Hierarchical Porous Activated Carbon-Supported Ruthenium Catalysts for Catalytic Cleavage of Lignin Model Compounds

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Abstract: The catalytic conversion of lignin model compounds was performed using Ru/C catalysts and an autoclave reactor. The Ru/C catalysts were prepared by the impregnation method using highly porous homemade activated carbon and characterized by XRD, SEM, and specific surface area. The catalytic reactions were performed in a high pressure/temperature reactor at different temperatures and with different solvents. The results showed that the novel Ru/C catalysts prepared from carbon supports activated by the KOH agent showed higher catalytic activity than the commercial catalyst. Ethanol and 2-propanol were suitable solvents for the cleavage of the β-O-4 ether bond of 2-phenoxy-1-phenyl ethanol (~65–70% conversion) over a Ru/C-KOH-2 catalyst at 220 °C in comparison to tert-butanol and 1-propanol solvents (~43–47% conversion of 2-phenoxy-1-phenyl ethanol). Also, the increase in reaction temperature from 200 °C to 240 °C enhanced the cleavage of the ether bond with an increase in phenol selectivity from 9.4% to 19.5% and improved the catalytic conversion of 2-phenoxy-1-phenyl ethanol from 46.6% to 98.5% over the Ru/C-KOH-2 catalyst and ethanol solvent. The Ru/C-KOH-2 catalyst showed outstanding conversion (98.5%) of 2-phenoxy-1-phenylethanol at 240 °C, 1 h, ethanol solvent. This novel hierarchical porous activated carbon-supported ruthenium catalyst (Ru/C-KOH-2) can be applied for the further conversion of the lignin compound.

Keywords: active carbon; biochar; Ru/C; lignin; β-O-4 aryl ether

1. Introduction

Activated carbon is a common material applied in adsorption and catalyst support. Several bio-activated carbons were synthesized from agricultural waste [1–7]. Those materials have some limitations in terms of pore structure resulting in the low dispersion of active metal on the surface, whereas shellfish have a hard structure that is easily converted into porous biochar [7], making them an excellent candidate for catalyst support. Additionally, Vietnam has a long coast from the north to the south with high seafood production, and the value of exported seafood was USD 8.89 billion in 2021 [8]. According to Vietnam Customs data, Vietnam’s shrimp exports in 2021 reached USD 3.9 billion [9]. In parallel with the development of seafood production, we are facing waste from seafood such as shrimp and crab shells. It is a great idea to convert them into a valuable product, such as activated carbon for adsorption and catalyst support.

Recently, Yu et al. revealed that the hierarchical porous biochar produced from shrimp shells can enhance adsorption capacity and avoid the drawback of agricultural material [7].
In addition, Zhao et al. developed 3D carbon nanosheets with a very high surface area (>1500 m²/g) by activation in a nitrogen atmosphere with KOH [10]. Also, biochar or active carbon is widely used as support for the catalytic reaction. Moreover, Ru is the active site for both lignin [11–17] and model lignin conversion [14,18–22] via the cleavage of C–C and C–O bonds. Cao et al. found that the activated carbon was excellent support with high benzyl phenyl ether conversion (88.8%) in comparison to MgO (53.2%), ZrO₂ (54.6%), Al₂O₃ (84.2%) at 160 °C, 1 MPa H₂, 2h, and methanol solvent. Also, Jiang et al. found that Ru/4-1AC exhibited a high catalytic activity with respect to diphenyl ether and benzyl phenyl ether as reactants at a mild condition [20]. In fact, the conversion of diphenyl ether and benzyl phenyl ether reached full conversion using the Ru/4-1AC catalyst at 150 °C, 1 MPa H₂, and with 2-propanol as a solvent [20]. The high catalytic activity was due to the high specific surface area, more defects, and small Ru metal particles. Additionally, Jiang et al. [20] revealed that the lower bonding energy of Ru₀ promoted the formation of active hydrogen from H₂ and 2-propanol, enhancing the breaking of the C–O bond and the catalytic performance. The cleavage of the C–O bond also depended on the adsorption energy of the reactant on the surface of Ru metal and the bond dissociation energy of the C–O bond [20]. However, most studies used high-pressure hydrogen to break the lignin bonds [12,14,15,17–21], which causes an increase in the cost of lignin depolymerization, and the presence of hydrogen can improve the hydrogenation reaction to reduce the formation of aromatic compounds. Hossain et al. found that metallic Ru is an active material for the decomposition of the β–O–4 linkage of lignin model compounds in the absence of hydrogen [23]. Therefore, the doping of metallic Ru on the surface of hierarchical porous biochar with a high surface area may enhance the cleavage of the β–O–4 linkage. In addition, the utilization of 2-propanol to model lignin compound conversion can tailor the product selectivity. Indeed, the presence of 2-propanol as a solvent promoted the cleavage of C–O bonds and enhanced the formation of aromatics more than that under only a H₂ atmosphere [22]. It is well known that protic 2-propanol solvent displays Lewis basicity, and is a good H-bond donor and a good H-bond acceptor [22], suggesting that solvent is an important factor in the catalytic activity and product selectivity.

In this work, we produced activated carbon from waste seafood materials as supports for the conversion of lignin model compounds, then doped metallic Ru on the surface of the activated carbon by wet impregnation followed by a reduction in the H₂ atmosphere. We hypothesize that the higher surface area of activated carbon produced by using KOH as an activating agent can enhance the distribution of metallic Ru leading to higher catalytic conversion. In addition, we expect that the well distribution of Ru metal on support with the high surface area can break the ether bond of the lignin model compounds (2-phenethyl phenyl ether and 2-phenoxy-1-phenylethanol) and further hydrogenation reaction to form phenol and ethyl benzene. The effect of reaction temperature and solvents was also performed and discussed.

2. Experimental

2.1. Catalyst Preparation

The catalysts were prepared through 2 periods including active carbon synthesis and doping Ru metal periods. In the first period, shrimp shells were collected from Ca Mau province (Vietnam), then the shrimp meat was removed, washed, dried under sunlight, crushed, and collected as powder with a size of 125–212 µm after being sieved. The powder was calcined in a homemade tubular reactor at 600 °C for 2 h under N₂ flow (50 cc/min). Subsequently, the obtained biochar was uniformly mixed with KOH (Fisher Chemical, ≥99.5%, Table S1) in the solid phase with a mass ratio of KOH to biochar of 1 or 2 [10]. The homogeneous mixture was treated in a homemade tubular reactor at 750 °C for 1.5 h under N₂ flow (50 cc/min). Next, the activated carbon was washed with 1 M HCl solution and deionized water until neutral pH and dried at 80 °C overnight. The final activated carbon samples were denoted as C-KOH-1 and C-KOH-2 with respect to the mass ratio of KOH to biochar of 1 and 2, respectively.
In the second period, 5% Ru/C catalysts were prepared using activated carbon synthesized via the impregnation method. Activated carbon synthesized was added into an aqueous solution of ruthenium (III) chloride hydrate (Across, 35–40% Ru, Table S1) and stirred for 3 h at room temperature. Then, Ru/C samples were reduced in hydrogen flow (50 cc/min) at 350 °C for 5 h after drying at 80 °C overnight. The final Ru/C samples were denoted as Ru/C-KOH-1 and Ru/C-KOH-2 with respect to the activated carbon supports. A visual scheme of the catalyst preparation is illustrated in Figure S1. Commercial Ru/C (Alfa Aesar, ruthenium, 5% on activated carbon powder, reduced, nominally 50% water wet, Table S1) denoted as Ru/C-CM was used as a reference.

2.2. Characterization

Powder X-ray diffraction (XRD) analysis and Scanning Electron Microscopy (SEM) were performed for the catalyst samples. The XRD analysis was performed on a Shimadzu 6100 X-ray diffractometer (Shimadzu Corporation, Kyoto, Japan) at a voltage of 40 kV, a current of 30 mA with CuKα radiation at the wavelength of 1.5406 nm, a scanning speed of 0.05°/s, and step size of 0.02° in the range 2θ from 10° to 60°. Scanning Electron Microscopy micrographs were obtained using a JEOL JSM-IT100 microscope (JOEL Ltd., Tokyo, Japan) after the samples were coated with gold. The specific surface area of Ru/C catalysts was measured by the adsorption of methylene blue using the Langmuir isotherm equation [24]. Activated carbon (15–110 mg) was added into 100 mL of methylene blue solution (200 mg/L) at neutral pH and stirred for 2 h at room temperature to reach equilibrium. The supernatant solution was filtered, and the liquid fraction concentration was measured by a UV-Vis at ~630 nm. The amount of methylene blue adsorbed was calculated by the difference in methylene blue concentration before and after adsorption. The q_m (maximum capacity) was calculated from the Langmuir isotherm equation:

\[
\frac{C_e}{q_e} = \frac{C_e}{q_m} + b
\]

and the specific surface area was

\[
S = \frac{q_m \times N_A \times a}{MW_{MB}} \left( \frac{m^2}{g} \right)
\]

where \(C_e\) (mg/L) is the equilibrium concentration of methylene blue in the solution after adsorption, \(q_e\) (mg/g) is the adsorption capacity, \(q_m\) (mg/g) is the maximum adsorption capacity, \(N_A\) is Avogadro number, \(a\) is the area adsorbed per molecule of methylene blue (130 Å²), and \(MW_{MB}\) is molecule weight of methylene blue (319.85 g/mol).

2.3. Lignin Model Compound Conversion

Catalytic conversion of lignin model compounds (2-phenethyl phenyl ether (PPE, 97%) and 2-phenoxy-1-phenylethanol (PPE-OH, 97%)) purchased from AmBeed (Table S1) was performed in a 50 mL autoclave reactor (ZZKD, model TGYF-C). A 30 mL stock solution of lignin model compounds (1% w.t./w.t.) and of dodecane (as internal standard) was added to the reactor with reduced Ru/C catalyst (0.05 g), then the reactor was sealed and purged with nitrogen to remove oxygen. The pyrolysis reaction was carried out at different temperatures and using different organic solvents purchased from Fisher, including ethanol (99.8%), 1-propanol (99.7%), 2-propanol (99.8%), and tert-butanol (99%) (Table S1), with a stirring rate of 600 rpm for 1 h. An ice water bath was used to stop the reaction by quenching. The lignin model compound conversion, product selectivity, and lignin conversion were calculated as follows:

\[
\text{Conversion} \ (\%) = \frac{\text{mole of reactant reacted}}{\text{initial mole of reactant}} \times 100\%
\]

\[
\text{Selectivity} \ (\%) = \frac{\text{mole of product generated}}{\text{mole of reactant reacted}} \times 100\%
\]
The reactants and products were analyzed by the Agilent 7890A GC equipped with Flame Ionization Detectors (FID) and an HP-5 column (30 m × 0.32 mm × 0.25 μm). The GC program was injection temperature of 275 °C and FID detector temperature of 300 °C, a split ratio of 1:30. The temperature started at 45 °C and increased at 10 °C/min to 120 °C, then was held for 1 min, next increased at 20 °C/min to 250 °C, then was held for 15 min. The reactants and products were identified by the HP 6890 GC equipped with an Agilent 19091S-443 mass spectrometer. An HP-5MS (30 m × 0.25 μm × 0.25 μm) was used for product separation along with He as carrier gas with the temperature program: injection temperature of 260 °C, a split ratio of 1:30. The temperature program started from 60 °C and was held for 1.5 min, increased at 10 °C/min to 120 °C, then was held for 1 min, next increased at 20 °C/min to 250 °C, then was held for 7 min. Mass scans were from 35 to 650 amu.

3. Results and Discussion
3.1. Characterizations of the Investigated Catalysts

The XRD patterns showed that the three catalysts possess mostly amorphous structures (Figure 1). Indeed, the percentage of Ru is only 5% wt. on a carbon support; therefore, the morphology of the catalysts mainly depends on the morphology of the supports. For the Ru/C-KOH-1 sample, the sharp peak at 44° indicated the presence of Ru⁰ [25,26], while the commercial Ru/C catalyst and Ru/C catalyst with C-KOH-2 support exhibited only broad peaks of amorphous structure. These results demonstrated that the peak of the metallic Ru or Ru oxide was extremely weak and Ru may exist in the form of small particle size [27]. The small particles of Ru distributed on the surface of the support can enhance the catalytic activity due to the well dispersion of active sites on the surface of the catalysts. The XRD patterns did not confirm the activities of the catalysts, but they revealed that the well dispersion of Ru can lead to the production of more active sites on the surface of the catalyst with respect to the presence of large Ru particle size.

![Figure 1. XRD pattern of investigated Ru/C catalysts.](image)

The morphology of homemade catalysts presented as more porous than the commercial catalyst (Figure 2). The commercial catalyst showed a honeycomb structure, while the homemade catalysts exhibited 3D interconnected porous networks resulting in a large specific surface area. In fact, using KOH as a treating agent at a high temperature (750 °C) will burn the carbon of the biochar from the first step of the preparation of the activated carbon from shrimp shells. The presence of KOH with carbon at high temperatures led to the formation of K and K₂CO₃ through the reaction 6KOH + 2C → 2K + 2H₂ + 2K₂CO₃.
K₂CO₃ can decompose to form K₂O and CO₂ via the reaction K₂CO₃ → K₂O + CO₂; these products can also react with a carbon of biochar to create porosity of activated carbon with two reactions of CO₂ + C → 2CO and K₂O + C → 2K + CO. In addition, the produced K₂CO₃ can burn carbon to form K and CO with the reaction K₂CO₃ + 2C → 2K + CO. The consecutive reactions of KOH and its product will burn the carbon of biochar to form porous materials. Figures S2 and S3 provide details on the morphology of Ru/C-KOH-1 and Ru/C-KOH-2 catalysts; they demonstrate that treating with KOH led to the production of porous networks of biochar. Moreover, the specific surface area of all the investigated catalysts (Table 1) proved the high porosity. The surface area of the homemade catalysts (1530 m²/g for Ru/C-KOH-1 and 1749 m²/g for Ru/C-KOH-2) in comparison to that of the commercial catalyst (~597 m²/g) indicated that a high mass ratio of KOH to biochar gave high surface area. These specific surface areas agreed with the same process performed by Zhao et al. [10]. The high specific surface area and high porous morphology of homemade Ru/C catalysts lead to a high dispersion of metallic Ru on the surface of the carbon support. As a result, homemade Ru/C catalysts can enhance catalytic activity in comparison to the commercial catalyst.

Table 1. The properties of investigated catalysts.

<table>
<thead>
<tr>
<th>Notation</th>
<th>% Ru</th>
<th>Source</th>
<th>Specific Surface Area (m²/g)</th>
<th>Preparation Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ru/C-CM</td>
<td>5</td>
<td>Alfa Aesar</td>
<td>~597</td>
<td>Commercial (reduced), used as received</td>
</tr>
<tr>
<td>Ru/C-KOH-1</td>
<td>5</td>
<td>Homemade</td>
<td>~1530</td>
<td>5% Ru on C-KOH-1, reduced at 350 °C for 5 h</td>
</tr>
<tr>
<td>Ru/C-KOH-2</td>
<td>5</td>
<td>Homemade</td>
<td>~1749</td>
<td>5% Ru on C-KOH-2, reduced at 350 °C for 5 h</td>
</tr>
</tbody>
</table>

Figure 2. SEM image of investigated Ru/C catalysts.
Table 1. The properties of investigated catalysts.

<table>
<thead>
<tr>
<th>Notation</th>
<th>% Ru</th>
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<td>~1749</td>
<td>5% Ru on C-KOH-2, reduced at 350 °C for 5 h</td>
</tr>
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</table>

3.2. Conversion of Lignin Model Compounds Using the Investigated Catalysts

The catalytic activity of Ru/C catalysts was performed using 2-phenethyl phenyl ether (PPE) and 2-phenoxy-1-phenylethanol (PPE-OH) as reactants. Figure 3 shows that the conversion of PPE-OH is higher than that of PPE over the same catalysts at 240 °C. Indeed, the conversion of PPE was very low (<3%) over all three Ru/C catalysts demonstrating that it is hard to break the β-O–4 ether bond at such conditions without hydrogen at 240 °C over Ru/C catalysts. In the case of the PPE-OH reactant, all three catalysts were active for PPE-OH conversion (Figure 3), and the main reactions were the dehydration of PPE-OH to form PPE (~50%) and the cleavage of ether bond to form phenol and acetophenone, which converted to ethylene benzene, styrene and 1-phenyl alcohol (Table 2, entries 1, 2, and 5). That suggested that the presence of the –OH group of Cα of PPE-OH provided a hydrogen source for the cleavage of the β–O–4 ether bond, which was not observed in the case of PPE. Our results were in agreement with the previous studies [23,28], in which the internal hydrogen of the –OH group of Cα was shown to act as a hydrogen source for the cleavage of ether bonds. Interestingly, both the homemade Ru/C catalysts including Ru/C-KOH-1 and Ru/C-KOH-2 exhibited higher catalytic activity in comparison to the commercial Ru/C-CM catalysts. That is possibly due to the high specific surface area (1749 m²/g for Ru/C-KOH-2 and 1530 m²/g for Ru/C-KOH-1) and high porous material (Figure 2) with respect to the Ru/C-CM catalyst (597 m²/g). The higher specific surface area allows the well dispersion of Ru on the surface of the support, resulting in the improvement of the number of active sites leading to a higher catalytic activity. In addition, it is well known that porous catalysts allow the entrance of molecules into the active sites where the reaction can occur, which help enhancement of the catalytic conversion of reactants over the highly porous homemade Ru/C-KOH-1 and Ru/C-KOH-2 catalysts. Interestingly, the homemade Ru/C-KOH-2 catalyst showed excellent activity (98.5% conversion of PPE-OH) at 240 °C, N₂ atmosphere, and was comparable to the CoMoS₂/C catalyst (~100% PPE-OH conversion at 300 °C, 50 bar initial H₂ pressure) [29], and the 5Ni–5Co/NbOₓ catalyst (100% PPE-OH conversion at 300 °C, 3 MPa H₂) [30], suggesting that our homemade Ru/C-KOH-2 can decompose PPE-OH at lower temperatures and without nitrogen.

Looking at the effect of the reaction temperature on the product selectivity and the activity of the Ru/C-KOH-2 catalyst (Figure 4), the catalytic activity increased with an increase in reaction temperature from 200 to 240 °C. The highest PPE-OH conversion (98.5%) was obtained at 240 °C after 1 h reaction without external hydrogen (Figure 4), demonstrating that the homemade Ru/C-KOH-2 catalyst is a promising catalyst for lignin depolymerization. The increase in reaction temperature also improved the cleavage of the ether bond to form phenol and the acetophenone derived such as ethyl benzene, while dehydration followed by hydrogenation to form PPE (72.1% at 200 °C) was the main reaction at low temperature (200 °C) (Table 2, entries 3–5). It can be concluded that the reaction temperature is an important factor for catalytic conversion and tailoring the product selectivity.
Moreover, catalytic conversion and product selectivity can be tailored by using different solvents (Figure 5, Table 2, entries 4, 6–8). The ethanol and 2-propanol solvents showed higher PPE-OH conversion with respect to 1-propanol and tert-butanol. The higher catalytic activity using ethanol and 2-propanol solvents is due to the low Lewis basicity of the solvent (donor number (DN) = 133.9 kJ/mol for ethanol, and 150.6 kJ/mol for 2-propanol) in comparison to those of 1-propanol (DN = 153.2 kJ/mol) and tert-butanol (DN = 159.0 kJ/mol) [31]. In fact, in the same manner, high Lewis basicity showed a low catalytic activity of lignin model compounds over the Raney Ni catalyst [31]. In addition, the solvent also tailored the product selectivity; both ethanol and 2-propanol displayed good solvents for the cleavage of the β–O–4 ether bond with ca. 18% phenol at 220 °C (Table 2, entries 4 and 7), while 1-propanol presented high dehydration and hydrogenation to form PPE (67%) and a low cleavage of the β–O–4 ether bond with ~11% (Table 2, entry 6). Interestingly, tert-butanol had the same performance as 1-propanol in the cleavage of the ether bond, but it showed a lower dehydration reaction and favored etherification of PPE-OH and tert-butanol with 37.2% selectivity. That suggested that tert-butanol was not a suitable solvent for lignin model compound conversion, and the proper solvents were ethanol and 2-propanol. Indeed, both ethanol and 2-propanol showed a low formation of 2-phenoxy-1-phenylethan-1-one (3.3% for 2-propanol, and 6.4% for ethanol solvent) and (E)-(2-phenoxyvinyl) benzene (3.2% for 2-propanol, and 6.2% for ethanol solvent) via dehydrogenation and dehydration of PPE-OH (Table 2), respectively, whereas the cleavage of the β–O–4 ether bond was a significant reaction after the production of PPE (52–57%).

The cleavage of the β–O–4 ether bond was notable, with the presence of phenol and acetophenone (Table 2). Importantly, the 2-propanol solvent showed a higher production of ethyl benzene than that of the ethanol solvent (Table 2, entries 4 and 7) suggesting that secondary alcohol (2-propanol) can donate more hydrogen than primary alcohol (ethanol) [22]. However, the products mostly contained aromatic compounds and less further hydrogenation reaction into cycloalkane due to the use of N2 atmosphere instead of H2 atmosphere pressure in the previous studies [29,30].

![Figure 3](image.png)

**Figure 3.** The conversion of 2-phenoxy-1-phenyl ethanol and 2-phenethyl phenyl ether over investigated Ru/C catalysts. Reaction conditions: 1 h, N2 atmosphere, 1 wt.% reactant/ethanol, 20 wt.% catalyst loading.
Entry | Catalyst | Solvent | Temp. (°C) | Conversion (%) | C=C | C=O | Others |
---|---|---|---|---|---|---|---|
1 | Ru/C-CM | Ethanol | 240 | 50.3 | 12.1 | 1.0 | 18.1 | 3.6 | - | 50.0 | 1.2 | - | 14.0 |
2 | Ru/C-KOH-1 | Ethanol | 240 | 89.2 | 18.7 | 6.3 | 19.3 | 1.7 | - | 48.2 | 1.2 | 2.4 | 0.9 |
3 | Ru/C-KOH-2 | Ethanol | 200 | 46.6 | 4.3 | 3.0 | 9.4 | 0.9 | 0.6 | 72.1 | 4.8 | 3.6 | 1.3 |
4 | Ru/C-KOH-2 | Ethanol | 220 | 70.9 | 4.4 | 8.2 | 16.4 | 0.7 | 2.6 | 52.2 | 6.4 | 6.2 | 2.9 |
5 | Ru/C-KOH-2 | Ethanol | 240 | 98.5 | 20.1 | 1.1 | 19.5 | 2.1 | - | 57.2 | - | - | - |
6 | Ru/C-KOH-2 | 1-propanol | 220 | 43.4 | 6.5 | 1.6 | 11.1 | 1.7 | - | 67.1 | 1.8 | 5.0 | 5.2 |
7 | Ru/C-KOH-2 | 2-propanol | 220 | 64.9 | 13.0 | 2.2 | 17.7 | 1.3 | 0.7 | 57.0 | 3.3 | 3.2 | 1.6 |
8 | Ru/C-KOH-2 | Tert-butanol | 220 | 47.1 | 0.8 | 6.9 | 10.2 | 0.7 | - | 14.2 | 13.3 | 14.4 | 39.5* |

* 37.2% ether of PPE-OH and tert-butanol.

Table 2. Conversion and product selectivity of 2-phenoxy-1-phenyl ethanol conversion over investigated Ru/C catalysts. Reaction conditions: 1 h, 1 wt.% reactant/solvent, 20 wt.% catalyst loading.

Figure 4. The conversion of 2-phenoxy-1-phenyl ethanol over Ru/C-KOH-2 catalyst at different temperatures. Reaction conditions: 1 h, N₂ atmosphere, 1 wt.% reactant/ethanol, 20 wt.% catalyst loading.

Figure 5. The conversion of 2-phenoxy-1-phenyl ethanol over Ru/C-KOH-2 catalyst with different solvents. Reaction conditions: 220 °C, 1 h, N₂ atmosphere, 1 wt.% reactant/solvent, 20 wt.% catalyst loading.
4. Conclusions

In this work, it can be concluded that homemade porous carbon supports activated by KOH, and Ru/C catalysts were successfully prepared and showed higher activity than the commercial catalysts. The –OH group of C\textsubscript{α} can act as an internal hydrogen source, supporting the cleavage of the β–O–4 ether bond of the lignin model compound. The reaction temperature and solvents can tailor the catalytic activity and product selectivity. An increase in reaction temperature from 200 °C to 240 °C decreased the selectivity of 2-phenethyl phenyl ether (~72% to 57%) and enhanced the selectivity of phenol (~9.4% to 19.5%) and ethyl benzene (~4.3% to 20.1%), while the ethanol and 2-propanol solvents improved the cleavage of the β–O–4 ether bond forming phenol (~16–17%) and styrene (8.2% for ethanol) or ethyl benzene (13.0% for 2-propanol). Ethanol and 2-propanol showed the highest breaking of the β–O–4 ether bond (~65–70% 2-phenoxy-1-phenyl ethanol conversion). 2-phenoxy-1-phenylethanol achieved the highest conversion (98.5%) over Ru/C-KOH-2 at 240 °C after 1 h reaction. The results demonstrated that the higher the surface area of activated carbon is, the higher the lignin model compound conversion is. The high surface area of activated carbon from waste seafood improved the conversion in comparison to the commercial one. These activated carbons can be used for several catalytic reactions using support.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/en15228611/s1, Figure S1: The scheme of the preparation of catalysts; Figure S2: SEM image of Ru/C-KOH-1 catalyst; Figure S3: SEM image of Ru/C-KOH-2 catalyst; Table S1: List of chemicals/reagents used in this study.

Author Contributions: Conceptualization, T.K.P.; Methodology, X.-T.P., V.A.T., K.B.V. and T.K.P.; Formal analysis, V.A.T., L.-T.T.T. and T.-H.N.; Investigation, T.K.P.; Data curation, X.-T.P., L.-T.T.T., T.N.P.N., T.H.L., H.H. and K.B.V.; Writing—original draft, X.-T.P. and T.K.P.; Writing—review & editing, T.K.P.; Supervision, T.K.P.; Project administration, T.K.P.; Funding acquisition, T.K.P. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest: The authors declare no conflict of interest.

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