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Preparation of Activated Carbon and Silica Particles from Rice Straw

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Supporting Information

**ABSTRACT:** An efficient three-step process using toluene/ethanol, NaClO₂, and KOH has been successfully devised to isolate pure cellulose from rice straw while generating two filtrates as activated carbon and silica precursors. The NaClO₂ dissolution filtrate contains oxidized lignin and hemicellulose as carbon precursors as well as sodium carbonates as activating agents for direct carbonization (800 °C) into highly porous (0.90 cm³/g), high specific surface area (997 m²/g), activated carbon particles (100–500 nm). The KOH dissolution filtrate contains mainly potassium silicate that could be precipitated by dilute acidified poly(ethylene oxide) and calcinated (500 °C) to pure, uniformly sized (100–120 nm), nonporous silica nanospheres. Deriving these additional activated carbon and silica particles along with nanocellulose creates advance materials while fully utilizing all major components in rice straw, the highest quantity agricultural crop byproduct in the world.

**KEYWORDS:** Activated carbon, Porous, Monodispersed silica, Green chemistry, Rice straw utilization.

## INTRODUCTION

Lignocellulosic biomass, such as agricultural crop residues, forestry byproducts, and municipal waste, is a rich source of renewable energy and materials. Lignocellulosic materials have been converted to biofuel such as ethanol, hydrogen, and other combustible gases, as well as nanocellulose, carbon, and silicon-based materials. Cellulose nanocrystals and nanofibrils have been isolated from various major agricultural residuals including rice straw, wheat straw, and soy hulls. Direct thermal processing of various biomass has also generated charcoals, activated carbon, and silicon-based advanced materials including mesoporous silica as well as silicon carbide and nitride. Simultaneous derivation of parallel products from specific biomass for full utilization has not been given much attention.

Rice straw represents the largest agricultural byproduct around the world. Rice is the largest cereal crop and the highest valued agricultural commodity ($187 billion in 2011) in the world. Although third in quantity (723 million MT in 2011) behind sugar cane and maize, rice production generates the highest quantity of byproduct as rice straw accounts from 1 to 1.5 kg per kg of rice grain harvested. Direct use has presented some shortcomings as rice straw is a marginal feed compared with other cereal straw and causes severe furnace fouling and ash production when burned to produce steam. Other utilization of rice straw has mainly involved single product development by converting certain components while removing others employing biochemical, chemical, and/or thermal processes. Ethanol production was improved by enzymatic saccharification of cellulose and hemicellulose, while hydrogen-rich gas production was made efficient via microwave-assisted pyrolysis of rice straw. Long, highly crystalline, cellulose fibers have been extracted from rice straw via alkali and enzymatic methods. Activated carbons were prepared from rice straw by KOH activation and carbonization at 800–900 °C or preoxidation at 200 °C and (NH₄)₂HPO₄ activation at 700 °C to reach 1900 and 1150 m²/g specific surface areas, respectively, comparable to commercially available activated carbon products. Silica nanospheres were prepared from alkali dissolution of burned straw ashes and then acid precipitation to better control nanoparticle sizes from 16 to 100 nm. Uniform nanodisks were also prepared by sulfuric acid precipitation of dissolved silica from rice straw ashes, followed by freeze-drying. Silicon carbide and nitride nanorods were fabricated by direct pyrolysis of rice straw under nitrogen from 1400 to 1800 °C.

The significant lignocellulotics, that is, 32–47% cellulose, 19–27% hemicellulose, and 5–24% lignin, as well as 7–20% silica and trivial amount of waxes and minerals in rice straw present opportunities for simultaneous development of multiple products. We have developed a simple approach to isolate cellulose, lignin/hemicelluloses, and silica components in rice straw with minimal chemical and energy input. Pure cellulose was extracted from rice straw via efficient NaClO₂–KOH process with at least 36% yield, where dewatering in 2:1 v/v toluene/ethanol extraction was followed by lignin removal via acidified NaClO₂ and then hemicellulose and silica isolation by KOH. Cellulose nanocrystals and nanofibrils have been derived from pure rice cellulosics via sulfuric acid hydrolysis and (TEMPO)-mediated oxidation, respectively, and then assembled into fibrous and porous matrices.

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The goal of this work was to develop additional advanced materials from the as-derived extracts of two dissolution streams in isolating pure cellulose toward utilization of all major rice straw components, that is, lignin, hemicelluloses, and silica. NaClO2 and KOH were used as the former is a strong oxidant that could break the strong bonding among the lignocellulosics, and the latter could dissolve silica in rice straw. The NaClO2 dissolution stream from the dewaxed rice straw contains oxidation products of lignin and hemicellulose as well as sodium byproducts. As lignin and hemicelluloses were intrinsically bound to each other and thus very difficult to be completely separated without sacrificing one or another to soluble fragments, it is advantageous and economic to use this lignin/hemicelluloses mixture together as a carbon source, while sodium salts already present could serve as the activating agents to produce porous structures without needing further addition of chemicals. The KOH dissolution stream from the dewaxed rice straw contains oxidation products of lignin and hemicellulose as well as sodium byproducts. Activation of these two precursors could be thermally converted to carbon and silica products via a single-step pyrolysis and calcinations at 800 and 500 °C, respectively.

**EXPERIMENTAL DETAILS**

**Chemicals.** Rice straw (Calrose variety) used in this study was from the 2009 harvest in the Sacramento valley in northern California. Toluene (C₆H₅CH₃, ACS grade, Fisher Scientific), ethanol (CH₃CH₂OH, anhydrous, histological grade, Fisher Scientific), sodium chloride (NaClO₂, 80%, Fluka), glacial acetic acid (CH₃COOH, 99.7%, ACS GR, EMD), poly(ethylene oxide) (PEO) (Mₚ = 600 kDa, Sigma-Aldrich), and potassium hydroxide (KOH, 85%, EM Science) for fractionating rice straw components were used as received. Water used was purified by a Milli-Qplus water purification system (Millipore Corporate, Billerica, MA). All concentration and yield percentage values were based on weight unless otherwise specified.

**Preparation of Activated Carbon and Silica Particles from Rice Straw.** Fractional extraction of lignin/hemicelluloses and silica from rice straw was first performed by the NaClO2 treatment as shown in Figure 1. Rice straw was washed thoroughly with water to rid of dirt, dried, and then milled (Thomas-Wiley Laboratory Mill model 4, Thomas Scientific, U.S.A.) to pass through mesh 60. Rice straw powders were Soxhlet extracted with 2:1 toluene/ethanol (v/v) at 55 °C for 24 h to remove all lipophilic and hydrophilic nonstructural components (Figure 1). The dewaxed rice straw powder was placed in 1.4 wt % NaClO2 under acidic condition (pH ~5 adjusted by 10% acetic acid) at a 15 mL/g liquid-to-solid ratio at 70 °C for 6 h and filtered to yield holocellulose/silica and filtrate 1. α-Cellulose was isolated from holocellulose by extracting with 5 wt % KOH at a 20 °C for 24 h to give pure cellulose and dissolved silica and hemicelluloses in filtrate 2. Both filtrate 1 and 2 were then concentrated by heating at 90 °C to half their volumes. The remaining filtrates 4 and 5 contained mostly water with very little solutes. Ethanol in filtrate 4 may be recovered by distillation.

**Preparation of Activated Carbon.** Ethanol was added to the concentrated filtrate 1 at 3 times its volume to precipitate alkali-soluble lignin together with some hemicelluloses (LH). The LH powders were Soxhlet extracted with 2:1 toluene/ethanol (v/v) at 55 °C for 24 h to remove all lipophilic and hydrophilic nonstructural components (Figure 1). The dewaxed rice straw powder was placed in 1.4 wt % NaClO2 under acidic condition (pH ~5 adjusted by 10% acetic acid) at a 15 mL/g liquid-to-solid ratio at 70 °C for 6 h and filtered to yield holocellulose/silica and filtrate 1. α-Cellulose was isolated from holocellulose by extracting with 5 wt % KOH at a 20 °C for 24 h to give pure cellulose and dissolved silica and hemicelluloses in filtrate 2. Both filtrate 1 and 2 were then concentrated by heating at 90 °C to half their volumes. The remaining filtrates 4 and 5 contained mostly water with very little solutes. Ethanol in filtrate 4 may be recovered by distillation.

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powders were heated to 800 °C and held for up to 0.5 h, all under flowing N₂ at 100 mL/min. Finally, they were cooled to ambient temperature in 12 h. The particles were washed with 5% HCl and water to remove residual salts and other small hydrocarbon impurities and then dried at 105 °C for 0.5 h to yield activated carbon (AC).

### Preparation of Silica Particles

Acidified PEO solutions at 0.2%, 0.35%, 0.5%, and 1% were prepared by dissolving 0.04, 0.07, 0.1, and 0.2 g of PEO, respectively, in 20 g of 2% HCl and stirred for 6 h. Concentrated filtrate 2 was added slowly to each acidified PEO aqueous solution to form a milky white mixture and centrifuged (Centrifuge 5804R, Eppendorf) at 5000 rpm for 15 min. The precipitate was then washed with water thoroughly and dried in a desiccator as silica and lignin/hemicelluloses/PEO (SHLP). The dried SHLP powder was placed in a quartz tube (2 cm inner diameter) and calcinated under flowing air (100 mL/min) in a furnace (Mini-Mite, Lindberg/Blue). The sample was heated at 10 °C/min to 105 °C and then 500 °C; the sample was held for 0.5 h at each temperature. The obtained silica after calcination was cooled under flowing air (100 mL/min) to room temperature in 12 h. Filtrate 4, SHLP, and silica were referred to those obtained at 0.35% PEO unless stated otherwise.

### Analytical Methods

The yields were calculated by the percentage of extract or product mass over the original rice straw mass, both 0.1 mg accuracy (BP 300S, Satorius). The aqueous filtrates from rice straw isolation shown in Figure 1 were precipitated as precursors to be subsequently converted to AC and silica particles, respectively. The compositions and structures of both filtrates, their precipitates, and final products were examined by UV–vis, FTIR, and elemental analysis to determine their compositions and to assess the isolation process.

#### Chemical Structures of Extracts and Final Products

NaClO₂–KOH process for isolating rice straw components involved three steps, yielding pure cellulose as well as filtrates 1 and 2 (Figure 1a). The washed and dried rice straw was refluxed in a 2:1 toluene/ethanol (v/v) ratio at 55 °C for 24 h to yield 94.7% dewaxed rice straw and a green-yellow distillate containing surface oils, pigments, and possibly organic soluble lignin. The dewaxed rice straw was then treated by 1.4% NaClO₂ at pH 5 adjusted by acetic acid at 70 °C for 6 h and then 5% KOH at 70 °C for 24 h to obtain pure cellulose as well as the NaClO₂ and alkaline dissolution streams, that is, filtrates 1 and 2, respectively. Adding ethanol to filtrate 1 under the basic condition precipitated the dissolved lignin/hemicelluloses (LH) at 5.7% of the original rice straw mass (Figure 1b). Adding the basic filtrate 2 to the dilute acidified PEO precipitated silica along with remaining lignin/hemicelluloses (SHLP) at similar yields of 22.1 – 23.7%, increasing to 0.2 – 1% PEO concentrations (Figure 1c). At 0.35% PEO, the silica/hemicelluloses/lignin (SHL) yield was 20.7%, assuming all PEO precipitated.

#### UV–Vis Spectra of the Filtrates

The UV–vis spectrum of filtrate 1 exhibited strong broad absorbance below 300 nm (Figure 2), ascribing to partially oxidized and/or decomposed lignin from NaClO₂, possibly a polylignol dehydrogenative copolymer of sinapyl alcohol, coniferyl alcohol, p-coumaryl alcohol, and hydroxycinnamic acid esters. Filtrate 2 showed reduced yet clear UV absorbance below 300 nm, indicating the

\[
V_{mp} = \frac{(S_n - S_{n+1}) \times (t_n + t_{n-1})}{2} \times 15.47
\]

where \(S_n\) and \(t_n\) are the surface area derived from the slope of tangent and the thickness of absorbed layer at the \(n\) point in the \(t\)-plot, respectively, and 15.47 was the constant of converting the gas volume to liquid volume at STP.

### RESULTS AND DISCUSSION

#### Yields and Efficiency of Sodium Chlorite Isolation

The NaClO₂–KOH process for isolating rice straw components involved three steps, yielding pure cellulose as well as filtrates 1 and 2 (Figure 1a). The washed and dried rice straw was refluxed in a 2:1 toluene/ethanol (v/v) ratio at 55 °C for 24 h to yield 94.7% dewaxed rice straw and a green-yellow distillate containing surface oils, pigments, and possibly organic soluble lignin. The dewaxed rice straw was then treated by 1.4% NaClO₂ at pH 5 adjusted by acetic acid at 70 °C for 6 h and then 5% KOH at 70 °C for 24 h to obtain pure cellulose as well as the NaClO₂ and alkaline dissolution streams, that is, filtrates 1 and 2, respectively. Adding ethanol to filtrate 1 under the basic condition precipitated the dissolved lignin/hemicelluloses (LH) at 5.7% of the original rice straw mass (Figure 1b).

Adding the basic filtrate 2 to the dilute acidified PEO precipitated silica along with remaining lignin/hemicelluloses (SHLP) at similar yields of 22.1 – 23.7%, increasing to 0.2 – 1% PEO concentrations (Figure 1c). At 0.35% PEO, the silica/hemicelluloses/lignin (SHL) yield was 20.7%, assuming all PEO precipitated.
The presence of some alkaline-soluble lignin and incomplete lignin removal in the previous NaClO₂ step. The broad absorption peak in the 360 nm region of the filtrate 2 spectra is consistent with the expected alkaline-soluble lignin, possibly various lignin derivatives of o,p-dihydroxystilbenes, α-carbonyl phenolics, esters of p-coumaric, and ferulic acids, as well as charge-transfer complexes from the carbonyl and carbonyl-conjugated heteroaromatic compounds. Filtrate 3 showed very little absorbance below 300 nm, indicating effective precipitation of lignin in LH by ethanol. Filtrate 4 also exhibited reduced peak intensity below 300 nm, showing the presence of a small amount of alkaline-soluble lignin in this final filtrate. The UV-vis spectrum suggested that most lignin in rice straw was extracted by NaClO₂ dissolution in silica, leaving yet a small residual lignin in ethanol precipitation in LH, while some lignin present in the lignin-rich LH and silica/hemicelluloses, and PEO SHLP precipitated from reaction with the strongly oxidative NaClO₂. precipitated from chains, and aromatic skeleton vibration. Therefore, LH C aliphatic hydroxyl and ether groups. The broad band at 1630 cm⁻¹ could be from moisture overlapping with various C=O stretching, C=C stretching in phenylpropanoid side chains, and aromatic skeleton vibration. Therefore, LH precipitated from filtrate 1 consisted mainly of oxidized lignin from reaction with the strongly oxidative NaClO₂, SHLP precipitated from filtrate 2 with diluted PEO showed characteristic peaks of silica, lignin, hemicelluloses, and PEO (Figure 3). Silica was clearly evident by the prominent Si–O–Si asymmetric and symmetric stretching peaks at 1090 and 460 cm⁻¹, respectively, as well as a Si–O deformation peak at 795 cm⁻¹. The presence of lignin was evident by the benzene C=C stretching peak at 1460 cm⁻¹. However, the peak intensity decreased greatly compared to that of LH, suggesting the reduced lignin composition in SHLP. The broad shoulder at 1205 cm⁻¹ was ascribed to the various C–O–C stretching from hemicelluloses and PEO. The broad shoulder at 1640 cm⁻¹ was from moisture overlapping with C=C stretching and various esters and ketone structures, such as β-ketone ester, α-β unsaturated ketone, and β diketone (enol form) in hemi-celluloses. The broad 3430 cm⁻¹ peak as well as minor peaks at 2930 and 2835 cm⁻¹ were ascribed to hydroxyls from moisture, lignin/hemicelluloses, and silica surfaces.

The pyrolytic product of LH from heating at 800 °C showed little characteristic FTIR peaks of either lignin or hemicelluloses as expected. The broad OH stretching peak around 3440 cm⁻¹ greatly decreased in intensity compared to LH, clearly showing the loss of hydroxyls and is consistent with transformation of hydrophilic lignin/hemicelluloses to hydrophobic carbon. The only two small peaks at 1454 and 1380 cm⁻¹ were ascribed to aliphatic C–H bending. Thus, the FTIR of pyrolyzed LH is consistent with conversion to carbon with few lignin and hemicelluloses features.

The FTIR spectrum of SHLP calculated at 500 °C showed only silica characteristic peaks, that is, Si–O–Si asymmetric and symmetric stretching at 1080 and 460 cm⁻¹, respectively, and Si–O deformation at 780 cm⁻¹, as well as the broad hydroxyl stretching peaks at 3440 and 1630 cm⁻¹, indicating absorbed moisture or the hydrophillic nature of silica. None of the lignin, hemicelluloses, and PEO characteristic peaks was observed, confirming their removal upon calcination.

UV–vis results clearly showed that lignin-rich LH and silica/hemicelluloses-rich SHLP were successfully isolated in filtrates 1 and 2, respectively, while FTIR confirmed that the isolated lignin in LH and hemicelluloses in SHLP were oxidized and degraded by the oxidative NaClO₂ and then thermally converted to carbon and silica, respectively.

**Elemental Analysis of Extracts.** The elemental compositions by EDX show LH to consist of 38.0% C, 42.8% O, 18.6% Na, and 0.6% Si (Table 1). The high Na and O contents suggested LH contained oxy-salts of sodium, possibly sodium carbonates, oxidative products of lignin/hemicelluloses, and acetic acid in the NaClO₂ step. The continuous evolution of odorless bubbles when adding crude LH powder into dilute aqueous HCl indicated gaseous products and was consistent with the presence of carbonate salts in crude LH. To further investigate the compositions of inorganic salts, LH was calcinated at 500 °C for 6 h. The yellow color of LH turned to a white color after calcination (Figure S1, Supporting Information) and was shown by EDX to have the elemental composition of Na₂CO₃ (Figure S1, Supporting Information), confirming the presence of sodium carbonates in crude LH. AS LH was precipitated from aqueous solution, sodium carbonate should exist in the form of monohydrate after drying at 60 °C. Under this assumption, monohydrate sodium carbonate
content in the crude LH precipitate would be 50.1%, leaving 49.9% to be lignin and hemicelluloses (LH). Such a unique composition allowed LH to be directly pyrolyzed into AC, without the need to add additional activating chemicals, making this pathway superior than previously reported approaches. SHLP consisted of 16.6% C, 51.7% O, and 29.7% Si, showing its elemental compositions to be mainly silica (64%) and lignin/hemicelluloses/PEO (36%). This three-step toluene/ethanol, NaClO₂, and KOH isolation process isolated 5.3% waxes and organic extracts, 36% highly pure cellulose, 3% LH, and 20.7% SHL, or 65% of precursors, leaving about 35% rice straw components as soluble from NaClO₂ oxidation and KOH dissolution in the remaining filtrates.

The chars pyrolyzed from LH after dilute HCl washing consisted of 81.7% C, 15.8% O, and 2.5% Si, confirming substantial carbon with little silica impurities. After calcinating SHLP at 500 °C for 0.5 h, only 47% Si and 53% O were detected, while no carbon was present. This mass percentage is equivalent to a 1:2 Si/O atomic ratio or that of pure silica.

**Thermal Properties of Extracts.** The thermograms of LH showed a very sharp exothermic peak at 60 °C and a small exotherm around 105 °C (Figure 4a) with respective 24.4% and 5.3% mass losses (Figure 4b), reflecting the transition from sodium carbonate decahydrate to monohydrate as well as moisture loss from lignin and hemicelluloses. The endotherm at 300 °C is attributed to the decomposition of hemicelluloses, while two exotherms at 430 and 475 °C were likely from decomposition and further charring of lignin, corresponding to the major 19.2% mass loss, that is, from 70.7% at 105 °C to 51.5% at 550 °C. The solid mass was lowered to 47.6% when heated to 800 °C initially and slightly lowered to 45.6% when held for additional 30 min.

The thermal analysis further supported the compositions derived from EDX that the crude LH at ambient temperature was a mixture of sodium carbonate monohydrate and decahydrate as well as lignin/hemicelluloses. Assuming the mass loss at 105 °C is solely caused by the transformation of sodium carbonate monohydrate to the anhydrous form, the weight percentages of sodium carbonate monohydrate and Na in crude LH were estimated to be 48.3% and 17.9%, respectively (eqs 1 and 2), very close to the 50.1% estimated from EDX elemental analysis. These values are slightly higher than the atomic compositions due to the missing hydrogen in the EDX. The composition of crude LH precipitate at 105 °C would thus be estimated to be 44.4% anhydrous sodium carbonate and 55.6% lignin/hemicelluloses (eq 3). Therefore, the final pyrolyzed product could be a mixture of lignin char and various forms of sodium, sodium carbonate, sodium oxide, and elementary sodium, all of the latter removed in the wash to obtain 1.3% activated carbon (AC) from the starting rice straw.

SHLP showed an endothermic shoulder below 105 °C (Figure 4c) accompanied by a slight 4% mass loss from moisture (Figure 4d). A broad exothermic peak centered at 350 °C was observed along with a significant 33% mass loss, that is, from 96% at 105 °C to 63% at 500 °C, due to thermal decomposition of hemicelluloses/lignin/PEO. This quantity was consistent with the 64% silica from the EDX analysis. When held at 500 °C for 0.5 h, the DSC thermograph baseline shifted endothermically, while the solid mass slightly decreased from 63% to 61.5%, indicating further combustion of the residual carbon char, obtaining 14% pure silica from the starting rice straw.
On the basis of the TGA analysis, the LH component contained 51% sodium salt or about 2.8% yield of lignin/hemicelluloses from NaClO2 dissolution of rice straw (e.g., filtrate 1). SHLP consisted of 61.5% silica, 29.3% lignin/hemicelluloses, and 9.2% PEO or 14% silica and 6.7% lignin/hemicelluloses yields from the KOH dissolution stream (e.g., filtrate 2). From these and our prior report on cellulose,3 this three-step toluene/ethanol acidic NaClO2−KOH process has shown to isolate 5.3% waxes and organic extracts, 36% celluloses, 9.5% lignin/hemicelluloses, and 14% silica from rice straw, that is, 65% of rice straw. The lignin/hemicelluloses and silica were eventually converted to 1.3% AC and 14% pure silica.

Surface and Morphology of Activated Carbon and Silica. The LH powders were gray in color and appeared as packed particulates in over 20 μm sizes (Figure 5a). After pyrolysis at 800 °C for 30 min, the obtained AC appeared as irregularly shaped porous clusters of 100–500 nm-sized...
442 particles (Figure 5b), which are much smaller than the ACs in
443 the previous studies.16−18 These much shorter diffusion lengths
444 contribute to faster adsorption rate, which is a desirable
445 property of AC absorbent. The TEM images showed the semi-
446 crescent AC particles had about a 450 nm Feret diameter. The
447 randomly distributed slit-shaped micropores and small
448 mesopores were observed within the particle (Figure 5c).
449 Such porosity was generated by sodium carbonate activation as
450 well as pyrolytic decomposition of hemicelluloses and removal
451 of sodium byproducts from washing.
452 The SEM showed smaller and more narrowly distributed
453 SHLP particles with increasing PEO concentrations (Figure S2,
454 Supporting Information). Semi-spherical particles from 100 to
455 200 nm sizes were obtained at 0.2% PEO. With increasing PEO
456 concentrations to 0.35%, more uniformly sized nanospheres
457 between 100 and 150 nm were formed (Figure 5d−f), possibly
458 due to better capping of particles preventing them from
459 aggregating and/or growing into larger particles. At 0.5 wt %
460 PEO and above, however, the particles became irregularly
461 shaped and polydispersed in sizes less than 50 nm, possibly
462 from easy sintering during calcination. Only the SLHP particles
463 precipitated from 0.35% acidified PEO remained similar in size
464 after calcinations. Such a PEO precipitation approach has
465 proven to be fast and effective, without the need for the time-
466 Figure 6. Nitrogen adsorption−desorption isotherms of (a,b,c,d) of LH and AC (800 °C, 0.5 h, N₂) and (e,f) SHLP and silica (500 °C, 0.5 h, air):
(a,e) isotherm, (b) BJH neck-size distribution, (c,f) BJH pore/cavity width distribution, and (d) micropore hydraulic diameter distribution.

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Table 2. Physical Properties of LH, AC, SHLP, and Silica Deduced from N₂ Adsorption–Desorption at 77 K

<table>
<thead>
<tr>
<th></th>
<th>LH</th>
<th>AC</th>
<th>SHLP</th>
<th>Silica</th>
</tr>
</thead>
<tbody>
<tr>
<td>BET surface area (m²/g)</td>
<td>3</td>
<td>997</td>
<td>7.9</td>
<td>7.2</td>
</tr>
<tr>
<td>BJH adsorption cumulative surface area between 1.7 and 300 nm width (m²/g)</td>
<td>3</td>
<td>249</td>
<td>6.6</td>
<td>6.1</td>
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<tr>
<td>single-point desorption pore volume (cm³/g)</td>
<td>0.006</td>
<td>0.90</td>
<td>0.015</td>
<td>0.014</td>
</tr>
<tr>
<td>BJH adsorption cumulative volume of pore between 1.7 and 300 nm width (cm³/g)</td>
<td>0.006</td>
<td>0.58</td>
<td>0.020</td>
<td>0.019</td>
</tr>
<tr>
<td>t-plot-derived micropore surface area between 0.7 and 2 nm width (m²/g)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>t-plot-derived micropore volume (cm³/g)</td>
<td>0</td>
<td>0</td>
<td>0</td>
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