Catalytic Hydrogenation of Alkylphenols for Renewable Caprolactone

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Abstract. Selective hydrogenation of lignin-derived alkyl-phenol to alkyl-cyclohexanone is a key step in the synthesis of renewable caprolactone from lignin-derived monomers. Selective hydrogenation of p-cresol, a model compound for lignin-derived monomers, to 4-methyl-cyclohexanone was conducted using Pd/ γ -Al₂O₃ in a continuous three-phase flow reactor, with side products of 4-methyl cyclohexanol. High conversion (85%) and selectivity (>93%) was demonstrated at ambient reaction pressure. Evaluation of the hydrogenation at different reaction parameters showed that the reaction selectivity was determined by the surface coverage of p-cresol and 4-methyl cyclohexanone. High selectivity to 4-methyl cyclohexanone was also attributed to the lower apparent activation barrier of p-cresol hydrogenation (67 ± 2 kJ mol⁻¹) compared to hydrogenation 4-methyl cyclohexanone (92 ± 11 kJ mol⁻¹), with a faster rate of initial hydrogenation of p-cresol relative to carbonyl hydrogenation of 4-methyl-cyclohexanone.

Introduction. The development of new processing technology to produce high value chemical intermediates from lignin-derived monophenols continues to advance with improvements in catalytic performance, separations, and process design, ultimately achieving cost parity with petroleum-derived chemicals.^{1–5} As one of the three major components in biomass, lignin is a large renewable source of phenolic material and a promising substitute feedstock to produce chemicals that are conventionally derived from petroleum.^{6,7} Recent progress in lignin processing and valorization has addressed the challenges inherent to lignin processing such as side reactions due to irreversible degradation and condensation of functionalized six-carbon aromatic chemicals. Reductive catalytic fractionation (RCF) is an emerging biorefinery process that involves initial solvolysis extraction to remove lignin from the lignocellulose cell wall; subsequent catalytic depolymerization and stabilization of the lignin-derived intermediates simultaneously prevent them from recondensation.^{8–11} The two main RCF product streams are the preserved carbohydrate pulp that consists of the original cellulose and hemicellulose and the extracted lignin oil consisting of lignin-derived dimers and oligomers.¹¹ Downstream hydrodeoxygenation (HDO) of the lignin-oil then yields alkyl-phenol molecules that serve as precursors for higher value materials such as alkyl-caprolactone (**scheme 1**).

Alkyl-caprolactones are potential biobased building blocks for the next generation of highperforming biopolymers, such as caprolactone-based polyurethanes, tough polyesters, and thermoplastic elastomers.^{12,13} Batiste et al., showed that polymerizing copolymers of different isomers of methyl caprolactones (MCL) created materials with high mechanical strength, toughness, and elasticity.¹² The addition of carbon branching from the short chain alkyl group reduced polymer crystallinity, which led to lower glass transition temperatures for elastomeric materials. Conventional polycaprolactone is an important ingredient in multiple industrial products including specialty polyurethane and thermoplastics.^{12–} ¹⁴ Newer polycaprolactone polymers with tunable physical properties due to varying alkyl side chains provide opportunity for application in new businesses.

A proposed reaction pathway (**scheme1**) to manufacture alkyl-caprolactone from lignin utilizes lignin-derived alkyl-phenol from the upstream lignin RCF process. Alkyl-phenol then proceeds through a two-step process of selective hydrogenation of the six-carbon aromatic ring to alkyl cyclohexanone followed by Baeyer-Villiger oxidation (BVO) to alkyl-caprolactone.^{15–19} Corma et al, has demonstrated the

ability to obtain high selectivity and activity towards alkyl-caprolactone through the Baeyer-Villiger oxidation on various alkyl-ketones using a Sn β zeolite with H₂O₂.²⁰ This study was then replicated by Yakabi et al in a continuous flow reactor which demonstrated high selectivity of BVO to caprolactone at ~60% conversion over a time on stream of 180 hours.¹⁹ Polycaprolactone was then produced from ring-opening polymerization of caprolactone or the corresponding alkyl-caprolactone using various organotin and various tin-based catalysts.^{12,13,21–23} At their end of use, these aliphatic polyester elastomers made from alkyl-caprolactones can be hydrolyzed using an enzyme and depolymerized back into its constituent monomers, thereby enabling these polymers to be chemically recycled and polymerized again (scheme 1).^{12,13,24,25}

A key step to develop the poly(alkyl-caprolactone)-from-lignin process is the ability to synthesize alkyl-cyclohexanone from lignin-derived alkyl-phenol in high yield. An efficient hydrogenation process requires the reaction to occur at high selectivity with negligible side product of the over-hydrogenated cyclohexanol. Cyclohexanone can be produced industrially from either an oxidative or reductive process. The oxidative pathway occurs through the oxidation of petrochemically-derived cyclohexane, but this process is known to be challenging due to its low reaction efficiency and slow catalytic turnover on redox molecular sieves catlaysts.²⁶ Alternatively, the reductive route to cyclohexanone can be achieved by either a two-step or one-step process. The two-step process selectively hydrogenates phenol to produce cyclohexanol, which is then dehydrogenated to produce cyclohexanone in a thermodynamically unfavorable reaction.²⁷ The one-step process requires selective hydrogenation of the phenol ring to make cyclohexanone and is preferred, since it requires less energy, downstream separation, and has a lower overall cost.

One step selective hydrogenation of the phenol ring can happen in either the gas phase^{28–31} or liquid phase.^{16–18,32–34} Unlike the gas phase, the liquid phase reaction to convert phenol to cyclohexanone occurs at lower operating temperatures, with the benefit of minimizing undesirable side reactions that normally occur in high temperature gas-phase conditions.³⁵ Liquid phase selective hydrogenation has been conducted using different supported noble metal particles, such as Pd^{16–18,32–34,36–38}, Pt^{39,40}, and Rh^{41–43} and on supported non-noble metal, such as Ni.^{44,45} Among the reported studies, Pd-based catalysts have been shown to achieve high selectivity to cyclohexanone (>98 mol%).^{46–53} These studies have also explored different characteristics of the support used for Pd metal particles, ranging from acid support such as alumina, basic supports such as MgO, and even carbon supports with various hydrophobicity and hydrophilicity.^{28,29,31,48,54,55} However, the extent of the effect of the support on the selectivity of the phenol hydrogenation remains in discussion and is less significant relative to the operating conditions and active site composition.

Despite numerous studies on selective hydrogenation of the C=C double bond of phenol to cyclohexanone, the role of additional alkyl chains on phenol, such as exists with lignin-derived monomers, has not been evaluated. The additional alkyl group on phenol present in these intermediates introduces additional challenges to the selective hydrogenation process, such as steric limitations of the reactant on surfaces and variable binding energy to surfaces due to the electron-donating characteristics of alkyl chains. In addition, most experimental studies of the selective hydrogenation of phenols were conducted in a batch reactor, without evaluation of the three-phase reactor behavior (solid catalyst, liquid reactant, and solvent, and H₂ gas) relevant for industrial application. In this study, hydrogenation of p-cresol, a model compound of lignin-derived intermediates, was evaluated using Pd/ γ -Al₂O₃ catalyst in a three-phase continuous flow catalytic reactor. The effects of reaction parameters including temperature, hydrogen partial pressure, and liquid residence time on the reaction were investigated to understand their effect on reaction productivity and selectivity to cyclohexanone. Moreover, capability to hydrogenate multiple different kinds of alkyl phenols was experimentally evaluated for assessing the performance of this catalytic reaction on a more complex lignin-derived intermediates.

Experimental Methods. Experimental methods include the preparation of catalytic materials, catalyst characterization, reactor design and setup, and methods of experimental results analysis.

Materials. Phenol, p-cresol (99%), 4-ethyl-phenol, 4-propyl phenols, n-dodecane (99%), and Pd(NO₃).2H₂O (40wt% Pd basis) were purchased from Millipore Sigma. Gamma-alumina (97%) was purchased from STREM Chemicals. Silica glass beads (30-50 microns) were purchased from Fischer Scientific. Deactivated quartz wool was purchased from RESTEK.

Catalyst synthesis and characterization. Pd (5 wt%) was supported on γ -alumina prepared by incipient wetness impregnation using a water solution of $Pd(NO_3) \bullet 2H_2O$. The catalyst solution was then stirred for 30 minutes and dried in an oven (75 °C) in air overnight. The catalysts were then calcined in air at 400 °C for four hours. Nitrogen physisorption data was measured at 77 K using an Autosorb 2 (Quantachrome) after outgassing at 573 K overnight. The catalyst surface area was determined using multipoint BET method from the N₂ adsorption data. CO chemisorption was conducted using Autosorb 2 (Quantachrome) after reduction pretreatment at 423 K (10 K min⁻¹) under flowing H₂. Following the reduction, the sample was evacuated for two hours and cooled to chemisorption temperature. Adsorption stoichiometry of complete site coverage was assumed to calculate the number of surface Pd atoms and dispersion.⁵⁶ The catalyst pore volume and diameter were calculated from the adsorption data.^{57,58} Powder X-ray diffraction (PXRD) patterns were collected using a Rigaku Smartlab SE diffractometer with a nickelfiltered Cu K α radiation beam ($\lambda = 0.1541$ nm, 40 kV, 30 mA). The XRD patterns were acquired in the 20 range of 5 to 80° under ambient conditions, employing a continuous measurement mode with a scanning speed of 5° min⁻¹. The high-angle annular dark-field imaging scanning transmission electron microscopy (HAADF-STEM) of the 5wt% Pd/ γ -Al₂O₃ sample powder by using Thermo Fisher Talos F200X at 200 kV of an accelerating voltage. The sample powder was ground using a quartz mortar and pestle. The ground powder was then suspended in acetone, and the resultant suspension was sonicated for five minutes. The sample suspension was drop-casted onto a lacey carbon grid (Oxford Instrument), and HAADF-STEM analysis was performed with the prepared sample grid.

Reactor setup. Hydrogenation experiments were conducted in a continuous fixed-bed catalytic reactor (Figure 1) made from ¹/₄" O.D. SS316 stainless steel tubing. The catalyst was mixed with an inert diluent (Si glass beads) and packed inside the reactor tubing using deactivated quartz wool. The packed reactor tube was heated using a heating furnace constructed from an aluminum tube wrapped with heating tape. The temperature of the reactor tube was monitored using 1/16" type K thermocouple. The top and bottom portion of the reactor were preheated using a tape heater. The temperature of the furnace, pre-, and post-heater were controlled using Omega (CN-7800) PID temperature controllers. The liquid feed was pumped using an HPLC pump (Cole Palmer V0009266), and gas was cofed using a gas flow controller from Alicat in a concurrent up-flow configuration. Pressure in the reactor was maintained using a springloaded back pressure regulator (GO regulator). Liquid effluent from the reactor was collected in a collection vessel made from 1-inch stainless steel tubing and set at ambient temperature. Liquid samples were periodically collected from the collection vessel; the vessel was drained, and the liquid sample was analyzed offline using GC-FID (Agilent 7890A) equipped with quantitative carbon detector (POLYARC). An Agilent HP-INNOWAX column (19091N-113, 30m x 0.32 mm x 0.25 micron) was used in the GC for separation of the components in the liquid samples. Reactions species were identified and quantified using an external standard calibration.

Flow reactor experiments. In a standard hydrogenation experiment, 0.1 gram of 5 wt% Pd/γ-Al₂O₃ was mixed with 1.0 gram of solid diluent (30-50 microns Si glass beads) and packed inside the reactor tube with deactivated quartz wool on both ends of the packing. The catalyst was reduced at 150 °C at 10 °C min⁻¹ ramp rate and a one hour hold in 120 mL min⁻¹ 10 v/v% H₂ in nitrogen and then returned to the desired reaction temperature. To start the reaction, the reactor was pressurized to the desired reaction pressure using the back pressure regulator using the feed gas composition condition that will be used in the following reaction. The liquid feed solution (0.02 g alkyl-phenol/ 1 mL dodecane or 0.182 M) was then pumped into the reactor at 1.0 mL min⁻¹ flowrate. The gas flow controller flowrate was also set to the desired gas flowrate. Liquid samples were collected by partially draining the collection vessel, after which the volume of the collected liquid was measured. After the collection vessel was partially drained, ~3 mL of recently accumulated liquid sample was collected for chemical analysis. The conversion, selectivity, and carbon balance of the alkyl-phenol reaction were calculated as follows.

% Conversion =
$$\frac{n_{alkyl \, phenol,t=0} - n_{alkyl \, phenol,t=t}}{n_{alkyl \, phenol,t=0}} \times 100$$
 Eq. 1

% Selectivity =
$$\frac{n_{alkyl cyclohexanone,t=t}}{n_{alkyl phenol,t=0} - n_{alkyl phenol,t=t}} \times 100$$
 Eq. 2

% Carbon Balance =
$$\frac{6n_{alkyl \text{ phenol,t=t}} + 6n_{alkyl \text{ cyclohexanone,t=t}} + 6n_{alkyl \text{ cyclohexanol,t=t}}}{6n_{alkyl \text{ phenol,t=0}}} \times 100$$
 Eq. 3

Measurement of the apparent barrier and turnover frequency (TOF) of the p-cresol conversion and 4-methyl cyclohexanone formation were conducted at 333, 343, 353, 363, and 373 K. Reactions were conducted in the flow reactor using pure hydrogen gas flow at ambient pressure. Reaction rates were measured at alkylphenol conversion lower than 12% to ensure differential reactor. A series of preliminary experiments showed that reaction rate is independent of the flowrate (see supporting information)^{59–63}.

Response Surface Method Model. The effects of three experimental parameters were evaluated including temperature, hydrogen pressure, liquid residence time toward rate of p-cresol conversion (- $r_{p-cresol}$) and net generation rate of 4-methyl cyclohexanone ($r_{4-methyl cyclohexanone}$) by Box-Behnken design using Minitab software ver. 21.2. To ensure uniform distribution of each factor, symmetric code of levels was assigned to each experimental factor as shown in **Table S1** in the supporting information. Fifteen experimental trials were designed according to the specified levels of factors as shown in **Table S2** in the supporting information. Each trial was carried out in triplicate, while central point experiments (data points at level code 0 for each experimental factor) were conducted without any duplication. Analysis of variance (ANOVA) was used to analyze the Response Surface Method (RSM) models of rate of p-cresol conversion and net generation rate of 4-methyl cyclohexanone with confidence level (α) of 0.05. All experimental trials to collect data for the response surface model were performed using 0.1 gram of catalyst mixed with 1 gram of Si glass beads as inert diluent and p-cresol solution with 0.02 g/mL concentration.

Results and Discussion. *Catalyst characterization of Pd/Al*₂*O*₃. The 5 wt% Pd/Al₂O₃ used in this study was synthesized using incipient wetness impregnation and is characterized as shown in **Figure 2**; this material was selected for its common use as an industrial catalyst for hydrogenation chemistry. The surface area of the catalyst measured using BET was 166.5 m²/g with a corresponding pore volume of around 0.43 cc g⁻¹. The N₂ adsorption isotherm of the synthesized 5 wt% Pd/ γ -Al₂O₃ is shown in **Figure 2A**. The similar isotherm curve between the synthesized 5 wt% Pd/ γ -Al₂O₃ and the γ -Al₂O₃ indicates that there were no significant structural changes to the γ -Al₂O₃ support during the impregnation process, despite a minimal reduction in total pore volume upon Pd deposition. The XRD patterns of γ -Al₂O₃, unreduced Pd/ γ -Al₂O₃ are shown in **Figure 2B**. Additionally, comparison of XRD between the calcined and reduced Pd/ γ -Al₂O₃ catalyst shows that the Pd nanoparticles were reduced during the activation process, and no sharp peak signals of Pd particles were observed showing the absence of large particles. The distribution of Pd nanoparticles was quantified via imaging using a HAADF STEM technique, where there were no large micron-scale Pd particles observed on the catalyst (**Figure 2C**). Analysis of the STEM image (**Figure 2D**) by measuring the longest diameter of the Pd particle size shows an average particle diameter of ~9 nm.

Up-flow packed bubble column reactor. The flow reactor used to study the selective liquid hydrogenation of alkyl-phenol was configured to have co-current up-flow for both the liquid phase and the gas phase feed. Up-flow configuration was selected, since it has been reported to improve catalyst wetting efficiency especially in laboratory scale liquid-gas flow reactors.^{64–66} The catalyst bed consisted of the 5 wt% Pd/Al₂O₃ catalyst powder mixed and diluted with 30-50 micron Si glass beads; this was held in place on the top and bottom with an inert quartz wool packing. The catalyst was mixed with diluent material to

prevent channeling of the liquid and increase contact between the liquid reactant and the catalyst powder. The p-cresol reactant was solubilized in n-dodecane prior to feeding to the reactor. Solvent n-dodecane was selected for its wide range of solubility with the alkyl-phenol for the considered reaction conditions; it is also an inert liquid material that will not participate in the hydrogenation reaction. The operating temperature range (60-150 °C) evaluated in this study was selected within the range that is below the boiling point of any of the reagents and reaction products. This up-flow packed bubble column reactor was used in the rest of this study to optimize operation conditions for maximum selectivity of hydrogenated alkyl-phenol, with the experimental parameters including liquid space time, reaction temperature, and hydrogen gas feed partial pressure.

Continuous flow p-cresol hydrogenation. Catalytic flow reactor performance was first assessed by performing selective hydrogenation of p-cresol to 4-methyl-cyclohexanone. A liquid feed of 0.182 M p-cresol dissolved in dodecane was co-fed into the reactor with pure hydrogen at 100 °C and ambient pressure. The liquid flowrate was 0.5 mL/min, with a WHSV of 6 h⁻¹. As shown in **Figure S1** provided in the supporting information, the average conversion of p-cresol was stable at ~85% with >93% selectivity to 4-methyl-cyclohexanone over the course of 12 hours on stream. Over the course of 12 hours, the catalyst bed underwent approximately ~1400 reaction turnovers per site.

Reactor residence time. In the evaluated three-phase catalytic flow reactor, the product distribution from reactive hydrogenation of p-cresol can change depending on the progress of the sequential reaction from 4-methyl cyclohexanone to 4-methyl cyclohexanol. This will depend on the residence time of the reaction species in the flow reactor. The conversion of p-cresol and selectivity to 4-methyl-cyclohexanone are depicted in **Figure 3** as a function of the liquid residence time and the co-feed gas composition. Variation of liquid residence time was achieved by changing the liquid flowrate fed to the catalyst bed, while the amount of catalyst and diluent and the volume occupied by the catalyst bed remained constant across all experimental trials. All of the measurements in **Figure 3** were performed at a reaction temperature of 100 °C and total pressure of 100 psi. At the lower concentration of hydrogen (10% v/v) in the feed gas stream, the conversion of p-cresol was 25% at low residence time (0.74 min). The conversion of p-cresol was 7.45 minutes. The reaction selectivity to 4-methyl-cyclohexanone was maintained at 100% at lower liquid residence time up to about three minutes where the selectivity then subsequently decreased to 71% at highest residence time of 7.45 minutes.

Similar behavior of reaction conversion and selectivity evolution was observed when the hydrogenation was performed under high hydrogen concentration (100% v/v) in the gas stream, where the p-cresol conversion increased at longer residence time. Selectivity also decreased at higher conversion and longer residence time, resulting from the promotion of the second hydrogenation reaction step to produce 4-methyl cyclohexanol from 4-methyl cyclohexanone. Higher concentration of H₂ in the gas stream helped to promote the overall hydrogenation reaction at a faster rate at any given residence time. The conversion at residence time of 1.24 minutes. The selectivity to 4-methyl cyclohexanone was 95% at the lowest residence time of 0.74 minutes and monotonically decreased as the liquid residence time increased, showing that the produced 4-methyl cyclohexanone from p-cresol was further hydrogenated to 4-methyl cyclohexanol.

The progression of the selectivity profile with increasing reaction conversion indicated that the hydrogenation occurred sequentially, where the formation of 4-methyl cyclohexanol (reaction byproduct) happened through the formation of the intermediate 4-methyl cyclohexanone. The promotion of 4-methyl cyclohexanone hydrogenation at longer residence time and high p-cresol conversion showed that the second hydrogenation step from 4-methyl-cyclohexanone to 4-methyl-cyclohexanol occurred due to both the higher concentration of 4-methyl cyclohexanone formed from first hydrogenation step and the longer contact time of the cyclohexanone intermediate with the catalyst.

Temperature and hydrogen partial pressure effect. The conversion and selectivity of p-cresol hydrogenation was evaluated at various temperatures and hydrogen pressures. Reaction was carried out in the range of 60 ° C to 150 °C, and at various hydrogen concentrations in the gas stream at 10, 25, 50, and 100 v/v% as presented in **Figure 4**. The gas flowrate was maintained at 120 mL min⁻¹ for all experiments

with the hydrogen concentration controlled by co-flowing nitrogen. All experiments were performed using a weight hourly space velocity of 12 grams of cresol gram of catalyst⁻¹ h⁻¹, and the reactor total pressure at 100 psi. As depicted in **Figure 4**, the conversion of p-cresol increased with increasing temperature across all hydrogen concentration in the gas stream. At lower H₂ gas concentration, the conversion increased from 4% conversion to 25% conversion for 60 °C to 110 °C and remained constant at ~27% for temperatures higher than 110 °C. At higher H₂ concentration in the gas stream (\geq 25 vol%), the conversion of p-cresol converged to >99% at a temperature of 130 °C and higher. The increasing conversion of p-cresol at elevated temperature showed that hydrogenation can be promoted to completion by the reaction temperature independent of the hydrogen concentration at hydrogen concentrations of 25% and higher. In contrast, the maximum conversion when the hydrogen concentration was 10 vol% was only ~20%. Hydrogen is the limiting reactant at 10 vol%, but not at higher concentrations.

The selectivity of the reaction towards 4-methyl-cyclohexanone generally decreased at higher reaction temperature and H_2 concentration. The selectivity to 4-methyl cyclohexanone was maintained above 97% at reaction temperature from 60 °C to 90 °C at different hydrogen concentrations in the gas stream. The reaction selectivity then decreased gradually at reaction temperature above 100 °C for hydrogen concentrations of 25 vol% and higher. At high hydrogen concentration in the gas stream (50 vol% and 100 vol%), the selectivity decreased significantly at temperatures from 110 °C to 150 °C. Changes in reaction selectivity resulted from the promotion of the latter step of hydrogenation that converted 4-methyl cyclohexanone to the undesired 4-methyl-cyclohexanol.

To evaluate the relationship between the extent of p-cresol conversion and the reaction selectivity to the desired 4-methyl cyclohexanone, the conversion and selectivity profile of these different p-cresol hydrogenation data were plotted together as shown in **Figure 5**. The conversion versus selectivity profile collected at different temperatures and hydrogen concentrations in the gas stream showed that all experimental data points collapsed into a square-shaped relationship. The reaction selectivity to 4-methyl cyclohexanone was maintained at >95% when the conversion of p-cresol was below 70% for all feed hydrogen concentrations. The selectivity to 4-methyl-cyclohexanone decreased when the conversion of p-cresol reached 80%. This indicates that the selectivity of the p-cresol hydrogenation reaction was independent of the amount of hydrogen in the gas stream but depended instead on the extent of conversion of p-cresol. The relationship observed in **Figure 5** between the selectivity and conversion indicated a simple proposed mechanism leading to unselective catalysis and over-hydrogenated product. For low conversion of p-cresol hydrogenation of desorbed 4-methyl-cyclohexanone. Only after p-cresol was sufficiently reduced in concentration was 4-methyl-cyclohexano able to adsorb to Pd active sites and further react to 4-methylcyclohexanol.

Response Surface Method Analysis. To further elaborate the relationship between the rate of pcresol conversion and rate of 4-methyl cyclohexanone generation to the reaction operating parameters, we generated a response surface method (RSM) model (Figure 6). The rate of p-cresol conversion and net generation of 4-methyl cyclohexanone was determined in units of mole gram-Pd⁻¹ hr⁻¹. The analysis of variance table and the regression equation in uncoded units are presented in the supporting information. The RSM model shows a statistically significant linear effect of all individual factors to conversion of pcresol and a significant two-way interaction between reaction temperature and liquid residence time. The two-way interaction between the liquid residence time and the reaction temperature is presented in Figure 6A & 6C. The two-way interaction shows that there are two different regimes of temperature's effect on pcresol conversion. At high liquid residence time (2 min), temperature only minimally changed to the conversion. However, the effect of temperature was significant when the reaction was carried out at short liquid residence time (0.5 min). The small effect of temperature at high residence time was caused by the rapidly depleting concentration of p-cresol in the catalyst bed due to the p-cresol conversion rapidly reaching 100% at high residence time. The effect of hydrogen pressure to cresol conversion to hydrogen pressure is minimal when compared to either reaction temperature or liquid residence time (see supporting information).

The net generation of 4-methyl cyclohexanone was also assessed by the RSM model (**Figure 6B**). The model predicted that the net generation of 4-methyl cyclohexanone is independent of the hydrogen pressure used. The surface plot from the RSM model of net 4-methyl cyclohexanone generation depicted two-way interaction between reaction temperature and liquid residence time, similar with the relationship between temperature and residence time with p-cresol conversion. The effect of temperature was significant at moderate and low liquid residence time, where elevated temperature resulted in higher net generation of 4-methyl cyclohexanone and contributed to higher reaction selectivity.

The calculated conversion and product generation was then used to map the percent conversion of p-cresol (**Figure 6C**) and reaction selectivity (**Figure 6D**, obtained from dividing the values in **Figure 6B** with **6A**). The prediction from the RSM model was consistent with the experimental measurement shown in **Figure 5**, where the reaction selectivity to 4-methyl cyclohexanone production only decreased after a certain level of p-cresol conversion was achieved. According to prediction from the RSM model, the reaction operating parameters can be selected for a combination of low-to-medium residence time (0.5 - 1.0 min) and reaction temperature (80 - 100 °C) to maximize the selectivity and yield of the desired 4-methyl cyclohexanone while ensuring high catalyst productivity. Whereas the hydrogen pressure was shown to have a more minimal effect in determining the reaction selectivity and activity.

Kinetic Measurement. The high reaction selectivity favored at low temperature can also be explained from comparison of the separately measured kinetics of the two-step cresol hydrogenation. The catalytic turnover frequency (TOF) was determined by calculating the rate based on the number of surface palladium active sites measured by the CO chemisorption. The Arrhenius plot comparing the activity of pcresol hydrogenation and 4-methyl cyclohexanone is shown in Figure 7. The measured turnover frequency of p-cresol hydrogenation was at least two times greater than 4-methyl cyclohexanone hydrogenation in the temperature range assessed (333-373 K). The reaction apparent activation barrier for p-cresol hydrogenation was 67 ± 2 kJ mol⁻¹ in comparison to the apparent activation barrier for 4-methyl cyclohexanone at 92 ± 11 kJ mol⁻¹. The apparent barrier measured is similar to apparent barrier of 70 kJ mol⁻¹ reported in literature for phenyl ring hydrogenation on Pd catalyst.^{36,67} This shows that energetically the second hydrogenation step (4-methyl cyclohexanone to 4-methyl cyclohexanol) is less favorable and contributes to the high reaction selectivity obtained. The higher TOF and lower apparent barrier for p-cresol hydrogenation indicated that selective hydrogenation can be achieved by operating at low temperature hydrogenation, where there was a faster rate of initial hydrogenation of the phenyl ring in the p-cresol compared to ketone hydrogenation at the cyclohexanone intermediate. Similar findings was also reported where low temperature hydrogenation of phenol on Pd resulted in higher yield of cyclohexanone due to preferred desorption of the cyclohexanone over further hydrogenation of cyclohexanone to cylohexanol⁴⁶.

Caprolactone alkyl groups. In practice, lignin derived phenols can have alkyl groups at different positions on the phenyl ring of different carbon-chain lengths. An effective continuous process needs to be able to selectively hydrogenate these alkyl-phenols at low temperature and moderate pressure. Monomers with increasing length of the alkyl chain at the para position were evaluated as the feedstock for the selective hydrogenation in this continuous process. Hydrogenation of cresols isomers with methyl group at different positions was also conducted. The conversion of several different alkyl-phenols and the selectivity of the alkyl-cyclohexanone are presented in Figure 8 for identical reaction conditions (373 K, 120 mL/min H₂). The highest extent of conversion was observed for phenol, with less active reactions containing the addition of methyl, ethyl, and propyl groups at the para position. The reaction was less productive as the length of the alkyl group increased. However, the reaction selectivity to the cyclohexanone intermediate was maintained at equal level of 93% for the same reaction conditions. The location of the alkyl group had a strong effect towards the hydrogenation activity. Hydrogenation activity was similar when the methyl group was located at the para and meta position. However, the rate of hydrogenation was reduced (3x lower) when the methyl group was located at the ortho position. Independent of the differences in reaction productivity, the high selectivity (>93%) obtained using the different alkyl-phenols showed that the reactions still went through the similar simple mechanism observed from p-cresol hydrogenation. The effect of the addition of these alkyl groups was investigated by comparing the apparent barrier and the initial rate of p-cresol hydrogenation with 4-propylphenol hydrogenation. The apparent barrier was measured to be equal (Figure

S7 in supplemental information) between p-cresol hydrogenation (67 \pm 2 kJ/mol) and 4-propylphenol hydrogenation (69 \pm 4 kJ/mol). However, the 4-propylphenol underwent a slower initial rate of phenyl ring hydrogenation. This can plausibly be attributed to the stronger steric effect from the longer alkyl chain in 4-propylphenol, but both reactants underwent the same hydrogenation process, evident from the equal barrier of the two catalytic reactions.

Conclusions. The selective hydrogenation of lignin-derived monophenols is an important step in creating a viable pathway to produce high value branched caprolactone monomers from renewable sources. In this work, the gas-liquid two-phase selective hydrogenation of p-cresol, a model compound of lignin-derived phenols, was evaluated using 5 wt% Pd/ γ -Al₂O₃ in an up-flow packed bubble column reactor. Hydrogen pressure in the system only had minimal effect to the reaction's productivity when compared to liquid residence time and reaction temperature. High hydrogenation selectivity to alkyl-cyclohexanone (>93%) was obtained for all reactions with less than 80% conversion of p-cresol. The hydrogenation selectivity was found to be dependent on the catalyst surface coverage of the adsorbed p-cresol, which inhibits secondary hydrogenation of desorbed 4-methyl cyclohexanone on the catalyst. The apparent barrier and turnover frequency measurement from the phenyl ring hydrogenation of p-cresol and carbonyl hydrogenation of the 4-methyl cyclohexanone intermediate showed faster initial rate of the phenyl ring hydrogenation that is favored at lower temperatures.

Acknowledgements. This work was supported as part of the Bottle Center funded by the U.S. Department of Energy under award #DE-EE0009304.

Keywords. Caprolactone, lignin, catalysis, phenol, hydrogenation

Supporting Information. The supporting information can be found online at X:

	Surface area (m²/g)	Pore Volume (cm ³ /g)	Pd dispersion
5wt% Pd/γ- Al ₂ O ₃	167	0.43	0.26
γ -Al ₂ O ₃	182	0.48	-



Scheme 1. Selective catalytic hydrogenation of alkyl-phenols derived from lignin to form alkyl-cyclohexanones for production of renewable caprolactone. The alkyl-phenol can be obtained from poplar-lignin through reductive catalytic fractionation process. The alkyl-phenol can then undergo selective hydrogenation to alkyl-cyclohexanone with some side reaction of further hydrogenation of the cyclohexanone to the cyclohexanol. The produced alkyl-cyclohexanone can be oxidized through Baeyer-Villiger Oxidation to make alkyl-caprolactones, which can be polymerized to polyesters. At their end-of-use, the polyesters can be chemically recycled to generate the renewable caprolactone monomer again.



Figure 1. Experimental diagram for gas-liquid-solid hydrogenation of alkyl-phenols to alkyl-cyclohexanone. Liquid alkyl-phenols solution is fed using an HPLC pump in an up-flow configuration into the catalyst bed. H_2 or N_2 gas is cofed with separate mass flow controller into the catalyst bed also in an up-flow configuration. Pressure is maintained using a spring loaded back pressure regulator. Reactor effluents were collected periodically from the collection vessel into a sample vial.



Figure 2. Catalyst characterization of synthesized 5wt% Pd/ γ -Al₂O₃. (**A**) X-ray diffraction peaks of γ -Al₂O₃ (blue), 5wt% Pd/ γ -Al₂O₃ after calcination (red), and after reduction (black). Key: * = Pd metal, + = Pd oxide. (**B**) Nitrogen physisorption isotherm of 5wt% Pd/ γ -Al₂O₃ and γ -Al₂O₃. HAADF STEM image of synthesized 5wt% Pd/ γ -Al₂O₃. (**C**) STEM image of catalyst particle at 100 nm scale. The Pd particles are signified by the bright particles. (**D**) The particle size distribution of the Pd particles on the 5 wt% Pd/ γ -Al₂O₃ catalyst. Particle size is measured using the ImageJ software by measuring the longest diameter of the particles. The average particle size is measured at 9.2 nm.



Figure 3. Conversion of p-cresol and selectivity to 4-methyl-cyclohexanone over different liquid residence time. The liquid residence time is varied by changing the liquid feed flowrate. The different hydrogen concentration was obtained through dilution with nitrogen gas. Reaction condition: 373 K, 100 psig total pressure, 0.1 gram of 5wt% Pd/ γ -Al₂O₃, 120 mL/min total gas flow, 0.182 M p-cresol in dodecane. Error bars are represented in 95% confidence intervals.



Figure 4. Conversion of p-cresol and selectivity to 4-methyl-cyclohexanone over various reaction temperature and hydrogen concentration in the gas stream. The hydrogen concentration was changed by co-flowing nitrogen gas. Reaction condition: 100 psig total pressure, 0.1 gram 5wt% Pd/ γ -Al₂O₃, 120 mL/min total gas flowrate, 1 mL/min liquid flow, 0.182 M p-cresol in dodecane. Error bars are represented in 95% confidence intervals.



Figure 5. Selectivity to 4-methyl-cyclohexanone plotted versus conversion of p-cresol. The data plotted was obtained from measurements and reaction conditions performed in figure 5. Each color represents different H_2 concentration in the gas stream across the varying reaction temperature. Reaction condition: 100 psig total pressure, 0.1 gram 5wt% Pd/ γ -Al₂O₃, 120 mL/min total gas flowrate, 1 mL/min liquid flow, 0.182 M p-cresol in dodecane. Error bars are represented in 95% confidence intervals.



Figure 6. (A) Surface plot of p-cresol conversion (mol of p-cresol converted/ g. Pd/ hr) as a function liquid residence time and reaction temperature as assessed by the response surface method model. (B) Surface plot of net generation rate of 4-methyl cyclohexanone (mol/g. Pd/hr) as a function of reaction temperature and liquid residence time as assessed by the response surface method model. (C) P-cresol conversion surface plot as calculated from response surface model. (D) Surface plot for 4-methyl cyclohexanone selectivity as a function of reaction temperature and liquid residence time. Selectivity values were obtained by dividing the calculated values in figure (B) with (A). The measured experimental data points are presented by the circles data point. Reaction condition: 100 psig total pressure, 0.1 gram 5wt% Pd/ γ -Al₂O₃, 120 mL/min total gas flowrate, 0.182 M p-cresol in dodecane.



Figure 7. Arrhenius plot (333K-373 K) of p-cresol hydrogenation and 4-methyl cyclohexanone hydrogenation on 5wt% Pd/ γ -Al₂O₃. Reaction conditions: ambient pressure, 120 mL/min H₂ gas flowrate, 0.01 gram 5wt% Pd/ γ -Al₂O₃ (p-cresol), 0.5 gram 5wt% Pd/ γ -Al₂O₃ (4-methyl cyclohexanone), 0.5 mL/min liquid flowrate, 0.182 M p-cresol/4-methyl cyclohexanone in dodecane. Error bars are represented in 95% confidence intervals.



Figure 8. Conversion of alkyl-phenol and selectivity to alkyl-cyclohexanone of phenolic species with different position and length of alkyl chain. Reaction condition: 373 K, 100 psig, 100 mg 5wt% Pd/γ-Al₂O₃, 120 mL/min H₂ gas flow, 1 mL/min liquid flow, 0.182 M reactant in dodecane. Error bars are represented in 95% confidence intervals.

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