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# Efficient hydrogenolysis of biomass-derived furfuryl alcohol to 1,2- and 1,5- pentanediols over nonprecious Cu-$Mg_3AlO_{4.5}$ bifunctional catalyst

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**1,2-Pentanediol and 1,5-pentanediol with high yield (~80%) could be achieved over a simple but efficient nonprecious Cu-$Mg_3AlO_{4.5}$ bifunctional catalyst in the hydrogenolysis of biomass-derived furfuryl alcohol. The cooperative catalysis of highly dispersed metallic Cu and basic $Mg_3AlO_{4.5}$ drastically increases the activity and chemoselectivity.**

Furfurals are key important platform molecules produced from abundant lignocellulosic materials by acidic hydrolysis.[1] The catalytic transformation of renewable furanic compounds to valuable chemicals and fuels has attracted much attention in recent years.[2] The hydrogenolysis of C-O bond in furan ring is considered to be the most effective method for the synthesis of useful diols, such as 1,2-pentanediol (1,2-PeD) and 1,5-pentanediol (1,5-PeD) from furfural (FA) and its derivatives of furfuryl alcohol (FFA) and tetrahydrofurfuryl alcohol (THFA) (Figure 1).[2b-d, 3] Adkins *et al.*[4] pioneered this reaction process and reported the first hydrogenolysis of FFA over a $CuCr_2O_4$, and 1,2-PeD and 1,5-PeD with yields of 40% and 30% were achieved at 448 K and 10-15 MPa, respectively. Zhang *et al.*[3c] also obtained a high yield of 1,2-PeD (42.1%) in the hydrogenolysis of FFA using a Ru/$MnO_x$ catalyst at mild conditions of 423 K and 1.5 MPa $H_{2,}$ while no 1,5-PeD was generated. Recently, Tomishige and co-workers[3a, 5] have systemically studied the THFA hydrogenolysis over a serial of Rh or Ir catalysts promoted with acidic low-valent metal oxides ($ReO_x$, $MoO_x$ or $WO_x$) at lower temperatures of 373–393 K at 8 MPa $H_2$. The highest yield of 1,5-PeD reached 94% (over Rh-$ReO_x$/C)[5b] and Ir-$ReO_x$/$SiO_2$ was found to present the highest turnover frequency (TOF) value.[5c] Other groups also achieved good performances in the hydrogenolysis of THFA to 1,5-PeD by using Rh/MCM-41 in supercritical $CO_2$,[6] Rh-$ReO_x$/C[2c] or Ir-$VO_x$/$SiO_2$[3d]. Recently, Xu *et al.*[3b] attempted the direct conversion of FA into 1,5-PeD and 1,2-PeD in an alcohol solvent using a Li-modified Pt/$Co_2AlO_4$ catalyst, and attained high conversion (100%) and moderate yield to 1,2-PeD (16.2%) and 1,5-PeD (34.9%) at 413 K, 1.5 MPa $H_2$. Very recently, remarkably high yield of 1,2-PeD (73%,together with 8% 1,5-PeD) or 1,5-PeD (78.2%) was achieved in the hydrogenolysis of FA over a hydrotalcite-supported Pt catalyst [2d] or a Rh-added Ir-$ReO_x$/$SiO_2$ catalyst[3f], respectively. Clearly, these previous efforts have demonstrated the feasibility of PeDs production by the selective hydrogenolysis of furanic compounds. However, these studies still encounter low activities or selectivities for the target PeDs, or the use of noble metals or chromium containing catalysts.

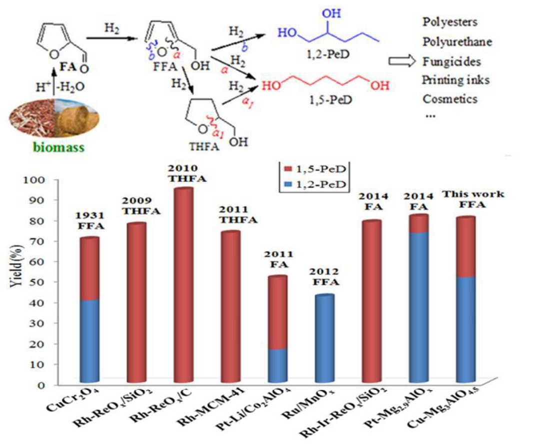

Figure 1. Selected catalyst systems for furan ring hydrogenolysis of substrates derived from FA.

We herein report the first successful example on the efficient hydrogenolysis of FFA to useful PeDs with combined yield up to 80% on a Cr-free bifunctional base-metal catalyst (Cu-$Mg_3AlO_{4.5}$) (Figure 1). The result is the highest yield reported so far on non-precious catalysts and is comparable to or even greater than those obtained on widely reported noble metal catalysts. The Cu nanoparticles were highly dispersed in the matrix of the layered double oxides of $Mg_3AlO_{4.5}$ (LDO) with large amount of weak basic sites.

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Table 1 and Table S1 show the conversions and selectivities of FFA hydrogenolysis at 413 K and 6.0 MPa $H_2$ on various catalysts. As can be seen, Cu-LDO catalysts prepared by co-precipitation method with Cu loadings from 2-30 wt% were active and especially selective in the hydrogenolysis of FFA to 1,2-PeD and 1,5-PeD (entries 1-3,6,7). The conversion of FFA increased with increasing Cu loading of the Cu-LDO catalysts, then passed a maximum of 63.1% on 10Cu-LDO and decreased to 31.9% by further increasing Cu loading to 30 wt%. Similarly, the selectivity to 1,2-PeD and 1,5-PeD on Cu-LDO catalysts was improved gradually with the increase of Cu content and reached the maximum values of 50.0% and 30.5%, respectively, in the case of 10Cu-LDO. For comparison, we also studied the catalytic performances of the LDO dispersed cheap metals of Co and Ni, and noble metals of Ru, Pt and Rh by co-precipitation. 10Ni-LDO and 10Co-LDO presented rather low activities in FFA hydrogenolysis, and THFA was found to be the major products (entries 11 and 12). Pt supported on LDO was active and selective in the hydrogenolysis of FFA to 1,2-PeD and 1,5-PeD (entry 8), which is in line with previous reports.[2d,3b] However, the 2Pt-LDO catalyst presented inferior conversion and selectivity to PeDs even in comparison with 2Cu-LDO catalysts, probably because a lower amount of Pt was applied in this work. Previous study shows that high catalyst amount is beneficial for the hydrogenolysis of FA.[2d] To our delight, 1,2-PeD (~51% selectivity) and 1,5-PeD (~29% selectivity) with combined yield up to 80% at ~100% FFA conversion was achieved on 10Cu-LDO with a higher catalyst amount at 24 h reaction (entry 4). Note that high yield of 1,2-PeD (45.2%) and 1,5-PeD (25.5%) could also be attained when FA was directly used as reactant at 100% FA conversion with 0.4 g Cu of 10Cu-LDO (entry 5). The conversions of FFA on 2Rh-LDO and 2Ru-LDO were extremely high (>99%), nonetheless, THFA was found to be the predominant products (selectivity >79%) (entries 8 and 9), showing the high activity of Ru and Rh in the hydrogenation of C=C in furan ring.[3c,7,3c, 8] Note that the FFA conversion and combined selectivity to 1,2-PeD and 1,5-PeD over 10Cu-LDO are 2.6 and 1.6 times higher than those for a commercial $CuCr_2O_4$ catalyst, respectively (entry 15).

Table 1.The catalytic properties of various catalysts for the selective hydrogenolysis of FFA.[a]

| Entry | Catalysts | Conversion (%) | Selectivity (%) | | |
|---|---|---|---|---|---|
| | | | 1,2-PeD | 1,5-PeD | THFA |
| **1** | 2Cu-LDO[b] | 40.3 | 35.2 | 23.5 | 3.6 |
| **2** | 5Cu-LDO | 47.6 | 43.4 | 24.0 | 3.2 |
| **3** | 10Cu-LDO | 63.1 | 50.0 | 30.5 | 3.9 |
| **4** | 10Cu-LDO[c] | >99 | 51.2 | 28.8 | 1.8 |
| **5** | 10Cu-LDO[c,d] | >99 | 45.2 | 25.5 | 3.1 |
| **6** | 20Cu-LDO | 53.4 | 44.6 | 29.5 | 4.3 |
| **7** | 30Cu-LDO | 31.9 | 32.1 | 21.4 | 4.8 |
| **8** | 2Pt-LDO[b] | 28.5 | 23.1 | 10.8 | 63.0 |
| **9** | 2Rh-LDO[b] | >99 | 13.6 | - | 79.7 |
| **10** | 2Ru-LDO[b] | >99 | 0.1 | 0.1 | 95.7 |
| **11** | 10Ni-LDO | 3.2 | 2.9 | - | 81.2 |
| **12** | 10Co-LDO | 5.0 | 2.6 | - | 55.7 |
| **13** | 10Cu/LDO-IM | 27.3 | 16.0 | 10.3 | 40.8 |
| **14** | 10Cu/LDO-PM | 16.7 | 13.7 | 8.8 | 35.4 |
| **15** | Pure Cu | 7.9 | 2.1 | 1.4 | 6.4 |
| **16** | LDO | N.R. | - | - | - |
| **17** | $CuCr_2O_4$ | 24.4 | 34.1 | 15.6 | 3.6 |

[a] Reaction conditions: 40 g 10 wt% FFA in ethanol solution, FFA : active metal = 20 :1 (wt%), reaction temperature 413 K, 6 MPa $H_2$, 8 h. PeD = pentanediol, THFA = tetrahydrofurfuryl alcohol. [b] 40 g 2.5 wt% FFA in ethanol solution. [c] 0.40 g Cu, reaction time: 24 h. [d] 40 g 10 wt% FA in ethanol solution.

Clearly, the above results show the outstanding performance of the 10Cu-LDO catalyst in FFA hydrogenolysis to 1,2-PeD and 1,5-PeD. Almost no reaction took place when THFA was used as reactant at the similar conditions as FFA (not shown), indicating harsh reaction conditions are required for the hydrogenolysis of THFA, which is in line with previous studies[3b, c]. Therefore, the weak affinity for C=C bonds (not favourable for the hydrogenation of FFA to THFA)[2b, 9] and high efficiency for C-O bond hydrogenolysis on Cu[10] render it a good candidate for the hydrogenolysis of FFA to PeDs at mild conditions. In addition, the 10Cu-LDO catalyst can be facilely recycled and reused. No significant decline in FFA conversion and selectivities to 1,2-PeD and 1,5-PeD was seen in 6 runs (Figure S1 in ESI), showing the high stability of the catalyst in FFA hydrogenolysis.

To elucidate the superior performance of the Cu-LDO catalysts prepared by co-precipitation method, their surface structure and chemical-physical properties were characterized by XRD, SEM, BET, $N_2O$ chemisorption, $CO_2$-TPD, and the results were shown in Table S2 and Figures S2-S6 in ESI. XRD characterizations revealed that the dried precursors of the Cu-LDO catalysts exhibited typical structure of Mg-Al layer double hydroxides ($CuMg_3Al$-LDHs), even with Cu loadings up to 30 wt% (Figure S2A in ESI). After calcination in air at 773 K, the LDHs precursors transformed to MgO and spinel $MgAl_2O_4$ phase with their layered structure well preserved (Figure S3 in ESI), and no obvious diffraction peaks assignable to CuO could be detected (Figure S2B in ESI), showing the high dispersion of CuO in the calcined samples. The BET surface areas of the calcined CuO-LDO samples declined uniformly from 212.4 to

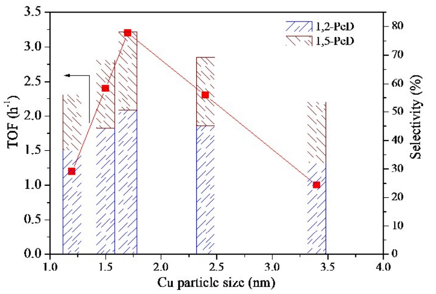


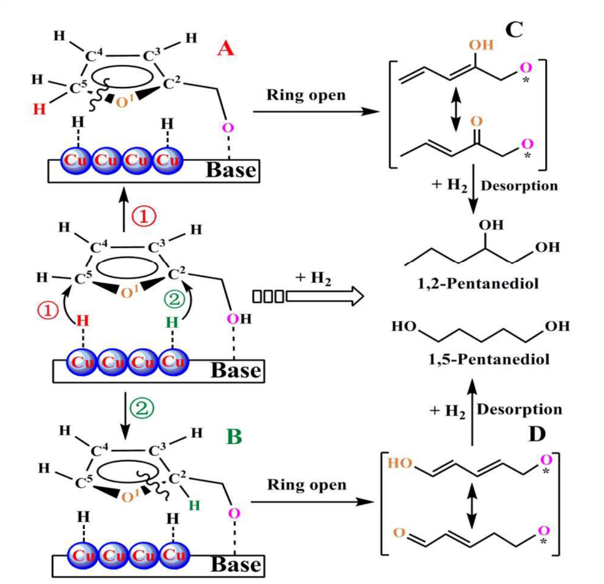
Figure 2. Dependence of TOFs and selectivities to 1,2-PeD and 1,5-PeD in FFA hydrogenolysis on Cu particle sizes for Cu–LDO catalysts with different Cu loadings. Reaction conditions: 40 g 10 wt% FFA in ethanol solution, 413 K, 6 MPa $H_2$, ~30% FFA conversion. TOF is defined as the mol of 1,2-PeD and 1,5-PeD generated per Cu site per time, Cu site was determined by $N_2O$ chemisorption.

149.2m$^2$ g$^{-1}$ with increasing Cu loadings from 2 to 30 wt%; and similarly, the Cu dispersion of the catalysts decreased monotonously with the increase of Cu loading. Note that even the 30Cu-LDO catalyst possessed a high dispersion of 32.8%. Accordingly, the Cu particle sizes of the catalysts, determined by $N_2O$ chemisorptions, increased gradually from 1.2 to 3.4 nm with increasing Cu loadings from 2 to 30 wt%. All the Cu-LDO catalysts presented weak basic sites (as evidenced from $CO_2$ desorption peaks that were terminated below 573 K) (Figure S4),[11] and their amounts decreased gradually with increasing Cu loadings. Thus, in comparison with the 10Cu/LDO-IM catalyst prepared by traditional impregnation method and the physical mixture of Cu$^0$ + LDO (Table 1, entries 11 and 12), the much higher conversions and selectivities to 1,2-PeD and 1,5-PeD over Cu-LDO catalysts prepared by co-precipitation method (Table 1, entries 1-3,6,7) would be ascribed to the high dispersion of Cu (Table S2 in ESI), and the intimate and effective interaction of Cu and basic LDO support. Obviously, the cooperative catalysis of Cu metal surface and basic LDO drastically increases the activity and chemoselectivity in the hydrogenolysis of FFA to 1,2-PeD and 1,5-PeD. It should be noted here that the XRD and SEM characterizations also verified the high structural stability of the 10Cu-LDO catalyst during repeated runs in FFA hydrogenolysis (Figure S5 and S6 in ESI).

Besides the highly dispersed Cu nanoparticles on the basic LDO support, which is essential for the selective formation of PeDs, the FFA hydrogenolysis reaction is also governed by the Cu particle sizes, as can be seen from Figure 2. The intrinsic activity, *i.e.* TOF, increased sharply from 1.2 h$^{-1}$ to a maximum of 3.2 h$^{-1}$ with increasing Cu particle size from 1.2 nm for 2Cu-LDO to 1.7 nm for 10Cu-LDO, and then dropped to 1.0 h$^{-1}$ by further increasing Cu size to 3.4 nm for 30Cu-LDO. Similarly, the combined selectivities to 1,2-PeD and 1,5-PeD increased from 56.0% at 1.2 nm to a maximum of 78.1% at 1.7 nm and then decreased to 53.5% at 3.4 nm. Such volcanic variations of the TOFs and PeDs selectivities with Cu sizes indicate a structure-sensitive nature of FFA hydrogenolysis over Cu-LDO catalysts[12], and a superior catalytic performance at ~1.7 nm. It is known that the surfaces of smaller metal nanoparticles contain more coordinatively unsaturated surface sites compared to the surfaces of larger ones.[13] The higher degree of unsaturated bonds leads to the stronger chemisorption of reactants, intermediates and products. Wang and Liu [14] ascribed the increase in the turnover rate with increasing Ru particle size in glycerol hydrogenolysis to the increase in the concentration of the available vacant Ru sites due to the weaker adsorption of the reactants and products on larger Ru particles. Analogously, the increase in TOFs and PeD selectivities of the Cu-LDO catalysts with elevating Cu domain (at Cu size <1.7 nm) in FFA hydrogenolysis is likely resulted from the decrease in the chemisorption strength of reactants and products on the Cu surface. The observed decrease of TOFs and PeD selectivities at Cu particle size >1.7 nm may be arisen from sterically hindering the approach of the C=C in the aromatic furan ring to the surface of a large Cu particle[9, 15], which would not facilitate the hydrogenation of furan ring to the partially hydrogenated intermediates, as will be discussed below. In addition, the decline in both active Cu sites (Table S2 in ESI) and basicity of the catalysts with increasing Cu loadings (Figure S4 in ESI) may be another reason for the lower activities and PeD selectivities of the catalysts with higher Cu loadings (>10 wt% with Cu size >1.7 nm). For more quantitative conclusions about such size effect, further studies would be needed.

On the basis of the above reaction results and the previous reports,[2d, 3c, 16] a catalytic reaction mechanism for the hydrogenolysis of FFA to 1,2-PeD and 1,5-PeD over Cu-LDO was proposed in Scheme 1. Initially, the hydroxymethyl moiety of FFA adsorbed on and interacted with the surface basic sites of LDO to form an alcoholate species.[2d, 16a, b] Subsequently, the C$^4$=C$^5$ or C$^2$=C$^3$ bond of FFA was partially hydrogenated to form the key intermediate of A or B, and then the ring opening reaction happens via C$^5$-O$^1$ or C$^2$–O$^1$ bond cleavage.[3c] Finally the ring-opened species from C$^5$-O$^1$ or C$^2$–O$^1$ bond cleavage were quickly hydrogenated to 1,2-PeD or 1,5-PeD, respectively. The DFT study on the mechanism of furan hydrogenation and ring opening on Pd(111) by Vlachos and coworkers[16c] have demonstrated that the hydrogenation of the CH–O to form CH$_2$–O in furan ring decreases the barrier of C–O cleavage, rendering α-hydrofuran (HF) more prone to ring-opening compared to furan or β-HF. Analogously, the formation of the semi-hydrogenation species of A or B renders the production of PeDs from FFA possible over Cu catalysts. Note that because of the ring-opened species of FFA are highly reactive, the stabilizing effect of the basic LDO, similar to previously reported MnO$_x$ in Ru/MnO$_x$,[3c] would be very important for achieving high yield of PeDs. Further works on both experiments and DFT calculations are underway to more clearly elucidate the reaction pathways and mechanism for PeDs generations from FFA.

In summary, we have demonstrated a facile and highly



Scheme 1. Proposed reaction paths for FFA hydrogenolysis over Cu-LDO catalyst.

efficient route for the synthesis of 1,2-PeD and 1,5-PeD from biomass-derived FFA using a simple Cr-free inexpensive Cu-LDO bifunctional catalyst derived from a layered double hydroxide precursor. 1,2-PeD and 1,5-PeD with combined yield up to 80% was achieved on 10Cu-LDO at ~100% FFA conversion at 413 K and 6 MPa $H_2$. The catalyst possessed high stability in repeated runs, and the cooperative effect of well dispersed $Cu^0$ nanoparticles and basic LDO is suggested to play a critical role for attaining high yields of PeDs. The important findings in this work have great implication for the development of efficient and stable non-precious catalysts for the selective hydrogenolysis of biomass-derived furan compounds with multifunctional groups to valuable products.

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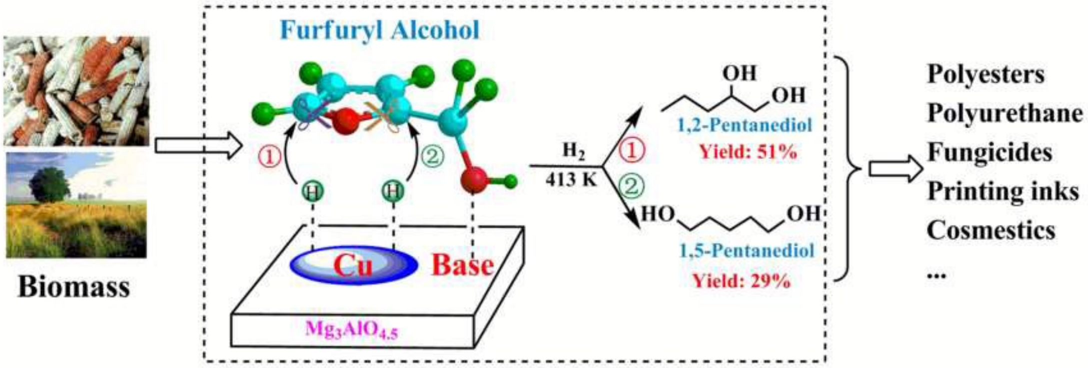
## Notes and references

1. (a) R. Karinen, K. Vilonen, M. Niemelä, *ChemSusChem*, 2011, **4**, 1002; (b) R. J. van Putten, J. C. van der Waal, E. de Jong, C. B. Rasrendra, H. J. Heeres, J. G. de Vries, *Chem. Rev.*, 2013, **113**, 1499; (c) S. P. Teong, G. Yi, Y. Zhang, *Green Chem.*, 2014, **16**, 2015.
2. (a) M. Besson, P. Gallezot, C. Pinel, *Chem. Rev.*, 2014, **114**, 1827; (b) Y. Nakagawa, M. Tamura, K. Tomishige, *ACS Catal.*, 2013, **3**, 2655; (c) M. Chia, Y. J. Pagán-Torres, D. Hibbitts, Q. Tan, H. N. Pham, A. K. Datye, M. Neurock, R. J. Davis, J. A. Dumesic, *J. Am. Chem. Soc.*, 2011, **133**, 12675; (d) T. Mizugaki, T. Yamakawa, Y. Nagatsu, Z. Maeno, T. Mitsudome, K. Jitsukawa, K. Kaneda, *ACS Sustain. Chem. Eng.*, 2014, **2**, 2243; (e) J. Tuteja, H. Choudhary, S. Nishimura, K. Ebitani, *ChemSusChem*, 2014, **7**, 96; (f) M. J. Climent, A. Corma, S. Iborra, *Green Chem.*, 2014, **16**, 516; (g) S. Bhogeswararao, D. Srinivas, *J. Catal.*, 2015, **327**, 65; (h) S. Li, N. Li, G. Li, L. Li, A. Wang, Y. Cong, X. Wang, T. Zhang, *Green Chem.*, 2015, **17**, 3644.
3. (a) S. Koso, I. Furikado, A. Shimao, T. Miyazawa, K. Kunimori, K. Tomishige, *Chem. Commun.*, 2009, 2035; (b) W. Xu, H. Wang, X. Liu, J. Ren, Y. Wang, G. Lu, *Chem. Commun.*, 2011, **47**, 3924; (c) B. Zhang, Y. Zhu, G. Ding, H. Zheng, Y. Li, *Green Chem.*, 2012, **14**, 3402; (d) B. Pholjaroen, N. Li, Y. Huang, L. Li, A. Wang, T. Zhang, *Catal. Today*, 2015, **245**, 93; (e) S. Liu, Y. Amada, M. Tamura, Y. Nakagawa, K. Tomishige, *Green Chem.*, 2014, **16**, 617; (f) S. Liu, Y. Amada, M. Tamura, Y. Nakagawa, K. Tomishige, *Catal. Sci. Technol.*, 2014, **4**, 2535.
4. H. Adkins, R. Connor, *J. Am. Chem. Soc.*, 1931, **53**, 1091.
5. (a) S. Koso, N. Ueda, Y. Shinmi, K. Okumura, T. Kizuka, K. Tomishige, *J. Catal.*, 2009, **267**, 89; (b) K. Chen, S. Koso, T. Kubota, Y. Nakagawa, K. Tomishige, *ChemCatChem*, 2010, **2**, 547; (c) K. Chen, K. Mori, H. Watanabe, Y. Nakagawa, K. Tomishige, *J. Catal.*, 2012, **294**, 171.
6. M. Chatterjee, H. Kawanami, T. Ishizaka, M. Sato, T. Suzuki, A. Suzuki, *Catal. Sci. Technol.*, 2011, **1**, 1466.
7. R. Alamillo, M. Tucker, M. Chia, Y. Pagán-Torres, J. Dumesic, *Green Chem.*, 2012, **14**, 1413.
8. M. Chatterjee, K. Matsushima, Y. Ikushima, M. Sato, T. Yokoyama, H. Kawanami, T. Suzuki, *Green Chem.*, 2010, **12**, 779.
9. S. Sitthisa, T. Sooknoi, Y. Ma, P. B. Balbuena, D. E. Resasco, *J. Catal.*, 2011, **277**, 1.
10. (a) M. A. Dasari, P. P. Kiatsimkul, W. R. Sutterlin, G. J. Suppes, *Appl. Catal. A*, 2005, **281**, 225; (b) Z. Huang, F. Cui, H. Kang, J. Chen, X. Zhang, C. Xia, *Chem. Mater.*, 2008, **20**, 5090; (c) Z. Huang, J. Chen, Y. Jia, H. Liu, C. Xia, H. Liu, *Appl. Catal. B*, 2014, **147**; (d) H. Liu, Z. Huang, Z. Han, K. Ding, H. Liu, C. Xia, J. Chen, *Green Chem.*, 2015, **17**, 4281.
11. X. He, H. Liu, *Catal. Today*, 2014, **233**, 133.
12. R. A. Van Santen, *Acc. Chem. Res.*, 2009, **42**, 57.
13. J. N. Kuhn, W. Huang, C. K. Tsung, Y. Zhang, G. A. Somorjai, *J. Am. Chem. Soc.*, 2008, **130**, 14026.
14. S. Wang, K. Yin, Y. Zhang, H. Liu, *ACS Catal.*, 2013, **3**, 2112.
15. (a) S. Galvagno, G. Capannelli, G. Neri, A. Donato, R. Pietropaolo, *J. Mol. Catal.*, 1991, **64**, 237; (b) A. Chambers, S. David Jackson, D. Stirling, G. Webb, *J. Catal.*, 1997, **168**, 301.
16. (a) T. Mitsudome, A. Noujima, Y. Mikami, T. Mizugaki, K. Jitsukawa, K. Kaneda, *Angew. Chem. Int. Ed.*, 2010, **49**, 5545; (b) A. Navajas, G. Arzamendi, F. Romero-Sarria, M. A. Centeno, J. A. Odriozola, L. M. Gandía, *Catal. Commun.*, 2012, **17**, 189; (c) S. Wang, V. Vorotnikov, D. G. Vlachos, *Green Chem.*, 2014, **16**, 736; (d) S. Wang, V. Vorotnikov, D. G. Vlachos, *ACS Catal.*, 2015, **5**, 104.



The hydrogenolysis of biomass-derived furfuryl alcohol to 1,2-pentanediol and 1,5-pentanediol with high yield (~80%) could be achieved over a simple but efficient nonprecious Cu-$Mg_3AlO_{4.5}$ bifunctional catalyst. The cooperative catalysis of highly dispersed metallic Cu and the basic $Mg_3AlO_{4.5}$ drastically increases the activity and chemoselectivity.