A New Method for Solid Acid Catalyst Evaluation for Cellulose Hydrolysis

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Abstract: A systematic and structure-agnostic method for identifying heterogeneous activity of solid acids for catalyzing cellulose hydrolysis is presented. The basis of the method is preparation of a supernatant liquid by exposing the solid acid to reaction conditions and subsequent use of the supernatant liquid as a cellulose hydrolysis catalyst to determine the effects of in situ generated homogeneous acid species. The method was applied to representative solid acid catalysts, including polymer-based, carbonaceous, inorganic, and bifunctional materials. In all cases, supernatant liquids produced from these catalysts exhibited catalytic activity for cellulose hydrolysis. Direct comparison of the activity of the solid acid catalysts and their supernatants could not provide unambiguous detection of heterogeneous catalysis. A reaction pathway kinetic model was used to evaluate potential false-negative interpretation of the supernatant liquid test and to differentiate heterogeneous from homogeneous effects on cellulose hydrolysis. Lastly, differences in the supernatant liquids obtained in the presence and absence of cellulose were evaluated to understand possibility of false-positive interpretation, using structural evidence from the used catalysts to gain a fresh understanding of reactant–catalyst interactions. While many solid acid catalysts have been proposed for cellulose hydrolysis, to our knowledge, this is the first effort to attempt to differentiate the effects of heterogeneous and homogeneous activities. The resulting supernatant liquid method should be used in all future attempts to design and develop solid acids for cellulose hydrolysis.

Keywords: biomass; cellulose; cellulose hydrolysis; solid acid; solid acid catalyst

1. Introduction

As a major constituent of lignocellulosic biomass, cellulose is the planet’s most abundant source of renewable carbon [1]. Efficient conversion of cellulose to its constituent monomer, glucose, or other small molecules is the gateway to production of cost-effective second-generation biofuels and biochemicals [2,3]. Unfortunately, cellulose is resistant to depolymerization [4], and converting it into soluble products requires energy-intensive pretreatments [5–10], harsh conditions [11–16], excess enzymes [17–19], or expensive solvents [20,21] that contribute disproportionately to biofuel production costs [2,22].

Dilute acid pretreatment followed by enzyme hydrolysis is the most commercially advanced method of converting cellulose present in biomass into glucose [22]. Dilute acid pretreatment consists of hydrolyzing and removing the hemicellulose that protects the underlying cellulose, while enzymes depolymerize the remaining cellulose to produce glucose [23–26]. Unfortunately, sequential dilute acid pretreatment and enzyme hydrolysis
of cellulose for production of ethanol remain prohibitively expensive compared with petroleum fuels [22].

In the past several years, solid acids have been proposed as alternatives to homogeneous acids and enzymes for catalyzing cellulose hydrolysis [27,28]. Unlike homogeneous acids and enzymes, solid acids can theoretically be recycled with potential for corresponding reductions in cellulose conversion costs. However, in typical reaction conditions (>120 °C, >10 h), both the catalyst and the cellulose substrate are solids, and the mechanism of solid–solid catalytic action has not been elucidated, hindering rational catalyst development efforts [29].

Traditionally, catalyst design emphasizes development of structure–activity relationships [30], and this approach has also been adopted for design of solid acid catalysts for cellulose depolymerization [27]. Structure–activity data have then been combined with carbohydrate adsorption data to propose a mechanism that describes depolymerization as a two-step process involving solid–solid binding, followed by catalytic hydrolysis [31–35]. Bifunctional catalysts, possessing both carbohydrate-binding and acid groups, have been suggested as especially effective for cellulose hydrolysis [31,35–37]. While the bifunctional catalyst hypothesis may have a precedent [38,39], it suffers from the need for extensive structural catalyst characterization, ideally under reaction conditions or at least after use [40–43].

On the other hand, the field of solid acid-catalyzed cellulose hydrolysis may be impacted by confirmation bias where negative results are not published, thereby erroneously promulgating the bifunctional binding hypothesis [44]. Interestingly, some studies indicate that some of the most promising bifunctional solid acids release homogeneous acid species under cellulose hydrolysis conditions [40,41,43]. The result is parallel hydrolysis by solid acids (as desired) and homogeneous acids (which is undesired). Distinguishing between homogeneous or heterogeneous reaction promotion can be difficult, especially since homogeneous acids released during reaction have the potential to completely overwhelm the sought-after effect of the solid acid.

While the impact of homogeneous acid on cellulose hydrolysis has been acknowledged [40,45], the prevalence of the phenomenon for different catalyst types is not known, and no approach has yet been established to quantify the effect or even identify when it is present [46]. Despite the evidence of homogeneous acid hydrolysis [40], studies continue to propose new solid materials for catalyzing cellulose depolymerization, usually with incomplete characterization of the effects of homogeneous acids released under reaction conditions [42,47–50]. Accordingly, this raises the important question: how can homogeneous contributions to cellulose hydrolysis activity be differentiated from heterogeneous ones? A method for differentiating homogeneous from heterogeneous activity could be applied universally to new catalysts during the early stages of development, thereby helping to allocate resources to only the most promising materials. Ideally, differentiation should not depend on structural analysis, which can be costly and ultimately inconclusive given that even the release of what could be considered trace species can result in catalytic effects without impacting catalyst structure [45], instead consisting of a generalized approach that any lab can perform.

Accordingly, we aimed to develop a structure-agnostic approach that can be used to (1) identify catalysts with cellulose hydrolysis activity and minimal or negligible release of homogeneous acids during reaction, (2) account for the hydrolysis activity of the homogeneous acids when they are present, and (3) be applied regardless of reaction conditions. Once the effects of the homogeneous acid are known, then the remaining hydrolysis activity, if any, can be attributed to the solid acid. Unlike structure–property methodologies, a structure-agnostic approach does not rely on exhaustive structural characterization and can, therefore, avoid false structure–activity correlations made by characterizing a catalyst incompletely or under conditions other than those relevant to reaction [35,40]. A structure-agnostic procedure can be used as a screening tool for identification of promising materials.
Only after a promising candidate with heterogeneous activity has been identified is its
detailed characterization initiated, thus saving time and effort.

A structure agnostic catalyst evaluation methodology must satisfy several criteria
to be useful to the community. First, and most obviously, it needs to reliably separate
the effects of the homogeneous and solid acids on the observed cellulose hydrolysis and
require a minimum of additional experiments to do so. Second, the methodology should
use techniques that are accessible to the community, contrasting with characterization
techniques, many of which are prohibitively expensive or time-consuming and not available
in every lab. Conversion (or yield) measurements are the obvious choice, since all labs
working in this area will have the capability of measuring cellulose conversion and/or
glucose yields. Third, the method should be broadly applicable to all catalyst types and
reaction conditions.

The structure-agnostic approach for differentiating homogeneous and heterogeneous
activity must, therefore, be compatible with existing experimental methods. Different
methodologies have been applied for the catalytic evaluation of solid acids, as shown in
Scheme 1. The most widely used approach (Scheme 1a) is mixing cellulose and the solid
catalysts in a batch reactor, heating to reaction temperature, and carrying out the reaction
for a specified period. Clearly, this method cannot distinguish between heterogeneous and
homogeneous activity since both types of catalysts will be present in the reaction mixture,
as the solid catalyst degrades to generate soluble products.

Generation of soluble catalytic species during cellulose hydrolysis can be suppressed
by first exposing the solid catalyst to hydrothermal conditions more severe than those used
for the reaction itself [33,51]. This strategy is shown as Scheme 1b. The assumption is
that the harsh pretreatment will remove thermally and/or hydrothermally labile catalyst
components from the solid material [33,51], and the resulting solid is more hydrothermally
stable than the original. In this respect, the pretreatment can be viewed as a final step in
catalyst synthesis, with its objective being to improve catalyst stability. The disadvantage
to this method is that the pretreated catalyst may still release soluble acids under reaction
conditions, meaning that the potential contribution from homogeneous species is not
eliminated, and that structural characterization is still required.

A permutation of the catalyst pretreatment approach is repetitive recovery and reuse
of the catalyst [49,50,52,53]. Each use may remove a fraction of the potential soluble acids,
leaving most of them on the catalyst, resulting in a slow decrease in catalyst activity.
The catalyst must still be characterized before and after use, making the approach no
more definitive than simply using the catalyst a single time and characterizing it. Both
the hydrothermal pretreatment and catalyst reuse approach are prone to “false positives”,
i.e., falsely attributing meaningful heterogeneous activity to materials that do not possess
it, due to the unjustified assumption that the effects of homogeneous species have been
suppressed or eliminated.

A third option is shown in Scheme 1c [40,45]. Here, the focus shifts from characterizing
the catalyst itself to understanding the supernatant liquid obtained after hydrolysis. First,
the apparent activity of the solid catalyst is determined by measuring cellulose conversion
and/or soluble product yield as usual under a set of predetermined reaction conditions.
In a separate set of experiments, the fresh solid acid is treated under the same hydrothermal
conditions used for hydrolysis, now in the absence of cellulose. The supernatant liquid
from this test is then recovered and can be analyzed for putative catalytic species (e.g., H\(^+\))
before it is used as the liquid phase for cellulose hydrolysis under the same conditions as
before, this time in the absence of solid acid catalyst. Cellulose conversion and/or soluble
product yields are then measured after the supernatant liquid test for comparison with
results obtained using the solid acid.
Scheme 1. Experimental approaches for analyzing the apparent cellulose hydrolysis activity of the solid acid catalyst. In (a), a typical activity test consists of mixing cellulose, solid acid catalyst, and water, after which the temperature is elevated to carry out hydrolysis. In (b), the solid acid catalyst is pretreated at hydrothermal conditions that exceed the severity of those used for cellulose hydrolysis; after pretreatment, the catalyst is separated and used for cellulose hydrolysis test. In (c), the catalyst is treated at the same hydrothermal conditions used for hydrolysis, but in the absence of cellulose; the supernatant is separated and used for cellulose hydrolysis to determine the activity of homogeneous acid species generated. Red color of the liquid indicates potential presence of homogeneous catalysts generated by degradation of the solid acid, while blue is pure water.

In this work, we evaluate the use of the supernatant liquid obtained from hydrothermal treatment of solid acid catalysts as the basis of a structure-agnostic method for identifying heterogeneous cellulose hydrolysis activity. A series of representative catalysts was selected, and their activity for cellulose hydrolysis was measured at standard conditions chosen to achieve approximately 5–20% product yield. Solid acids were placed in liquid water under the same reaction conditions as used for hydrolysis, but in the absence of cellulose; the supernatant liquids from these reactions were recovered, filtered to remove catalyst particles, and then used as the reaction medium for hydrolysis of a new batch of cellulose at the same conditions as the other tests. A reaction engineering time study combined with modeling of the homogeneous acid activity was performed for a subset of these catalysts as an approach to determine whether “false negative” interpretations can be identified. Lastly, the effect of reactant–catalyst interactions on the release of homogeneous
catalysts was examined for representative catalysts. The results from this study can be used by the community in future work to develop solid acid catalysts with heterogeneous activity for cellulose hydrolysis and address the culture of reporting potentially interesting but possible misinterpreted findings obtained from new materials.

2. Materials and Methods

2.1. Materials

Avicel PH-101 cellulose, Amberlyst-15, H$_2$SO$_4$ (98%), 0.1 M HCl, 0.1 M NaOH, cellobiose, glucose, xylose, hydroxymethyl furfural (HMF), levulinic acid, and formic acid were purchased from Sigma-Aldrich (Burlington, MA, USA). Sulfated zirconia, Norit, and HZSM-5 (Si/Al = 38) were purchased from MEL Chemicals (Flemington, NJ, USA), Cabot Corporation, and ACS Material (Pasadena, CA, USA), respectively. $^{13}$C-enriched glucose was purchased from Sigma-Aldrich.

2.2. Catalysts Preparation

2.2.1. Sulfonated Humins (SH)

Xylose (20 g) and 98% H$_2$SO$_4$ (7 mL) were mixed with deionized water (17.7 MΩ·cm) to create a 100 mL solution with a 1:1 molar ratio of sugar to acid. This was then stirred at room temperature for 30 min. The resulting solution was then placed inside a 160 mL Teflon vessel, which was deposited into an aluminum autoclave for 24 h at 120 °C. The resulting mixture was allowed to cool for 12 h at room temperature and then washed with a 300 mL equimolar mixture of DI water and ethanol. The solid char phase was separated from the aqueous phase via vacuum filtration and dried for 24 h at 65 °C.

2.2.2. Sulfonated Activated Carbon (SAC)

Norit activated carbon was sulfonated in a similar fashion to a procedure used by Foo and Sievers et al. [33] Briefly, 10 g of Norit SX-1 was soaked in 500 mL of deionized water overnight, after which it was filtered and dried at 65 °C overnight. The activated carbon was then mixed with 78 mL of deionized water and 54 g of 98% H$_2$SO$_4$ and put in an autoclave. The mixture was placed in a preheated oven at 200 °C and allowed to react for 24 h, after which the autoclave was cooled in an ice bath. Following the treatment, the solids were filtered and washed twice with 1800 mL of deionized water for 24 h to remove any residual H$_2$SO$_4$, after which the solid material was filtered again and dried at 65 °C.

2.2.3. Sulfated Zirconia (SZ)

Sulfuric acid-doped zirconia oxide (MEL Chemicals Inc, Flemington, NJ, USA) was activated by placing the material in a preheated furnace at 550 °C for 16 h.

2.2.4. HZSM-5

HZSM-5 with an Si/Al ratio of 38 (ACS Materials) was calcined at 550 °C for 16 h.

2.2.5. CMP-SO$_3$H-0.3

The bifunctional polymer solid acid bearing chloromethyl and sulfonic acid groups was prepared according to the procedure reported by Zuo et al. and reproduced by Tyufekchiev et al. [35,40].

2.3. Catalyst Wash

The catalysts were washed repeatedly with deionized water (17.8 MΩ·cm) to remove any soluble acidic species present on the catalyst. Briefly, 1.5 g of catalyst was washed with 50 mL of water in a centrifuge tube. The pH of the washout and the suspension was measured until the value stopped changing with further wash. After the wash, the catalysts were dried at 65 °C overnight.
2.4. Solid-State Titration

Solid-state titration of the catalysts was carried out according to Boehm’s procedure [54]. Briefly, predetermined amounts of 0.1 M NaOH standard solution and solid acid catalyst were mixed. The mixture was shaken and allowed to ion exchange for 24 h. Next, an aliquot was taken and acidified with a predetermined volume of standard 0.1 M HCl. The acidified solution was then titrated with 0.05 M NaOH, while the pH was monitored with a digital pH meter (Denver Instruments, model 225, Bohemia, NY, USA). The number of acid sites in the solid catalyst was then calculated.

2.5. Hydrothermal Treatment for Supernatant Generation

Solid acid catalyst (0.2 g) was mixed with deionized water (2 mL) and treated in hydrothermal conditions at 150 °C for 15 h (10 h for CMP-SO\textsubscript{3}H-0.3, Amberlyst-15, and sulfated zirconia). After the reaction, the pH of the liquid was measured; the liquid and the solid were centrifuged, and the liquid was extracted with a syringe. The supernatant liquid was then analyzed with ion chromatography (IC) to characterize the leached species and stored for cellulose hydrolysis tests.

2.6. Cellulose Hydrolysis

Cellulose was hydrolyzed to determine the activity of the solid acid catalyst and the leached homogeneous acid. Briefly, solid acid catalyst (0.2 g) was mixed with cellulose (0.1 g) and deionized water (2 mL) in a 15 mL glass reactor vial and sealed with a Teflon cap and Viton O-ring. The reactor vial was submerged in a heated oil bath, and the mixture was left to react for a pre-determined duration (10 h for CMP-SO\textsubscript{3}H-0.3, Amberlyst-15, and sulfated zirconia; 15 h for all other catalysts) to achieve 5–20% soluble product yield. The reaction temperature in the vial was accurately measured with a modified screw-top cap equipped with an Omega K-type thermocouple. Temperature measurements made within reaction vessels placed in multiple locations within the thermal batch indicated that the reaction temperature was 150 ± 2.5 °C. After the reaction, the vial was centrifuged, and the liquid was extracted with a syringe. The soluble products of the hydrolysis were analyzed with HPLC.

In a similar fashion, the activity of the supernatant was determined by mixing 2 mL of the liquid from hydrothermally treated solid catalyst with cellulose (0.1 g) and reacted at the same conditions as above. The soluble products were quantified with high-performance liquid chromatography (HPLC) (Agilent Technologies, Santa Clara, CA, USA).

2.7. Hydrolysate Analysis

Products of cellulose hydrolysis were quantified with high-performance liquid chromatography (HPLC) using an Agilent 1200 Series instrument equipped with a refractive index detector (RID) and a diode array detector (DAD) for quantifying carbohydrates and furanic compounds, respectively. A Rezex ROA-Organic acid column (Phenomenex) maintained at 35 °C was used for separation, and the mobile phase was deionized water at 0.6 mL/min. The RID detector operated at 35 °C and the DAD detection wavelength was set to 284 nm. Calibration curves for cellobiose, glucose, HMF, levulinic acid, and formic acid were prepared by determining detector response to standardized solutions with concentrations of 0.25, 0.5, 0.75, 1, 1.25, 1.5, 1.75, 2, and 2.5 g/L. Yields of products were calculated on a theoretical molar basis as follows: $\frac{m_p \times M_{gu}}{m_c \times M_p} \times 100\%$, where $m_c$ is the mass of cellulose, $m_p$ is the mass of the product determined by HPLC, $M_{gu}$ is the molecular weight of glucose unit in cellulose, and $M_p$ is the molecular weight of the product.
2.8. Ion Analysis
Anion concentrations in the supernatant were quantified with a Dionex ICS-2100 Ion Chromatograph equipped with an AERS 500 anion electrolytically regenerated suppressor and a DS6 heated conductivity cell (ThermoFisher Scientific, Waltham, MA, USA). Anions were separated on a AS153 250 mm column equipped with an IonPac AG 2 × 50 mm guard. The mobile phase was 38.00 mM KOH, and its flow rate was held at 0.25 mL/min. Separation was carried at a column temperature of 30 °C, and detection was performed at a cell temperature of 35 °C.

The hydronium ion content was measured to within ±0.01 pH units using a pH meter (Denver Instruments, model 225) equipped with a glass, Ag/AgCl reference, 0–14 pH probe (Symphony pH Probes), calibrated with buffers of pH of 4 and 7.

2.9. Kinetic Modeling
A kinetic model consisting of ordinary differential equations describing cellulose hydrolysis to glucose was developed to relate the time evolution of solubilized catalysts with products of cellulose hydrolysis, in the presence and absence of solid acid. On review of the literature [55–59], the kinetic models proposed by Saeman were selected for the framework as the temperature, acid concentration ranges, and cellulose particle size used in developing Saeman’s kinetic analysis were in the same range as those examined in the current study. The cellulose hydrolysis reaction was modeled using a first-order rate law:
\[
\frac{d[C]}{dt} = -k \times [C],
\]
where the expression for the reaction rate constant and its dependence on acid concentration is defined as
\[
k = A \times [H^+]^n \times \exp\left(\frac{-E_a}{2.303 \times R \times T}\right),
\]
with \(A = 1.73 \times 10^{19} \text{ min}^{-1} \cdot \text{M}^{-1.34}, n = 1.34, \) and \(E_a = 179.5 \text{ kJ} \cdot \text{mol}^{-1}\) [55].

The time evolution of homogeneous species was captured using a simple first-order model that accounted for the pH measured in a separate time study. Experimental data were fit to determine the average value and uncertainty of the degradation rate constant that led to formation of homogeneous catalyst as H⁺. The derived H⁺ concentration as a function of time was substituted into the expression for the cellulose hydrolysis rate constant in Saeman’s model.

MATLAB® was used for solving the differential equation at variable temperature and solid acid catalyst degradation constant. The dependence on temperature, to which the model is especially sensitive, and the deviation for the catalyst degradation rate constant were simulated using a random number generator function. To model uncertainty, Monte Carlo simulations of the reaction system were performed, using reaction temperature (±2.5 °C) as the uncertain variable. Performing Monte Carlo simulations of reaction temperature captures uncertainty arising from natural variability in the thermal control system, as well as uncertainties in reaction rate parameters. For comparison, a kinetic study of cellulose hydrolysis using selected solid acid catalysts was carried out. The quantification of soluble products and soluble carbon balance was as described previously [40].

2.10. Interactions between Solid Acid Catalyst and Soluble Substrates
Glucose hydrolysis was studied as a model to probe interactions between the soluble products generated from cellulose hydrolysis. Briefly, the tests were identical to cellulose hydrolysis; the supernatant activity test was carried out using Amberlyst-15, but for a period of 2 h. \(^{13}\text{C}\) glucose was reacted with CMP-SO\(_3\)H-0.3 for 10 h; the solid material was then recovered and analyzed with solid-state nuclear magnetic resonance to study the species deposited on the solid catalyst and potential chemical bonding between those species and the solid acid.
2.11. Solid-State Nuclear Magnetic Resonance

The structure of the CMP-SO$_3$H-0.3 catalyst was analyzed using solid-state nuclear magnetic resonance (NMR) spectroscopy after mixing with $^{13}$C-enriched glucose at the same conditions used for cellulose reaction. Experiments were performed on a Bruker Avance 400 spectrometer (Billerica, MA, USA) at a 100 MHz $^{13}$C resonance frequency with high-power $^1$H decoupling, with magic-angle spinning (MAS) of 4 mm zirconia rotors in a double-resonance probe head at ambient temperature. $^{13}$C chemical shifts were calibrated to TMS, using 1-$^{13}$Cglycine ($\alpha$-form) at 176.49 ppm as a secondary reference. The composite-pulse multiCP pulse sequence [60] was used at 14 kHz MAS to obtain quantitative $^{13}$C-NMR spectra, with a 4 s recycle delay, 10 1.1 ms cross-polarization periods, and a final 0.55 ms CP time, each separated by a $^1$H repolarization time of 1.5 s. Corresponding spectra of non-protonated C and mobile segments were obtained after 68 $\mu$s recoupled $^1$H–$^{13}$C dipolar dephasing before detection [61]. To evaluate connectivity between protonated and non-protonated carbons in coked CMP-SO$_3$H-0.3, two-dimensional exchange with protonated and non-protonated spectral editing (EXPANSE) NMR spectra [62] were recorded with a mixing time of 10 ms. Since small residual diagonal peaks of arenes do not interfere with detection of most of the cross-peaks, the dipolar dephasing difference was not recorded, which maximized the signal-to-noise ratio. Standard 4.2 $\mu$s $^1$H and $^{13}$C 90° pulses were used in the experiments described above.

3. Results and Discussion

The objective of this work was the development and demonstration of a structure-agnostic method for identifying promising materials with heterogeneous activity for cellulose hydrolysis. In the first section, single-point solid activity and supernatant tests were performed for six materials, as shown in Scheme 1c. The second section demonstrates methods for evaluating false negatives, i.e., situations in which the supernatant test falsely indicates the absence of heterogeneous activity. The third section examines potential for false positives and introduces methods for evaluating reactant–catalyst interactions, which in the cases considered here are likely to give rise to false positives, i.e., incorrect identification of heterogeneous activity when none is present. The fourth and final section recommends a strategy for identifying solid acids with sufficient heterogeneous activity for cellulose hydrolysis to justify detailed studies.

3.1. Single-Point Measurements of Solid Acid and Supernatant Cellulose Hydrolysis Activity

For testing the new approach, we selected representative materials from four structural classes that have been commonly reported for cellulose hydrolysis: (1) Amberlyst-15 (AMB-15) as a polymer catalyst, (2) sulfonated humin (SH) and sulfonated carbon (SAC) as carbonaceous catalysts, (3) ZSM-5 in its protonated form and sulfated zirconia (SZ) as inorganic catalysts, and (4) partially sulfonated chloromethyl polystyrene (CMP-SO$_3$H-0.3) as a bifunctional catalyst [33,35,40,63–69]. Evaluation of these catalyst categories is sufficient for the current purpose of developing a structure-agnostic method for distinguishing heterogeneous from homogeneous activity. Testing several catalyst categories demonstrates the use of the approach for different types of catalysts, establishing its credibility for future use by others. Simplified structures of the catalyst are provided in Figure 1. Synthesis and modification procedures are provided in Section 2, as appropriate. In all cases, catalysts were washed extensively prior to use to remove water-soluble acids from their surfaces.
A structure-agnostic approach for discerning heterogeneous catalytic activity for cellulose hydrolysis should not require catalyst characterization. Nonetheless, to establish that the selected materials had the potential to be solid acid catalysts before proceeding to evaluating their activity, we first quantified their acid site densities using Boehm titration [54]. Data are provided in Table S1 (see Supplementary Materials). In all cases, the materials selected for this study possess titratable acid sites, with densities greater than 800 µmol·g⁻¹. Because of their external surface area and partially microporous pore structures, a fraction of these acid groups will be accessible to cellulose, making the selected materials plausible catalysts for cellulose hydrolysis.

Developing a method for discerning and quantifying heterogeneous catalytic effects benefits from selection of a standard condition that maintains modest conversion to minimize secondary reactions that can contribute to formation of insoluble species that can complicate data interpretation. Accordingly, the apparent cellulose hydrolysis activity of
the selected representative solid acids was determined at a standard reaction temperature (150 ± 2.5 °C) for reaction times of either 10 or 15 h, with the reaction time selected to maintain product yields obtained for the different catalysts at comparable values. The catalysts shown in Figure 1 were then tested for cellulose hydrolysis at the standardized conditions. Table S2 provides detailed product distribution data. In all cases, the products were glucose, levulinic acid, and formic acid, resulting in overall soluble product yields ranging from 2% to 25%, consistent with cellulose hydrolysis and subsequent dehydration of glucose [56].

Measured product yields shown in Table S2 were used to estimate averaged product formation rates as an indication of apparent catalytic activity. Figure 2 summarizes the averaged product formation rates for each of the six catalysts considered in this study (gray bars). The formation rates were calculated by summing the mass of all products in the reaction media as a proxy estimation of cellulose conversion. The apparent formation rates observed when the two polymer catalysts (CMP-SO$_3$H-0.3 and Amberlyst 15) were greater than those of the inorganic or carbonaceous catalysts. Product formation rates observed for the bifunctional polymer were greater than any of the other materials, a result that could casually be misattributed to enhanced catalyst–cellulose interaction due to the presence of chloride groups. The purpose of structure-agnostic differentiation of homogeneous and heterogeneous promotion is to test this and other similar attributions.

![Figure 2. Comparison of average product formation rate after cellulose hydrolysis with fresh solid acid catalyst (gray bars) and supernatant (red bars). The dotted line represents the activity of water-only in the absence of catalyst at the same conditions. Conditions: 150 °C (±2.5 °C) reaction temperature and either 10 or 15 h reaction time, 2 mL of water, 0.1 g of cellulose, and 0.2 g of catalyst.](image-url)
Product formation rates on their own are easily misinterpreted, and one way to reduce the likelihood of misinterpretation is to characterize the catalyst after use. However, only use of appropriate, quantitative characterization techniques can prevent misinterpretation. The tests that are appropriate for a given material depend on its specific chemistry, adding complexity and ambiguity to the process of post-reaction characterization. Instead, we advocate performing additional control tests, as shown in Scheme 1. Release of even trace species can influence observed product formation rates, meaning that characterization must be sufficiently sensitive to arrive at firm conclusions.

Because cellulose hydrolysis can occur in the absence of added catalyst, soluble product formation rates were next measured in the absence of any catalyst, but in the same reaction conditions under which catalyzed formation rates were measured. The resulting noncatalytic product formation rate is shown as the horizontal line in Figure 2. In nearly all cases, the yields (see Table S2) and product formation rates (Figure 2) observed in the presence of catalyst were greater than under noncatalytic conditions, with the only exception being H-ZSM-5. Accordingly, H-ZSM-5 can be eliminated from further considerations as a solid acid catalyst for cellulose hydrolysis, at least under the conditions considered here, as its activity is no greater than what could be expected without addition of catalyst. The likely explanation is that H-ZSM-5 has insufficient acid sites on its external surface to promote cellulose hydrolysis, and that it is sufficiently stable that it does not release soluble acids.

In addition to promoting greater product formation rates than observed in the absence of a catalyst, the activity of a solid catalyst toward cellulose hydrolysis must exceed that observed in the supernatant liquid obtained by treating the catalyst in hot liquid water in the absence of cellulose, as shown in Scheme 1c. Accordingly, Figure 2 includes product formation rates observed when the solid acid catalysts were replaced with their supernatant liquids (red bars) for direct comparison with rates observed in the presence of the solid catalyst itself; detailed soluble products yields are presented in Table S2. In all cases, the soluble product formation rates and yields obtained using the supernatant liquid were equal to (within the uncertainty) or greater than the yield obtained using the corresponding heterogeneous catalyst. This is a clear indication that all of the materials tested here release homogeneous catalyst during reaction.

The supernatant obtained from CMP-SO$_3$H-0.3 is especially active, consistent with previously observed formation of HCl (aq) when this catalyst is exposed to hydrolysis conditions [40]. In comparison, the activity of AMB-15 is comparable to its supernatant (within uncertainty). Unlike CMP-SO$_3$H-0.3, the activity of the AMB-15 supernatant is likely a consequence of release of sulfuric acid during reaction [74].

Figure 2 clearly implies that the selected materials either completely lack activity for cellulose hydrolysis (HZSM-5) or that any activity observed for them included contributions from soluble species formed during hydrothermal degradation of the solid. It does not, however, prove that all of the catalysts lack heterogeneous activity. To elucidate further, we investigated the acid characteristics of the catalysts themselves and the properties of the supernatant liquids.

To evaluate effects of homogeneous acids, we quantified acid leaching resulting from hydrothermal treatment. After exposure to hydrothermal conditions (again at 150 ± 2.5 °C and for either 10 or 15 h) in the absence of cellulose, the pH of the resulting suspension decreased by several units relative to that observed for a simple water washing at ambient conditions (gray bars in Figure 3a) for every catalyst, as shown as the red bars in Figure 3a. Accordingly, Figure 3a clearly establishes that hydrothermal treatment releases acids that were stable at room temperature. These soluble acid species can then contribute to the activity observed when the solid materials are used for cellulose hydrolysis, as implied by comparison of heterogeneous catalyst and supernatant liquid product formation rates shown in Figure 2.
The interpretation of leached acid catalysis is consistent with the relative activity of the polymer catalysts and the lack of activity observed for SH and HZSM-5 (Figure 2), since the pH measured for the supernatant liquid obtained from the polymers was comparable to pH values used in dilute acid pretreatment [23], whereas the pH obtained for SH and especially HZSM-5 was much less acidic. The pH values of the SAC and SZ materials were intermediate to these extremes, just as the activities of these catalysts were intermediate to the polymers and HZSM-5.

As part of developing a reliable catalyst screening approach, we took the extra step of quantifying anion concentrations in the supernatant liquids. Specific attention was paid to chloride and sulfate species, in accordance with the structures of the original catalysts (as shown in Figure 1). Figure 3b shows anion concentrations measured in the supernatants, plotted alongside measured H⁺ concentrations for comparison and for confirmation of charge balance. All of the catalysts, except HZSM-5, released anions into solution that could be measured using anionic chromatography. HZSM-5 likely releases Al and Si species, but they were not measured in this study [45,75]. Charges associated with measured cation and anion concentrations were nearly balanced, as required for charge neutrality, indicating that no other anions were released but not identified and quantified. Of the five catalysts that released anions, CMP-SO₃H-0.3 released mainly chloride ions, consistent with hydrolysis of the chloromethyl group that has been suggested as a carbohydrate-binding group (Figure 1) [40]. The remainder of the catalysts release mainly bisulfate, consistent
with degradation of sulfonic acid groups in AMB-15, SAC, and SH and the sulfate ions of SZ, resulting in sulfuric acid [76].

As a consistency check, the densities of acid sites on the solid catalysts were measured before and after hydrothermal treatment to determine the source of the soluble ionic species. Figure S1 in Supplementary Materials plots the amount of leached hydronium ions, the decrease in acid sites, and the amount of leached bisulfate ions. The data show that the loss of surface-bound acid sites is nearly in quantitative agreement with the released homogeneous acid species, consistent with the soluble acids arising directly from degradation of acid sites in the solid catalyst at the conditions used for hydrolysis.

The data in Figures 2 and 3 were then reanalyzed to identify underlying trends. Figure S2 (see Supplementary Materials) shows the product formation pseudo-first-order rate constants of the solid catalysts plotted versus the acid site density (Figure S2a) or the concentration of the leached acid in the supernatant (Figure S2b). The former shows weak correlation between acid site density and product formation rates, whereas Figure S2b reveals a much clearer correlation between acid in the supernatant and product formation rates. Again, Figure S2 points to a minor role for heterogeneous effects for the catalysts considered in this study.

The supernatant liquid tests are, therefore, entirely self-consistent. Generation of a supernatant liquid in the absence of cellulose results in a solution containing H+ and associated anions, the identities and concentrations of which are consistent with expectations and with measurements of acid site densities on the fresh and used solids. The approach is equally applicable to catalysts of many different categories. Of the six materials studied here, one lacks discernable activity when compared with noncatalytic conditions, and the other five result in product formation rates that are less than that observed with the supernatant liquid. The temptation is to conclude that heterogeneous effects are negligible for all of these materials. However, questions remain, specifically if the test is too stringent, resulting in false negatives, or too lax, resulting in false positives.

3.2. Evaluation of False Negatives

Figures 2 and 3 present data obtained at a single time point, which can obscure subtle catalytic effects. In fact, the supernatant test risks being overly stringent, as the pH of the actual reaction mixture is expected to decrease over time, yet the pH of the supernatant is fixed at a single value that is the lowest expected during the entire reaction. As a result, the supernatant test is prone to identification of false negatives and cannot be relied on to understand product distributions.

To help understand the potential for identification of false negatives, we first sought to establish whether the supernatant test can identify heterogeneous activity when it is expected to be present, using glucose dehydration as a simple homogeneous probe reaction. Unlike cellulose hydrolysis, glucose dehydration does not require solid–solid interaction, but can still be carried out at the same conditions as cellulose hydrolysis. Moreover, control tests on glucose can help understand the potential effect of solid acids on product distributions obtained from cellulose hydrolysis, even when the solid acid may not participate directly in hydrolysis.

For the purpose of testing solid acid activity for glucose dehydration, we used AMB-15, its supernatant, and sulfuric acid at the same pH as the supernatant. Analogously to Figure 2, Figure 4 plots the average glucose conversion rate and shows that, at the conditions tested, the presence of solid acid catalyst resulted in nearly double the glucose conversion when compared to its supernatant. This result is clear evidence of heterogeneous interactions between the solid acid and the soluble substrate that can be detected by the single-point measurement approach used in this study. Interestingly, the supernatant is still more active than sulfuric acid at the same pH, possibly implicating the role of counterions in the reaction mixture. Lastly, the greater activity observed for AMB-15 compared with both the supernatant and sulfuric acid clearly shows that the solid acid can impact product distributions obtained from cellulose hydrolysis, even under circumstances that apparently
preclude direct participation in the primary hydrolysis reaction step. Accordingly, solid acids can justifiably be used to control product distribution, a potentially useful objective in some instances.

Figure 4. Comparison of the average glucose conversion rates after glucose dehydration with fresh solid acid catalyst, its supernatant, and sulfuric acid. The supernatant was generated by treating AMB-15 at the same conditions as the glucose dehydration reaction. Sulfuric acid at the equivalent concentration (pH = 2.94) to that of the supernatant was used as a control. Conditions: 150 °C (±2.5 °C) reaction temperature and 2 h reaction time, 2 mL of water, 0.1 g of glucose, and 0.2 g of catalyst.

Having established that the supernatant test yields the expected result for a case in which heterogeneous catalysis is expected, we sought to quantify the effects of time varying pH on product yields. To do this, we adopted a reaction pathway analysis, as shown in Scheme 2. Here, the solid catalyst can potentially promote cellulose hydrolysis or glucose dehydration, either directly by heterogeneous activity or indirectly by leaching acids into solution. Each of these reactions, except solid–solid-catalyzed cellulose hydrolysis, can be described using existing kinetic models [55,56,77]; model comparison with observations affords a method to identify solid–solid catalysis. The concentration of H+ available for homogeneous catalysis varies over time, an effect that can easily be captured in a system of ordinary differential equations.
Scheme 2. Cellulose hydrolysis, product decomposition, and catalyst leaching reaction pathways. The red and green arrows indicate homogeneous and heterogeneous catalyzed reactions, respectively.

For the purposes of identifying solid–solid catalysis, we modeled cellulose hydrolysis using the rate expressions and parameters recommended by Saeman for homogeneous acids [55]. Figure S3 (see Supplementary Materials) confirms the accuracy of this approach by comparing its prediction for hydrolysis by each of the supernatants. Next, we coupled Saeman’s model with a simple empirical model to capture time-dependent release of homogeneous acid during reaction. For the purpose of the empirical acid release model, time-resolved measurements of the pH of the supernatant liquid obtained from CMP-SO$_3$H-0.3 and AMB-15 were made in the absence of cellulose (shown in Figures S4 and S5 in the Supplementary Materials). The supernatant pH measurements were consistent with a first-order rate law with a single best-fit rate constant, as shown in Figure S6. Potential heterogeneous effects were not explicitly included in the model; instead, model underprediction of experimental yields can be attributed to heterogeneous catalysis, and accurate predictions are attributable to a lack of heterogeneous effects on cellulose hydrolysis.

The last element that we included in the hydrolysis model is a way to capture the effects of uncertainties in key parameters. In fact, in our own experiments, we realized that differences in thermocouple placement could lead to differences in measured reaction temperature of ± 2.5 °C. Similarly, the best-fit rate constants used to describe acid leaching contained some uncertainty, as shown in Figure S6. Monte Carlo simulation methods captured the effects of parameter uncertainty on model predictions, as explained in more detail in Section 2.

The next step was to use the kinetic model to generate a series of predictions of cellulose conversion for use of AMB-15 and CMP-SO$_3$H-0.3. These are shown in Figure 5 as ranges resulting from the Monte Carlo simulations. In both cases, cellulose conversion increases smoothly with increasing reaction times, reaching values in the range from 18–25% for AMB-15 and 48–72% for CMP-SO$_3$H-0.3, with the difference corresponding to the more rapid release of acids from CMP-SO$_3$H-0.3 compared with AMB-15 (Figures S4 and S5).
Figure 5. Comparison of cellulose conversion (gray) predicted by using Saeman’s homogeneous acid cellulose hydrolysis model and time-dependent acid concentration and measured soluble carbon balance (red) as a function of reaction time. Data presented are for CMP-SO$_3$H-0.3 (top) and AMB-15 (bottom).

We measured soluble product yields as a proxy for cellulose conversion at specified timepoints obtained using CMP-SO$_3$H-0.3 and AMB-15 to compare with the predictions of the reaction model. Figure 6 contains plots of soluble product yields obtained for these two catalysts. In the case of AMB-15, the model accurately predicts the observed yields within the limits of uncertainty at all timepoints. The model actually overpredicts cellulose hydrolysis for the case of CMP-SO$_3$H-0.3, despite the fact that the reaction model completely lacks any heterogeneous pathways. Therefore, Figure 5 clearly shows that the risk of false negatives associated with the single-point method shown in Figure 3 is generally manageable. In cases where differentiating heterogeneous activity from homogeneous activity is especially important, the time-resolved method shown in Figure 6 can be used.
Performing the time-resolved study is tedious, and less labor-intensive approaches are, therefore, desirable. In fact, while the structure-agnostic approach provides no direct information on the stability of acid sites on a given catalyst, hypothesizing that some sites are more labile than others is not unreasonable. Motivated by this line of thinking, Foo and Sievers recommended pretreating candidate solids in a harsh hydrothermal environment to remove labile sites prior to using the treated material as a catalyst as an alternative method for eliminating homogeneous contributions to catalytic activity, as shown in Scheme 1b [33].

We selected the SH catalyst for endurance testing, as SH activity when used as a solid was equal (within uncertainty) to that of the supernatant, whereas the activity of most other catalysts tested here was exceeded by their supernatant. To simulate harsh treatment, the SH catalyst was subjected to a 24 h hydrothermal endurance test at 150 °C, conditions harsher than those used for activity testing, as shown in Scheme 1c. SH was recovered after the pretreatment and then used again for generation of a new supernatant liquid by treating it in water at 150°C for 15 h. As expected, the supernatant pH recovered for the pretreated SH was less acidic than that recovered from the original SH, 2.8 compared with 2.0, while the solid material retained 1.73 mmol/g of surface bound acid sites. This observation confirms that the endurance pretreatment successfully removed a fraction of labile acid sites, as intended.

The new supernatant and recovered SH were then used for cellulose hydrolysis. On the basis of previous results, we elected to ball mill the cellulose prior to the activity test, with the aim of increasing its reactivity [4]. Figure 6 provides the results as average product formation rates observed for the SH and the supernatant recovered after pretreatment. Even with the pretreatment, product formation rates observed with the supernatant liquid were nearly twice that observed for the solid SH. While the results of an endurance pretreatment test will depend on the catalyst being studied, Figure 6 clearly shows that an endurance pretreatment is not sufficient to eliminate potential catalytic effects of leached acids. Instead, we recommend the endurance test as a supplementary effort to the single-point supernatant test and time-resolved study, as the supernatant test is a more discerning approach for

**Figure 6.** Comparison of average product formation rate after hydrolysis of ball-milled cellulose with hydrothermally pretreated SH solid catalyst and its supernatant. The supernatant was generated as previously described. The dotted line represents the hydrolysis activity of water. Conditions: 150°C (±2.5 °C) reaction temperature 15 h reaction time, 2 mL of water, 0.1 g of cellulose, and 0.2 g of catalyst.
identifying when homogeneous effects are contributing to reactivity and the time-resolved study a more reliable way to reject false negatives.

3.3. False Positives Arising from Catalyst–Reactant Interactions

The last question we sought to address was the potential for missing key information leading to false positives by generating the supernatant for testing catalytic activity in the absence of cellulose. In fact, the actual reaction mixture contains many soluble species that can potentially react with the catalyst surface, promote acid leaching, or block acid sites, none of which would be captured by using a supernatant generated in the absence of cellulose and other reactants for comparison. For example, sulfonated catalysts have been shown to deactivate by forming esters with alcohols during esterification of fatty acids [78]. Model underprediction of yields obtained using CMP-SO$_3$H-0.3 as shown previously in Figure 6 might plausibly be explained by these types of effects.

Accordingly, the acid content of the supernatants formed when CMP-SO$_3$H-0.3 and AMB-15 were used for cellulose hydrolysis was measured and compared with the supernatants formed in the absence of cellulose. Figure 7 provides the results of this comparison, showing that the acid content of the supernatant obtained in the presence of cellulose was greater than in its absence for both catalysts, by a factor of two in the case of AMB-15. Figure 7 clearly shows that reactant–catalyst interactions can play an important role in acid leaching and, hence, apparent catalytic reactivity. The resulting acid content is greater when the supernatant is produced in the presence of cellulose, thereby opening the possibility of identification of false positives by the single-point supernatant test.

![Figure 7](image.png)

**Figure 7.** Acid concentration in the liquid medium after hydrothermal treatment of CMP-SO$_3$H-0.3 and AMB-15 in the absence of cellulose (red) and after cellulose hydrolysis at the same conditions. Reaction was carried out at 150°C for 10 h.
Practically, a solid catalyst that degrades to release homogeneous acids due to reacting with soluble products would not be applicable for cellulose hydrolysis and, thus, not merit further consideration. However, to safeguard against false-positive assignment of heterogeneous catalysis, the supernatant test can be extended. The pH after hydrolysis with the solid acid should be measured and compared to the pH of the supernatant generated without presence of cellulose. If the pH of the solution after hydrolysis is greater, then it is strong evidence of heterogeneous activity. On the other hand, if the pH is lower, as is the case in Figure 7, then additional test can be carried out to quantify the effect of soluble products on leaching kinetics. Lastly, the kinetic model proposed here can be applied to quantify the relative effects of homogeneous and heterogeneous catalysis similarly to the analysis presented in Figure 5.

To understand how the reaction mixture can influence acid leaching, we treated CMP-SO$_3$H-0.3 in a water solution of $^{13}$C-enriched glucose (0.1 g glucose in 2 mL water) at the reaction conditions applied for cellulose hydrolysis (150°C, 10 h), washed the catalyst with water to remove soluble species, and characterized the remaining solid with solid-state $^{13}$C-NMR. Figure 8a shows spectra arising from all carbon and of non-protonated or mobile carbon. Figure 8b shows the two-dimensional correlation spectrum between protonated and non-protonated or mobile carbons obtained for the charred CMP-SO$_3$H-0.3 catalyst (see Section 2 for details). The spectra show clear signatures of levulinic acid (~20%) and HMF (~4%). The majority of the signal is associated with various furanic and other aromatic structures, ketones, and carboxylic acids typical of hydrothermal char [73,79]. The presence of these species confirms that the acid surface acts as a nucleation agent for char, likely blocking access to acid sites and simultaneously detracting from the soluble carbon yield. The appearance of levulinate species—potentially bound directly to sulfonic acid on the catalyst surface—is especially interesting, as it suggests a reaction to form alkyl esters on the surface [78]. The reaction between levulinic acid and sulfonic acid liberates protons, thereby explaining the effect of the reaction mixture on the acid concentration of the supernatant shown in Figure 7. Accordingly, Figures 7 and 8 provide a caution that interactions between the reaction mixture and the catalyst can play important roles in some instances.

3.4. Recommended Protocol

Scheme 3 summarizes a comprehensive structure-agnostic strategy for differenting heterogeneous effects on cellulose hydrolysis from homogeneous ones. First, the catalyst itself is tested and its cellulose hydrolysis activity compared to that of water, followed by catalyst treatment at the same hydrothermal conditions to generate a supernatant; the cellulose hydrolysis activity of the supernatant is then determined. Second, after the supernatant comparison test, the stability of the catalyst should be tested in the presence of soluble cellulose hydrolysis products by pH measurements of the cellulose and cellulose-free supernatants. Differences should be taken into account when considering the results of the supernatant test. Third, provided that the solid acid is stable in the presence of the soluble species, kinetic modeling should be applied for detection and quantification of heterogeneous activity. After heterogeneous catalysis is quantified, the solid material can be subjected to structure–activity studies. In contrast, materials that do not exhibit greater activity than water, are very unstable in water, degrade in the presence of the cellulose hydrolysis products, or do not possess heterogeneous activity following kinetic modeling analysis can be excluded from further consideration.
Figure 8. Solid-state $^{13}$C-NMR analysis of CMP-SO$_3$H-0.3 after reaction with $^{13}$C-enriched glucose (150 °C, 10 h.). (a) MultiCP spectra of all C (black line) and of C not bonded to H or in mobile segments (red line). The chemical shifts of levulinic acid (simple numbers) and of HMF (primed numbers) are indicated. (b) 2D correlation between protonated and non-protonated or mobile carbons present in the glucose degradation products. Characteristic cross-peaks are labeled.

We recommend that future work on solid acid-catalyzed cellulose hydrolysis adopts at least steps 1 and 2 in Scheme 3. If the results of these steps are promising, step 3 should allow differentiation of heterogeneous activity from what now appears to be the almost unavoidably homogeneous variety. At that time, provided that heterogeneous activity accounts for the majority of the observed catalysis, the catalyst post-reaction can be characterized, regenerated, and reused. Adopting these steps will greatly reduce the likelihood of future misattributions and help allocate resources to the most promising materials.
Scheme 3. Process flow diagram of the structure-agnostic method for analyzing solid acid catalyst for cellulose hydrolysis.

This study focused on cellulose hydrolysis as an especially interesting and important test case. That stated, solid acid catalysis in water-rich solvents is an active area of research. A major challenge in liquid-phase catalysis is differentiating effects due to homogeneous products of degradation from the desired heterogeneous ones. Scheme 3 can easily be adapted for reactions other than cellulose hydrolysis, providing the community with a useful tool for rejecting unpromising catalysts and enabling judicious allocation of resources.

4. Conclusions

In this work, we developed a structure-agnostic methodology for evaluating solid acid catalysts for cellulose hydrolysis and detection of heterogeneous activity and applied it to six solid catalysts representing the main categories currently being considered. Comparison of results from a supernatant activity test with those obtained using the solid material can identify circumstances when solid acid materials leach catalytically active homogeneous acid species; every catalyst type considered here generated soluble acids capable of hydrolyzing cellulose, indicating a role of homogeneous acids for these test cases. By comparison, an alternative method consisting of harsh catalyst pretreatment was less effective at identifying homogeneous contributions from a heterogeneous catalyst.

A weakness of using a supernatant generated in the absence of cellulose is that it will contain a fixed amount of acid that may not be the same as that generated in the presence of cellulose. This can result in identification of false negatives when the acid content of the supernatant exceeds that of the actual reaction mixture or false positives in the opposite
case. For greater discernment, the time release of acids from the heterogeneous material into the supernatant liquid can be measured, followed by modeling and measurement of product yields obtained using the solid material. Similarly, reactions with soluble species, e.g., glucose, can be used to elucidate reactant–catalyst interactions.

On the basis of those results, we recommend supernatant liquid tests as a simplistic, yet powerful framework for rapid screening of solid acid materials for cellulose hydrolysis. The proposed methodology relies only on activity testing and avoids labor-intensive structural characterization. Only after a material’s heterogeneous activity has been established and verified should structure–activity studies be initiated. The approach can be utilized by the community for the design and development of solid acid catalysts for cellulose hydrolysis. Furthermore, it can be extended and implemented to other systems where catalyst degradation is of concern for the interpretation and quantification of activity.

Supplementary Materials: The following are available online at https://www.mdpi.com/article/10.3390/suschem2040036/s1. Figure S1: Comparison of the leached homogeneous acid concentration per gram of catalyst, the decrease of acid sites of the catalysts post hydrothermal treatment, and the concentration of the leached bisulfate species per gram of catalyst. Figure S2: Correlation between first order catalytic hydrolysis rate constant $k_{cat}$ of cellulose hydrolysis using fresh solid acid catalyst and amount of acid sites and concentration of leached homogeneous acid. Figure S3: Parity plot of measured soluble carbon balance versus predicted cellulose conversion by Saeman’s homogeneous acid hydrolysis model. Figure S4: Concentration of the leached homogeneous acid for Amberlyst-15 as a function of treatment temperature at 150 °C. Figure S5: Concentration of the leached homogeneous acid for CMP-SO$_3$H-0.3 as a function of treatment time at 150 °C. Figure S6: Kinetic analysis of homogeneous acid leaching from AMB-15 and CMP-SO$_3$H-0.3 assuming the leaching obeys first order kinetics. Table S1: Acid site density of the catalysts used in the current study measured by solid state Boehm titration. Table S2: Comparison of the yields (%) of most abundant soluble products generated by solid acid and leached homogeneous acid catalyzed cellulose hydrolysis.

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