
<td>1568±4.54</td>
<td>2695±0.88</td>
</tr>
<tr>
<td>Methylene number (mg/g)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>+ Contact time of 5 min</td>
<td>4.15±1.46</td>
<td>177.81±0.67</td>
<td>164.05±0.63</td>
<td>21.37±1.25</td>
</tr>
<tr>
<td>+ Contact time of 24 h</td>
<td>32.62±2.89</td>
<td>210.21±0.92</td>
<td>233.59±1.20</td>
<td>143.14±1.98</td>
</tr>
<tr>
<td>Pore volume (&gt; 1.3 nm; cm³/g)ᵃ</td>
<td>0.072</td>
<td>0.176</td>
<td>0.103</td>
<td>0.160</td>
</tr>
</tbody>
</table>

ᵃCalculated from incremental BJH (Barret–Joyner–Halenda) pore volumes larger than the pore with of 1.3 nm (cm³/g); mean values ± standard deviation.
Supplementary information for:

Characterizations of Activated Carbons from Golden Shower (Cassia fistula) upon Different Chemical Activation Methods with Potassium Carbonate

Figure captions

Figure S1. The pods bar of Cassia fistula (Golden Shower) (a), and their particle sizes of 0.106-0.25 mm (b)

Figure S2. Acidic oxygen functionalities on surfaces of the adsorbents

Figure S3. Point of zero charge of ACs and their precursors

Figure S4. Nitrogen adsorption/desorption isotherms (a) of GS, GSB, GSH, GSAC, GSBAC, and GSHAC; and pore size distributions (b) of GSB, GSAC, GSBAC, and GSHAC

Figure S5. The correlation between micropore volume, micropore surface area, and iodine number

Table caption

Table S1. Comparison on textural properties, total yield, and $S_{BET}$x total yield of ACs in this study with other ACs published in literatures
Figure S1. The pods bar of *Cassia fistula* (golden shower) (a), and their particle sizes of 0.106-0.25 mm (b)
Figure S2. Acidic oxygen functionalities on surfaces of the adsorbents
Figure S3. Point of zero charge of ACs and their precursors

(Digits in parenthesis indicate values of pH_{pzc} ± standard deviation)
Figure S4. Nitrogen adsorption/desorption isotherms (a) of GS, GSB, GSH, GSAC, GSBAC, and GSHAC; and pore size distributions (b) of GSB, GSAC, GSBAC, and GSHAC.
Figure S5. The correlation between micropore volume, micropore surface area, and iodine number
Table S1. Comparison on textural properties, total yield, and \( S_{\text{BET}} \times \) total yield of ACs in this study with other ACs published in literatures

<table>
<thead>
<tr>
<th>Activated carbon</th>
<th>( S_{\text{BET}} ) (m(^2/g))</th>
<th>Pyrolysis conditions</th>
<th>Yield (%)</th>
<th>Micro-pore volume/total pore volume</th>
<th>Activating reagents</th>
<th>Yield ( x ) ( S_{\text{BET}} )</th>
<th>References</th>
</tr>
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<td><strong>ACs produced from the one-stage chemical activation process (GSAC)</strong></td>
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<tr>
<td>Kraft lignin of spruce wood</td>
<td>2000</td>
<td>800 °C, 1 h, N(_2) flow</td>
<td>40.4</td>
<td>0.85/0.95</td>
<td>K(_2)CO(_3) ((1:1))</td>
<td>808</td>
<td>Hayashi et al. (200)</td>
</tr>
<tr>
<td>Chickpea husk</td>
<td>1778</td>
<td>800 °C, 1 h, N(_2) flow</td>
<td>22.5</td>
<td>0.75/0.82</td>
<td>K(_2)CO(_3) ((1:1))</td>
<td>400</td>
<td>Hayashi et al. (2002)</td>
</tr>
<tr>
<td><strong>Golden shower</strong></td>
<td><strong>1413</strong></td>
<td>800 °C, 4 h, O(_2) absence</td>
<td><strong>57.7</strong></td>
<td>0.55/0.66</td>
<td>K(_2)CO(_3) ((1:1))</td>
<td><strong>815</strong></td>
<td>This study</td>
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<tr>
<td>Soybean oil cake</td>
<td>1352</td>
<td>800 °C, 1 h, N(_2) flow</td>
<td>11.56</td>
<td>0.40/0.68</td>
<td>K(_2)CO(_3) ((1:1))</td>
<td>156</td>
<td>Tay et al. (2009)</td>
</tr>
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<td>Palm shell</td>
<td>1170</td>
<td>800 °C, 2 h, N(_2) flow</td>
<td>18.9</td>
<td>0.57/no mentioned</td>
<td>K(_2)CO(_3) ((1:1))</td>
<td>221</td>
<td>Adinata et al. (2007)</td>
</tr>
<tr>
<td>Grape seed</td>
<td>1166</td>
<td>800 °C, 2 h, N(_2) flow</td>
<td>24.6</td>
<td>0.46/0.48</td>
<td>K(_2)CO(_3) ((1:1))</td>
<td>287</td>
<td>Okman et al. (2014)</td>
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<td>Grape seed</td>
<td>1090</td>
<td>800 °C, 1 h, N(_2) flow</td>
<td>20.1</td>
<td>0.41/0.47</td>
<td>KOH ((1:1))</td>
<td>219</td>
<td>Okman et al. (2014)</td>
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<td>Soybean oil cake</td>
<td>618</td>
<td>800 °C, 1 h, N(_2) flow</td>
<td>4.11</td>
<td>0.143/0.29</td>
<td>KOH ((1:1))</td>
<td>25</td>
<td>Tay et al. (2009)</td>
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<tr>
<td>Commercial rice straw pulp</td>
<td>430</td>
<td>800 °C, 1 h, N(_2) flow</td>
<td>8.5</td>
<td>0.16/0.51</td>
<td>KOH ((4:1))</td>
<td>37</td>
<td>Basta et al. (2009)</td>
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<td>Raw rice straw</td>
<td>420</td>
<td>800 °C, 1 h, N(_2) flow</td>
<td>17.5</td>
<td>0.15/0.31</td>
<td>KOH ((4:1))</td>
<td>74</td>
<td>Basta et al. (2009)</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>$S_{BET}$ (m²/g)</td>
<td>Pyrolysis conditions</td>
<td>Yield (%)</td>
<td>Micro-pore volume/total pore volume</td>
<td>Activating reagents</td>
<td>Yield $\times S_{BET}$</td>
<td>References</td>
</tr>
<tr>
<td>-------------------------</td>
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<td>-------------------------------</td>
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<td>-------------------------------------</td>
<td>---------------------</td>
<td>----------------------</td>
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<tr>
<td>Rice straw</td>
<td>2200</td>
<td>800 °C, 1 h, N₂ flow</td>
<td>-</td>
<td>0.54/ 1.15</td>
<td>KOH (4:1)</td>
<td>-</td>
<td>Oh and Park (2002)</td>
</tr>
<tr>
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<td>1554</td>
<td>800 °C, 1 h, N₂ flow</td>
<td>13.5</td>
<td>0.59/0.93</td>
<td>KOH (4:1)</td>
<td>210</td>
<td>Basta et al. (2009)</td>
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<td>Commercial rice straw</td>
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<td>800 °C, 1 h, N₂ flow</td>
<td>18</td>
<td>0.25/0.76</td>
<td>KOH (4:1)</td>
<td>251</td>
<td>Basta et al. (2009)</td>
</tr>
<tr>
<td>Rice straw</td>
<td>1010</td>
<td>800 °C, 1 h, N₂ flow</td>
<td>-</td>
<td>0.34/ 0.64</td>
<td>KOH (1:1)</td>
<td>-</td>
<td>Oh and Park (2002)</td>
</tr>
<tr>
<td>Golden shower</td>
<td>812</td>
<td>800 °C, 4 h, O₂ absence</td>
<td>84.2</td>
<td>0.26/0.38</td>
<td>K₂CO₃ (1:1)</td>
<td>683</td>
<td>This study</td>
</tr>
<tr>
<td>Rice husk</td>
<td>379</td>
<td>800 °C, N₂ flow</td>
<td>39.2</td>
<td>0.39/0.65</td>
<td>H₃PO₄ (85% by weight)</td>
<td>149</td>
<td>Kennedy et al. (2004)</td>
</tr>
<tr>
<td>Activated carbon</td>
<td>( S_{\text{BET}} ) (m(^2)/g)</td>
<td>Pyrolysis conditions</td>
<td>Yield (%)</td>
<td>Micro-pore volume/total pore volume</td>
<td>Activating Reagents ( x ) ( S_{\text{BET}} )</td>
<td>References</td>
<td></td>
</tr>
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<td>------------------</td>
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<td>------------</td>
<td>----------------------------------</td>
<td>---------------------------</td>
<td>------------</td>
<td></td>
</tr>
<tr>
<td>Eucalyptus sawdust</td>
<td>2252</td>
<td>( 700 , ^\circ\text{C}, , 1 , \text{h}, ) ( \text{N}_2 ) flow</td>
<td>36</td>
<td>0.91/1.03</td>
<td>KOH (4:1)</td>
<td>810</td>
<td>Sevilla et al. (2011)</td>
</tr>
<tr>
<td>Commercial starch</td>
<td>2194</td>
<td>( 700 , ^\circ\text{C}, , 1 , \text{h}, ) ( \text{N}_2 ) flow</td>
<td>37</td>
<td>0.92/1.01</td>
<td>KOH (4:1)</td>
<td>812</td>
<td>Sevilla et al. (2011)</td>
</tr>
<tr>
<td>Commercial fufural</td>
<td>2179</td>
<td>( 700 , ^\circ\text{C}, , 1 , \text{h}, ) ( \text{N}_2 ) flow</td>
<td>34</td>
<td>0.91/1.03</td>
<td>KOH (4:1)</td>
<td>741</td>
<td>Sevilla et al. (2011)</td>
</tr>
<tr>
<td>Commercial glucose</td>
<td>2121</td>
<td>( 700 , ^\circ\text{C}, , 1 , \text{h}, ) ( \text{N}_2 ) flow</td>
<td>43</td>
<td>0.91/1.00</td>
<td>KOH (4:1)</td>
<td>912</td>
<td>Sevilla et al. (2011)</td>
</tr>
<tr>
<td>Commercial cellulose</td>
<td>2047</td>
<td>( 800 , ^\circ\text{C}, , 1 , \text{h}, ) ( \text{N}_2 ) flow</td>
<td>33</td>
<td>0.74/0.98</td>
<td>KOH (4:1)</td>
<td>676</td>
<td>Sevilla et al. (2011)</td>
</tr>
<tr>
<td>Commercial glucose</td>
<td>1612</td>
<td>( 800 , ^\circ\text{C}, , 3 , \text{h}, ) ( \text{N}_2 ) flow</td>
<td>-</td>
<td>0.35/0.86</td>
<td>KOH (3:1)</td>
<td>-</td>
<td>Huang et al. (2014)</td>
</tr>
</tbody>
</table>

**ACs produced from the two-stage chemical activation process via pre-hydrolysis carbonization (GSHAC)**
<table>
<thead>
<tr>
<th>Source</th>
<th>Temperature</th>
<th>Time</th>
<th>N&lt;sub&gt;2&lt;/sub&gt; Flow</th>
<th>KOH Ratio</th>
<th>KOH Concentration</th>
<th>O&lt;sub&gt;2&lt;/sub&gt; Absence</th>
<th>Yield</th>
<th>TG</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Commercial Sucrose</td>
<td>800 °C</td>
<td>3 h</td>
<td>-</td>
<td>0.73/0.79</td>
<td>-</td>
<td>Huang et al. (2014)</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Commercial Xylose</td>
<td>800 °C</td>
<td>3 h</td>
<td>-</td>
<td>0.25/0.83</td>
<td>-</td>
<td>Huang et al. (2014)</td>
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<tr>
<td>Golden shower</td>
<td>800 °C</td>
<td>4 h</td>
<td>-</td>
<td>0.50/0.68</td>
<td>-</td>
<td>790</td>
<td></td>
<td>This study</td>
<td></td>
</tr>
<tr>
<td>Commercial tapioca flour</td>
<td>800 °C</td>
<td>1 h</td>
<td>39.01</td>
<td>0.46/0.57</td>
<td>-</td>
<td>385</td>
<td></td>
<td>Pari et al. (2014)</td>
<td></td>
</tr>
<tr>
<td>Orange peel</td>
<td>600 °C</td>
<td>1 h</td>
<td>23.5</td>
<td>0.29/0.39</td>
<td>-</td>
<td>145</td>
<td></td>
<td>Fernandez et al. (2015)</td>
<td></td>
</tr>
</tbody>
</table>

*The ratio in parenthesis indicates the impregnation weight ratio of activating reagent to precursor.*
References


