Research Article

Highly Selective Reduction of Bio-Based Furfural to Furfuryl Alcohol Catalyzed by Supported KF with Polymethylhydrosiloxane (PMHS)

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Hydrogenation of bio-based furfural (FUR) to furfuryl alcohol (FFA) is tremendously expanding the application of biomass in many industries such as resins, biofuels, and pharmaceuticals. However, mass manufacture of FFA from FUR is restrained by strict requirements of reaction conditions and expensive catalysts. In this work, an economical and benign catalytic system, containing an easily prepared and reusable catalyst 5 wt.% KF/ZrO₂ and a low-cost hydrogen source polymethylhydrosiloxane (PMHS), was developed to be efficient for the hydrogenation of FUR to high-value FFA under mild conditions. The catalyst reactivity was found to be remarkably influenced by the support acid-base properties and KF loading doge. In the presence of 5 wt.% KF/ZrO₂, a high FFA yield of 97% and FUR conversion of 99% could be obtained at 25 °C in just 0.5 h, which was superior to those attained with other tested catalysts. The KF/ZrO₂ catalyst could be recycled at least five times, with the FFA yield slightly decreasing from 97% to 71%. The spare decrease in FFA yield is possibly attributed to the catalyst pore blocking, as clarified by SEM, BET, XPS, and ICP-MS measurements of the fresh and reused catalysts.

1. Introduction

Diversiform sustainable clean energies have been developed to get rid of the dependence of nonrenewable fossil energy and relieve environmental deterioration caused by combustion of fossil fuel in past decades [1–3]. In particular, biomass containing abundant carbon source is considered as the best source to replace fossil fuels, for the production of various biofuels such as biodiesel, ethanol, and 2,5-dimethylfuran [4–8]. In addition, through a series of chemical reactions including hydrolysis, dehydration, oxidation, hydrogenation, and hydrogenolysis, lignocellulosic biomass can be transformed into numerous value-added oxygen-containing heterocyclic compounds [9–17].

Furfural (FUR) is an important biomass-derived compound, which is mainly obtained from the xylose which is one of the main hydrolyzates of hemicellulose [18, 19]. Through the partial reduction of FUR, furfuryl alcohol (FFA) can be prepared. FFA is indispensable feedstock for the synthesis of diverse downstream compounds including ethyl furfuryl ether, tetrahydrofurfuryl alcohol, y-valerolactone, levulinic acid, and so on, all of which have wide applications in fuels, pharmaceuticals, and food and chemical industries (Figure 1) [20–29]. Up to now, artificial synthesis of FUR and FFA is of high cost and needs a complex conversion process, indicating that the hydrogenation of FUR not only enlarges the application of biomass but also sharply decreases the synthesis cost of various downstream compounds [30, 31].

The H-donor for the hydrogenation of FUR to FFA is classified as gas- and liquid-phase reaction processes, all of which have corresponding advantages and shortages.
Hydrogen gas as a gaseous H-donor has superiority in the product separation and thus is broadly applied in the diverse hydrogen reactions [32]. At room temperature, hydrogen gas is hard to react with other compounds until the reaction conditions change. High temperature and metal catalysts are effective for the activation of hydrogen gas. In industrial manufacture, the production of FFA from FUR and molecular hydrogen is completed at high temperatures catalyzed by noble metals (e.g., Au, Ru, Pd, and Pt) [33–36], nonnoble metals (e.g., Co, Cu, and Fe) [19, 37–40], and metallic oxides (e.g., CrCuO3) [41]. However, due to the high activity of metal catalysts, aldehyde group and furan ring can be both reduced in this reaction system, resulting in that most catalysts used in the hydrogenation of FUR to FFA are still applied in the laboratory scale. In addition, with the reaction temperature exceeding the boiling point of FUR (167°C), FFA can be efficiently prepared from gas state FUR and hydrogen gas in atmospheric pressure, which indicates that the hydrogenation of FUR can react in both vapor state and liquid state. At the relatively low temperature, hydroxyl, alcohol, acid, and similar liquid compounds with free hydrogen atoms are good H-donor for hydrogenation of FUR to FFA in the liquid phase. The Meerwein–Ponndorf–Verley (MPV) reduction which is used alcohol as liquid H-donor has been largely applied in the reduction of biomass platform molecules, which can simultaneously produce two useful compounds and thus attracts the attention of numerous researchers focusing on biomass valorization [42–44]. Generally, the catalysts performing high catalytic activity for the MPV reduction of FUR to FFA include acid-base bifunctional catalysts (e.g., Pd/HZSM-5 and MgO-Al2O3) [45, 46] and Lewis acid catalysts (e.g., Al-, Zr-zeolites, and Zr-, Al-, Hf-based catalysts) [47–49]. It is noteworthy that the drawbacks of the MPV reaction system such as difficult separation of products and relatively harsh conditions still trouble researchers in this research field. Besides gas-phase H-donor hydrogen gas and alcohol H-donor, increasing reports about the hydrogenation of FUR to FFA by another liquid H-donor hydrosilane have been presented in the past decade [50, 51]. In this reaction system, FFA is obtained from FUR in high selectivity under mild conditions (atmospheric pressure, <80°C), which makes up the imperfection of the reaction system when hydrogen and alcohol are used as H-donor.

For hydrosilane, polymethylhydrosiloxane (PMHS) as the cheapest hydrosilane agent and the by-product of the silicon industry is an ideal H-donor for the hydrogenation of FUR to FFA [8, 52, 53]. At the same time, PMHS is a green agent as it is nontoxic and having great chemical stability for water and atmosphere [54, 55]. Recently, a series of fluoride salts were reported for the conversion of aldehyde to corresponding alcohol by PMHS in highly selective and effective environment [56, 57]. However, the fluoride salts as homogeneous catalysts are not suitable for economically manufacturing FFA from FUR, for which a novel and recyclable catalyst KF/support is reported in this article. The catalyst prepared by the impregnation method provides a suitable carrier for KF to attach, which is favorable for the contract of the substrate with KF and preventing KF from the erosion of solvent and substrate [32, 58]. Through the impregnation method, the obtained solid catalyst that combines the high efficiency of KF and the heterogeneous property of support was developed to catalyze the hydrogenation of FUR to FFA at a lower cost.

2. Results and Discussions

2.1. Effect of Different Supports. For the impregnation method, the loading amount of active sites on the solid support is generally decided by the support porosity and
chemical property [59]. Therefore, the influence of different porous supports on the catalytic behavior of KF was initially investigated (Figure 2). The loading rate of all support catalysts is 3 wt.%

The results listed in Figure 2 show that KF supported on acidic montmorillonite K-10 (K-10) and alkaline hydroxyapatite microspheres (HAP) and nanomagnesium oxide (MgO) performed poor reactivity in this reaction system, which could be attributed to the ion exchange between the support with KF [60] or the competing reaction of fluoride ion and hydroxide released from the support [61], remarkably weakening the nucleophilic attack ability of KF. In connection with this, nanotitanium dioxide (TiO2) and zirconium oxide nanopowder (ZrO2) with both moderate acid and base sites supported KF showed relatively good catalytic activity for the conversion of FUR to FFA. In addition, due to the relatively high surface area of ZrO2, the catalyst using ZrO2 (75% FFA yield) as support had better catalytic reactivity than TiO2 (55% FFA yield). Therefore, ZrO2 which has both moderate acid and base sites and the relatively high surface area is the optimum support for catalyst KF/support.

2.2. Effect of the Loading Rate of KF. Apart from the support, the loading rate of KF is another important factor for the catalyst preparation via impregnation [62]. The KF/ZrO2 catalysts with different KF loading rates (1–15 wt.%) were prepared by the impregnation method for the test of catalytic activity (Figure 3). It was shown that 5 wt.% was the best loading rate of KF/ZrO2 catalyst and increasing the loading rate of KF gave rise to the slight reduction of the catalyst activity of KF/support catalyst. For the decrease of catalytic activity of 15 wt.% KF/ZrO2, this phenomenon could be attributed to the reduction of pore diameter which is caused by the excess of KF. To prove the inference, N2 adsorption-desorption isotherms of KF/support in different loading rates are presented in Figure S3. The hysteresis loop appearing in the N2 adsorption-desorption isotherms of KF/support in different loading rates is shown in Figure S3. The hysteresis loop appearing in the N2 adsorption-desorption isotherms of 5 wt.% and 15 wt.% KF/ZrO2 (Figure S3) is the phenomenon of decrease in pore diameter of 5 wt.% and 15 wt.% KF/ZrO2 catalysts, proving the inference why the catalytic activity of 15 wt.% KF/ZrO2 catalyst is declined. Through the optimization of the support type and the loading content of KF, 5 wt.% KF/ZrO2 shows the best catalytic activity for the hydrogenation of FUR to FFA. In addition, comparison of the results obtained in this work with those of previous studies for the conversion of FUR to FFA is presented in Table 1, which shows that 5 wt.% KF/ZrO2 is a more efficient catalyst for the selective hydrogenation of FUR to FFA.

2.3. Catalyst Characterization. The successful preparation of KF/ZrO2 by the impregnation method commonly keeps the original configuration of support and makes the active substrate KF uniformly distributed in the internal surface of ZrO2. According to the XRD patterns of KF/ZrO2 catalysts with different KF loading rates (1–15 wt.%) (Figure 4), it can be seen that the crystal structure of ZrO2 does not change significantly. The crystal faces of ZrO2 including (1, 1, 0), (−1, 1, 1), (1, 1, 1), (1, 0, 2), (−2, 2, 1), (1, 3, 0), and (1, 3, 1) are attributed to the diffraction peaks at 24.1°, 27.9°, 31.4°, 34.1°, 40.8°, 50.4°, 55.3°, and 59.6°, respectively. As can be seen from the XPS spectra of 5 wt.% KF/ZrO2 (Figure 5), the peaks of 690 eV and 290 eV that, respectively, correspond to the fluorine and potassium are detected, indicating that KF is successfully distributed in the external surface of the support. In the XRD pattern of KF/ZrO2, the diffraction peak at 39.5° can be observed, manifesting the formation of the
alkaline active species (K₃Zr₂F₁₁) by the chemical combination of K⁺ and oxygen species [67]. The results show that KF is immobilized on ZrO₂ which is realized by both physical adsorption and chemical interaction. It is known that ZrO₂ as a porous material has a relatively large surface area (ca. 80–110 m²/g), most of which is provided by the internal surface [68, 69]. Through comparison of the detection results obtained by XPS and ICP-MS analysis (Table 2), a relatively high K content of KF/ZrO₂ detected by ICP indicated that KF is successfully distributed in both the external and internal surface of ZrO₂. In addition, the thermostability of catalysts was detected by TG analysis, and the results show that the quality of KF/ZrO₂ is very stable, in which the catalyst weight is slightly decreased when the calcination temperature increases from 25 to 600°C.

2.4. Effect of Different Solvents. Five kinds of solvents were chosen for comparing the effect of different solvents on the reduction of FUR to FFA (Figure 6). For the protic solvent, methanol (MeOH) or n-butanol (n-BuOH) used as solvent showed relatively low reactivity (6% or 43% FFA yield and 11% or 44% FUR conversion, respectively). It was proposed that alcohol could react with PMHS to produce hydrogen gas [70], significantly decreasing the amount of PMHS for the reduction of FUR, which thus afforded lower FFA yield and FUR conversion. For the aprotic solvent, the order of reactivity is correlated with the order of the solvent polarity: N,N-dimethylformamide (DMF) > ethyl acetate (EA) > 2-methylfuran (2-MeTHF) (Figure 6). DMF as the relatively high polarity solvent shows the best FFA yield (97%) and FUR conversion (99%), for which DMF was considered as the optimum solvent for this reaction system.

2.5. Effect of PMHS Dosage and Hydroisilane Type. Effect of PMHS dosage was investigated from 0.5 to 4 equiv. at intervals of 0.5 equiv. (Figure 7). It was obvious that the low dosage of PMHS could not provide enough H-donor to complete the reduction of FUR to FFA and the excess dosage of PMHS against the dissociation between FFA and PMHS, thus reducing the yield of FFA [71]. PMHS with 2.5 equiv. H⁻ was found to be the optimum dosage of PMHS, which is in favor of the FUR to FFA hydrogenation in an economical and efficient way.

After confirming the optimum dosage of PMHS, there are eight kinds of hydrosilanes that are used for the study of hydroisilane type (Table 3). For the hydrosilanes containing phenyl species, phenylsilane (PS) and diphenylsilane (DPS) showed very good activity in the reduction of FUR to FFA, giving FFA yield in >99% or 99.0%, respectively. For the hydrosilanes not containing phenyl species, 99% FFA yield could be obtained using PMHS as H-donor, which is the highest FFA yield (1–75%) among the hydrosilanes not containing phenyl groups. From the point of economy, although using hydroisilanes containing phenyl groups as H-donor achieved high FFA yields, the price of PS and DPS is 72 and 38 times higher than that of PMHS.
respectively [50], which is too expensive to carry out for practical application. As the cheapest hydrosilane, PMHS performed relatively high FFA yield (99%) as well, for which PMHS is considered as the optimum hydrosilane from the examined hydrosilanes.

2.6. Catalyst Recycling Study. The reusability of 5 wt.% KF/ZrO₂ was also investigated, and the obtained results are shown in Figure 8. After five consecutive runs, the FFA yield marginally decreased from 97% to 71%.

From the XRD pattern of reused 5 wt.% KF/ZrO₂ catalyst, it was revealed that the crystallization of the catalyst was decreased after recycles (Figure 4). This is the reason why the catalyst activity is slightly decreased could be attributed to the catalyst pore blocking by the PMHS-based resin, which is a typical by-product of reaction system using PMHS as H-donor [72]. To prove the reasonability of the inference, the characterizations of reused 5 wt.% KF/ZrO₂ by SEM, BET, XPS, and ICP-MS are conducted. Firstly, from the SEM image of the reused catalyst (Figure S1), it can be seen that the surface of the catalyst is covered by an unknown substrate. For the XPS spectra of reused 5 wt.% KF/ZrO₂ (Figure 5), the characteristic peak of silicon (102 eV) was detected, indicating that 5 wt.% KF/ZrO₂ is covered by PMHS-based resin. The BET isotherms and pore diameter analysis suggest that the pore diameter is reduced after use (Figures S2 and S3). Thus, the SEM image of the reused catalyst (Figure S1), it can be seen that the surface of the catalyst is covered by an unknown substrate. For the XPS spectra of reused 5 wt.% KF/ZrO₂ (Figure 5), the characteristic peak of silicon (102 eV) was detected, indicating that 5 wt.% KF/ZrO₂ is covered by PMHS-based resin. The BET isotherms and pore diameter analysis suggest that the pore diameter is reduced after use (Figures S2 and S3). Thus, the SEM image of the reused catalyst (Figure S1), it can be seen that the surface of the catalyst is covered by an unknown substrate.

Table 2: Composition of the fresh and reused catalysts detected by XPS and ICP analysis.

| Entry | Detection method | Sample                | K (mol%) | F (mol%) |
|-------|------------------|-----------------------|----------|----------|
| 1     | ICP              | 5 wt.% KF/ZrO₂        | 3.58     | —        |
| 2     | ICP              | Reused 5 wt.% KF/ZrO₂ | 3.02     | —        |
| 3     | XPS              | 5 wt.% KF/ZrO₂        | 2.99     | 3.79     |
| 4     | XPS              | Reused 5 wt.% KF/ZrO₂ | 0.01     | 0.01     |
based resin, the slight loss of KF is another factor for the decrease in the catalytic activity of 5 wt.% KF/ZrO₂ after use. The atomic analysis of fresh and reused 5 wt.% KF/ZrO₂ catalyst by ICP-MS (Table 2) indicates that KF was not significantly leached (by ca. 0.56%). Meanwhile, the hot filtration experiments (Figure 9) confirm the heterogeneous catalytic behavior of the solid catalyst. Therefore, the main factor that decreases the catalytic activity is the PMHS resin which covers the external surface of 5 wt.% KF/ZrO₂.

3. Conclusion

In summary, the KF/ZrO₂ catalyst was successfully prepared by the impregnation method and had good reactivity for the
reduction of FUR to FFA using PMHS as H-donor. For the support of the catalyst, ZrO$_2$ as a porosity material of chemical inertness maintains the original configuration after the process of impregnation. Meanwhile, 5 wt.% KF/ZrO$_2$ as an appropriate loading rate of KF keeps the porosity of support and high reactivity of KF. The benign reaction system was optimized, and thus, 97% FFA yield and 99% FUR conversion were achieved by this reaction system at 25°C after 0.5 h. Through the comparison of seven kinds of commercial hydrosilanes and PMHS, PMHS is considered as hydrosilane of the high price-performance ratio. The reusability of 5 wt.% KF/ZrO$_2$ is good, which further reduced the cost of the reaction system. After 5 times run, the FFA yield was slightly decreased from 97% to 71%, due to the pore of 5 wt.% KF/ZrO$_2$ covered by PMHS-based resin.

4. Materials and Experiments

4.1. Materials. Polymethylhydroxiloxane (>99.0%), potassium fluoride (>99.9%), 2-methylfuran (>99.9%), 1,3,3,5,5-pentamethyldiisiloxane (>98.0%), nanotitanium dioxide (>99.8%), hydroxyapatite microspheres, and naphthalene (>99.0%) were purchased from Shanghai Aladdin Bio-Chem Technology Co., Ltd. Triethoxysilane (>97.0%), 1,1,1,3,5,5,5-heptamethyltrilsiloxane (>98.0%), triethylsilane (>98.0%), trimethoxysilane (>95.0%), and phenylsilane (>97.0%) were bought from Tokyo Chemical Industry Co., Ltd. N,N-Dimethylformamide (>99.5%), methanol (>99.5%), and tetrahydrofuran (>99.5%) were purchased from Guangdong Guanghua Sci-Tech Co., Ltd. n-Butanol (>99.5%) and ethyl acetate (>99.5%) were obtained from Shanghai Shenbo Chemical Co., Ltd. Diphenylsilane (>97.0%) and zirconium dioxide nanopowder (>99.5%) were purchased from Alfa Aesar Chemicals Co., Ltd. Nanomagnesium oxide (>99.0%), montmorillonite K-10, and others were purchased from Beijing Innochem Technology Co., Ltd.

4.2. Preparation of Catalyst. A series of KF/support catalysts were prepared through an impregnation method. KF solution was prepared at first, where a desired amount of KF was dissolved into 2mL pure water. Then, 1g support was added into the solution. The mixture was heated at 60°C with stirring for 6h. Finally, the mixture was dried at 80°C for 12 h, and the catalyst was ground for the test of catalytic activity. Through the impregnation method, active compound KF was distributed in the internal and external surface of the support by two steps. First, the support is completely immersed in the solution containing a moderate amount of KF until the cavity of support is full of KF solution by capillarity. Second, through a drying process, the solvent in the KF solution is completely volatilized, making the active compound KF be attached to the support surface.

4.3. Catalyst Characterization Techniques. BET (Brunauer–Emmett–Teller) surface areas of the porous materials were determined from nitrogen physisorption measurements at liquid nitrogen temperature on a Micromeritics ASAP 2460 instrument. Scanning electron microscopy (SEM) images were obtained by using field-emission scanning electron microscopy (FESEM; JEOL, EOL, JSM-6700F, 5 kV). Thermogravimetry (TG) analysis was determined by a NETZSCHA STA 449 F3 Jupiter. XPS (X-ray photoelectron spectroscopy) measurements were recorded using a Physical Electronics Quantum 2000 Scanning ESCA Microprobe (Physical Electronics Inc., PHI, MN) equipped with a monochromatic Al Kα anode. The data of XRD (X-ray diffraction) of the powder samples were obtained by using a Rigaku International D/max-TTR III X-ray powder diffractometer with Cu Kα radiation and 2θ scanned from 5° to 80°. The quantitative elemental analysis of samples was completed by coupled plasma mass spectrometry (ICP-MS, Elan DRC II, PerkinElmer, Sciex).

4.4. Catalytic Transfer Hydrogenation. A plastic sealed tube is a vessel where the FFA hydrogenation reaction was carried out. In a general process, FUR (0.5 mmol, 0.048 g), KF/ZrO$_2$ (25 mg), DMF (2 mL), and PMHS were added successively into a 15 mL plastic tube and then the lid was covered. Afterward, the sealed tube filling with the reaction mixture was put into the oil bath that was kept at 25°C. Upon completion, methanol (2 mL) was added to quench the reaction, and the reaction mixture was filtered by a 0.2 μm filter membrane for GC analysis.

4.5. Product Analysis. The quantitative analysis of the reaction mixture was fulfilled by GC (Agilent 6890N) equipped with an HP-5 capillary column (30m × 0.320mm × 0.25μm) and flame ionization detector (FID) detector. The programmed temperature for GC analysis is set as follows: maintaining at 60°C for 1 min, heating from 60 to 230°C in the rate of 10°C/min, and holding for 4 min. Naphthalene was employed as an internal standard for the quantitative analysis of the samples. The standard curves of FUR and FFA were recorded with GC by plotting different concentrations of FUR or FFA with specific concentrations of naphthalene, and the obtained curves are shown in Figures S5 and S6. The substrate conversion and product yield are calculated using the following equations, based on the standard curves made from commercial samples:

\[
\text{conversion} \ (%)= \left(1 - \frac{\text{mole of residual substrate}}{\text{mole of initial substrate}} \right) \times 100%,
\]

\[
\text{yield} \ (%)= \frac{\text{mole of product}}{\text{mole of initial substrate}} \times 100%,
\]

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.
Authors’ Contributions
Zhaozhuo Yu and Weibo Wu contributed equally to this work.

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Supplementary Materials
SEM images (Figure S1), pore distribution (Figure S2), N2 adsorption-desorption isotherms (Figure S3), and TG curves (Figure S4) of solid catalysts, as well as standard curves of FUR (Figure S5) and FFA (Figure S6) are provided. (Supplementary Materials)

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