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Highly selective synthesis of 2,5-bis(aminomethyl) furan via catalytic amination of 5-(hydroxymethyl) furfural with NH₃ over a bifunctional catalyst†

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The development of facile protocols for the selective synthesis of biomass-derived diamine is a highly desirable pursuit in the field of heterogeneous catalysis. Herein, a simple and highly efficient bifunctional CuNiAlOx catalyst was developed for the one pot transformation of 5-(hydroxymethyl)furfural (5-HMF) into 2,5-bis(aminomethyl)furan (BAF) using a two-stage reaction process. Cu₄Ni₁Al₄O_x was found to be the most effective catalyst for this reaction, affording BAF in 85.9% yield. Our results could promote controllable conversion and utilization of biomass resource.

Amines are an important class of nitrogen-containing chemicals and are widely used in the synthesis of pharmaceuticals, agrochemicals, surfactants, dyes, polymers, and biologically active compounds.1 Among the different amines, primary diamines are some of the most useful monomers for the production of polyamides and polyureas which were widely employed in everyday life including automotive, aerospace, electrical and electronics, building, and biomedicine industry.2 Traditionally, they are produced from carbonyl and alcohol compounds which are derived from fossil resources. However, the depletion of fossil resources is a big concern as well as the environmental impact associated with their usage. Furthermore, there is a rising demand for biocompatible polymers to be used in industry, for example, in packaging and biomedicine. Therefore, the application of renewable resources to replace fossil resources for the production of primary diamines is highly desired.

Biomass as a renewable and ubiquitous resource is considered as the next generation feedstock for the chemical industry. Utilization of biomass as raw material has potential to replace diminishing fossil fuels with renewable feedstocks, thereby alleviating the dependence on petro-based materials, and reducing pollution.3 In addition, biomass-derived diamine monomers would meet the rising demand for biocompatible polymers. Therefore, the development of effective methods for the preparation of diamines from bio-based renewable

materials is an attractive prospect in view of establishing the sustainable development of societies.4 As one of the most important platform molecules derived from biomass, 5-(hydroxymethyl)furfural (5-HMF) is attracting increasing attention owing to the unique and versatile chemical structure containing both aldehyde and hydroxyl groups. 5-HMF could be used to synthesize 2,5-bis(aminomethyl)furan (BAF); however, selective synthesis of BAF from 5-HMF is a challenging task because the transformation is prone to form a series of byproducts of secondary, tertiary and polymeric amine species.6 Thus, many multi-step routes were developed for the synthesis of BAF. Komanoya et al. developed a two-step method for the synthesis of BAF, in which 5-HMF was firstly converted into 5-(hydroxymethyl)furfurylamine (HMFA) over Ru/Nb₂O₅ catalyst and then converted into BAF over a homogenous [Ru(CO) ClH(PPh₃)₃] catalyst.⁷ Lin and co-workers have prepared BAF with 45.7% yield through the hydroxymethyl group of 5-HMF into amide group with CH3CN by Ritter reaction, followed by reductive amination of aldehyde groups with NH₃ and hydrolysis of amide to primary amine8, Kim et al. reported the reductive amination of 2,5-diformylfuran to BAF over acid treated RANEY®-Ni catalysts with a yield of 42.6%.6 Xu and coworkers have demonstrated that BAF could be efficiently synthesized in 94.1% yield from hydrogenation of 2,5-diformylfuran dioxime which was generated from oximation of 2,5diformylfuran (DFF).9 Compared to the above two or multi-steps methods, the direct amination of easily available 5-HMF to BAF would be advantageous with respect to atom efficiency and step economy. To date, however, only few catalytic systems dealing with direct transformation of 5-HMF into the BAF have been established. In 2018, an elegant method for the direct amination of 5-HMF with ammonia to BAF with 85% yield was achieved in the presence of homogeneous Ru/phosphine ligand complex.10 Recently, Wei and co-workers presented an effective

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RSC Advances

method for direct conversion of 5-HMF into BAF with 60.7% yield using a RANEY®-Ni catalyst.¹¹ However, the use of the noble metal and organic ligand as well as the low product yield is unsatisfactory. Therefore, it is still desirable for the development of an efficient heterogeneous catalytic system for the conversion of 5-HMF to BAF.

According to a mechanistic investigation, the hydrogenborrowing reaction of hydroxyl group with NH3 is considered the rate-determining step of direct amination of 5-HMF to BAF. 11 The key point to realize this reaction is to develop highly active and selective sites for hydrogen-borrowing reaction of hydroxyl with NH3, in which catalytic dehydrogenation of hydroxyl to the corresponding C=O and catalytic hydrogenation of resulted imine are involved.12 It is well-known that nickel has an excellent catalytic hydrogenation ability in hydrogenation reaction and copper possesses a good catalytic dehydrogenation ability in borrowing-hydrogen reactions.¹³ Thus, a bifunctional catalyst combining both excellent catalytic dehydrogenation properties of copper and good catalytic hydrogenation properties of nickel might be a good choice for this hydrogen-borrowing reaction. In addition, it has been reported that the formation of a series of by-products, i.e., secondary amines, oligomer and undesired hydrogenated byproducts, resulted mainly from condensation of reactive dialdehyde and diamine products during the amination of 5-HMF with NH₃.6 If the two-stage consecutive reaction process was adopted, in which hydrogen-borrowing reaction of hydroxyl with NH₃ occurred after the completion of reductive amination of aldehyde with NH3, it would prevent formation of reactive dialdehyde and thus it would reduce the by-products. Therefore, we speculated that the combination of bifunctional Cu-Ni catalyst and employing a two-stage reaction process in one-pot might realize highly selective synthesis of BAF from 5-HMF. Herein, we describe the controllable diamination of 5-HMF with NH₃ to BAF in 85.9% yield over a bifunctional CuNiAlO_x catalyst using a two-stage reaction process (Scheme 1). The route in this work is atom efficient and an environmentally friendly process as water is the only byproduct generated.

To validate our hypothesis, the one-pot amination of 5-HMF (1a) to BAF (3a) was initially investigated with NH₃ in the presence of CuNiAlO_x catalyst, Na₂CO₃ co-catalyst, under 4.5 MPa of H₂ in 1,4-dioxane at 90 °C for 6 h, then at 210 °C for

Previous works:

HO NH2

HO NH2

HON NH2

HON NH2

HON NH2

HON NH2

HON NH2

HON NH3

Cal. H₂, Na₂CO₃

H₄ H₄ N₄ NH₄

Cal. H₅, Na₂CO₃

H₄ NH₄

NH₅

Cal. H₅, Na₂CO₃

H₄ NH₅

NH₅

NH₅

NH₆

NH₇

NH₇

NH₇

NH₈

NH₈

Cal. H₇ Na₂CO₃

H₄ Na₂CO₃

H₄ Na₂CO₃

NH₈

NH₉

NH

Scheme 1 Catalytic synthesis of BAF from 5-HMF.

18 h (Table 1). The catalyst used here was prepared by a coprecipitation method by adding an aqueous solution of Na_2CO_3 and NaOH to a $Cu(NO_3)_2$, $Ni(NO_3)_2$ and $Al(NO_3)_3$ solution. The precipitates were washed with deionized water, dried in air at $100\,^{\circ}$ C for 12 h and reduced under H_2 flow at $450\,^{\circ}$ C for 3 h. The $CuNiAlO_x$ catalysts are denoted as $Cu_mNi_nAl_yO_x$ $(m:n:y:x=molar\ ratios\ of\ Cu,\ Ni,\ Al\ and\ O)$.

Clearly, with the increase of Cu: Ni ratios in these catalysts, the yield of BAF and mass balance of the reaction were gradually improved, and a 75.2% yield of BAF with 83.3% mass balance was achieved when Cu₄Ni₁Al₄O_r was used as a catalyst (Table 1, entry 3). However, both the yield of BAF and the mass balance were obviously decreased when the Cu: Ni ratio was further increased. Possibly, the increasing of Cu: Ni ratio would increase the generation of di-aldehyde, which might result in the formation of oligomers and lower yield of BAF. When Cu₁- Al_1O_x and $Ni_1Al_4O_x$ were prepared by using the same procedure as $Cu_4Ni_1Al_4O_x$, and subsequently used as the catalysts in direct amination of HMF, the yields of BAF were <50% (Table 1, entries 6 and 7). It should be noted that the lower yield of 60.3% was obtained with physical mixtures of Cu₁Al₁O_x (3.38 g) and Ni₁- Al_4O_r (1.51 g) as catalyst. These results suggested that the synergetic effect of Cu and Ni species might be crucial to realize this transformation. Then, the effect of the catalyst loadings on amination of 5-HMF with NH3 was studied (Table S1, ESI†). The yield of BAF was decreased to 65.9% with 76.2% mass balance when the amount of Cu₄Ni₁Al₄O_x was reduced to 1.5 g. Additionally, increasing the amount of Cu₄Ni₁Al₄O_r to 2.5 g gave the similar result as the 2.0 g Cu₄Ni₁Al₄O_x. The influence of the amounts of Na₂CO₃ as co-catalyst and NH₃ on the catalytic reaction was also investigated, and it was discovered that

Table 1 Catalyst screening and optimization of reaction condition for direct amination of 5-HMF (1a) to BAF $(3a)^a$

		Conv. ^b [%]	Yield ^b [%]		Mass
Entry	Catalysts	1a	2a	3a	balance [%]
1	$Cu_1Ni_4Al_4O_x$	100	18.7	46.1	64.8
2	$Cu_1Ni_1Al_{1.6}O_x$	100	5.8	56.3	62.1
3	$Cu_4Ni_1Al_4O_x$	100	8.1	75.2	83.3
4	$Cu_6Ni_1Al_{5.6}O_x$	100	5.6	60.4	66.0
5	$Cu_{19}Ni_1Al_{16}O_x$	100	13.9	36.6	50.5
6	$Cu_1Al_1O_x$	100	8.1	36.9	45.0
7	$Ni_1Al_4O_x$	100	26.0	45.5	71.5
8 ^c	Cu ₄ Ni ₁ Al ₄ O _x	100	9.5	85.9	95.4
9^d	$Cu_4Ni_1Al_4O_x$	100	5.9	63.7	69.6
10^e	$Cu_1Al_1O_x/Ni_1Al_4O_x$	100	12.6	60.2	72.8

^a Reaction conditions: 5-HMF (10 g, 79.4 mmol), NH₃ (23 g, 1352.9 mmol), catalyst (2.0 g), Na₂CO₃ (0.915 g, 8.6 mmol, 11 mol% to 5-HMF), H₂ (4.5 MPa), 1,4-dioxane (50 mL), 90 °C for 6 h then 210 °C for 18 h. ^b Determined by GC-FID using biphenyl as the internal standard material. ^c 90 °C for 9 h then 210 °C for 18 h. ^d The catalyst was recovered and reused for the 3rd run. ^e The catalyst was the mixture of Cu₁Al₁O_x (3.38 g) and Ni₁Al₄O_x (1.51 g).

Paper

8.6 mmol Na₂CO₃ and 1352.9 mmol NH₃ are the optimal amounts (Tables S2 and S3, ESI†). Na₂CO₃ act as a base to promote the hydrogen transfer reaction. It should be noted that the addition of excess NH3 is indispensable to increase the selectivity towards the primary amine, thus achieving good BAF yield and mass balance. Furthermore, the impact of H₂ pressure was studied (Table S4, ESI†). Lower BAF yield and mass balance were obtained when H₂ pressure was reduced from 4.5 MPa to 3.0 MPa. H₂ shifts the equilibrium from imine to amine product, and also maintains the catalyst activity by avoiding carbonaceous deposits. Next, temperature screening of the second stage of the reaction showed that reducing the reaction temperature to 190 °C lowered the yield of BAF and substantially increased the yield of HMFA (2a), while raising the reaction temperature to 220 °C decreased mass balance (Table S5, ESI†). This observation suggests that 210 °C is the suitable temperature for the reaction. Investigation of the reaction time of first and second stage demonstrated that higher yield of 85.9% with 95.4% mass balance was afforded by prolonging the reaction time of first stage from 6 h to 9 h (Table 1, entry 8 and Tables S6 and S7, ESI†). It should be noted that HMFA was only produced after the first reaction stage, and the yield of BAF gradually increased to 75.2% after 18 h at the second stage, and remained constant even after prolonging the reaction time to 34 h. The above results clearly indicated that the reaction proceeded via reductive amination of aldehyde functional group of 5-HMF with NH₃ at 90 °C, followed by hydrogen-borrowing reaction of hydroxyl group with NH₃ at 210 °C. Finally, the Cu₄Ni₁Al₄O_x is easily recovered by simple filtration and it could be used for three catalytic cycles without significant decline in catalytic performance, indicating the good stability of the catalyst (Table 1, entry 9). In order to figure out whether the reaction takes place homogeneously or heterogeneously, a leaching experiment was performed (Fig. S4†). After 2 h of reaction of HMF with NH3 over Cu4Ni1Al4Ox at 210 °C and separating the solid catalysts, further reaction was operated on the residual liquids for another 16 h. Clearly, the reaction stopped after removing the solid catalyst. This observation demonstrates that the leached Cu and Ni should not be the active species.

The prepared catalytic samples were characterized by X-ray diffraction (XRD), transmission electron microscopy (TEM), Xray photoelectron spectroscopy (XPS), and N2 adsorptiondesorption to reveal their structures. At first, XRD patterns of the different CuNiAlOx catalysts were obtained to elucidate the crystal structures of the samples (Fig. 1).

The Cu₁Ni₄Al₄O_x catalyst shows diffraction peaks at 36.9°, 43.5°, 63.2°, and 75.4°, which can be ascribed to the diffraction peaks of NiO(111), NiO(200), NiO(220), and NiO(311) (JCPDS card no: 47-1049). For the Cu₁Ni₁Al_{1.6}O_x, except for the diffraction peaks of the NiO, additional reflections are also visible at 38.9°, and 50.4°, which can be assigned to CuO(200) and Cu(200), respectively (CuO, JCPDS card no: 89-5899; Cu, JCPDS card no: 89-2838). With the increase of Cu: Al ratios in these catalysts, characteristic Cu(111), Cu(200), Cu(220), CuO(-111), CuO(200), and CuO(-202) reflections appearing at 43.2° , 50.4° , 74.1°, 35.6°, 38.9°, and 48.9°, respectively, were detected for

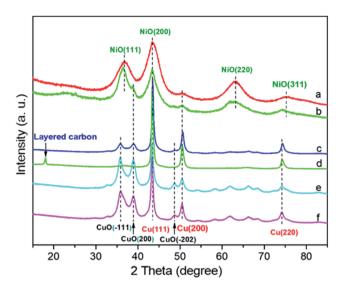


Fig. 1 XRD patterns of fresh and reused CuNiAlO_x catalysts. (a) Cu₁- $Ni_4Al_4O_x$, (b) $Cu_1Ni_1Al_{1.6}O_x$, (c) $Cu_4Ni_1Al_4O_x$, (d) reused $Cu_4Ni_1Al_4O_x$, (e) $Cu_6Ni_1Al_{5.6}O_x$, (f) $Cu_{19}Ni_1Al_{16}O_x$

Cu₄Ni₁Al₄O_x, Cu₆Ni₁Al_{5.6}O_x, and Cu₁₉Ni₁Al₁₆O_x (CuO, JCPDS card no: 89-5899; Cu, JCPDS card no: 89-2838). Moreover, there were no peaks observed for Ni species for Cu₄Ni₁Al₄O_x, Cu₆-Ni₁Al_{5.6}O_x, and Cu₁₉Ni₁Al₁₆O_x, which implied that the nickel species might be amorphous state or highly dispersed. Compared with fresh Cu₄Ni₁Al₄O_x, a new diffraction peak located at 18.0° indicating formation of the layered carbon (JCPDS card no: 50-1363) and disappearance of CuO phase were observed in Cu₄Ni₁Al₄O_x catalyst reused for three times. Thus, we suppose that the Cu in CuNiAlOx catalysts might promote the borrowing-hydrogen reaction but the role of CuO is still unclear14 and speculate that a slight loss of the catalytic activity could be attributed to formation of the layered carbon on the surface of Cu₄Ni₁Al₄O_x catalyst.

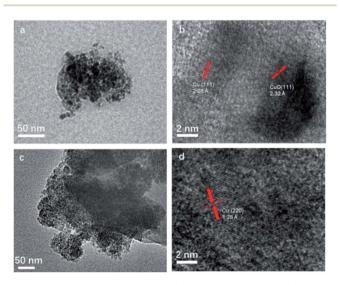


Fig. 2 TEM images of the catalysts. (a and b) Cu₄Ni₁Al₄O_x, (c and d) reused Cu₄Ni₁Al₄O_x

RSC Advances

The CuNiAlO $_x$ catalysts were further characterized by TEM. Fig. S1† shows TEM micrographs of CuNiAlO $_x$. TEM analysis (Fig. 2) of the best Cu $_4$ Ni $_1$ Al $_4$ O $_x$ catalyst showed the formation of mainly Cu and Ni nanoparticles with sizes of 10–30 nm. The crystal lattices of Cu(111) and CuO(111) can be observed clearly in the magnified TEM micrographs. Compared with fresh Cu $_4$ Ni $_1$ Al $_4$ O $_x$ catalyst, the HRTEM images of the catalyst which was used three times showed that the crystal lattices of Cu(111) was maintained and the crystal lattices of CuO(111) was not observable, which are in good agreement with XRD results.

Furthermore, the surface composition of the CuNiAlO_x catalysts was analyzed by XPS. The XPS spectra of Cu 2p of fresh Cu₄Ni₁Al₄O_x is shown in Fig. 3a.

The XPS spectra of fresh Cu₄Ni₁Al₄O_x display two main peaks at 932.4 and 952.3 eV that can be attributed to Cu 2p_{3/2} and Cu 2p_{1/2} binding energies of Cu⁰ or Cu¹⁺. Considering that metallic copper was observed from XRD patterns and HRTEM image of the Cu₄Ni₁Al₄O_x catalyst, we suppose that binding energy of 932.4 eV might be assigned to the metallic copper. Other binding energies at 933.9 eV for Cu 2p_{3/2} and 953.9 eV for Cu 2p_{1/2} are ascribed to Cu²⁺. In addition to these peaks, shake-up satellite peaks were observed in the region of 940-945 eV (Cu $2p_{3/2}$) and 959-965 eV (Cu $2p_{1/2}$), also indicating the presence of Cu²⁺ species in Cu₄Ni₁Al₄O_x catalyst. According to XPS-peakdifferentiation-imitating analysis, the ratio of Cu⁰/Cu²⁺ is 4.7 : 1. Fig. 3b shows Ni 2p spectra of $Cu_4Ni_1Al_4O_x$ catalysts. The peaks of the Ni 2p XPS spectrum at 855.4 eV (Ni 2p_{3/2}) and 856.7 eV (Ni $2p_{1/2}$) were in accordance with NiO. Besides these peaks, shake-up satellite peaks were observed in the region of 857-865 eV (Ni $2p_{3/2}$) and 877-884 eV (Ni $2p_{1/2}$). Additional spectra for the other catalysts can be found in the ESI (Fig. S2†).

The N₂ adsorption–desorption tests (Fig. S3, ESI†) showed that the BET surface areas of the Cu₁Ni₄Al₄O_x, Cu₁Ni₁Al_{1.6}O_x, Cu₄Ni₁Al₄O_x, Cu₆Ni₁Al_{5.6}O_x, Cu₁₉Ni₁Al₁₆O_x, Cu₁Al₁O_x and Ni₁-Al₄O_x were 202.39, 169.75, 101.16, 83.35, 68.16, 79.77, and 326.21 m² g⁻¹, respectively (Table S8, ESI†). Therefore, the high selectivity of Cu₄Ni₁Al₄O_x should not be attributed solely to its high surface area. It can be inferred that the good catalytic performance of Cu₄Ni₁Al₄O_x catalyst in the direct amination of HMF to desired BAF product is attributed to bulk Cu and highly dispersed Ni species for the dehydrogenation and hydrogenation properties, respectively.

In conclusion, we have successfully developed an efficient methodology for highly selective synthesis of biomass-derived

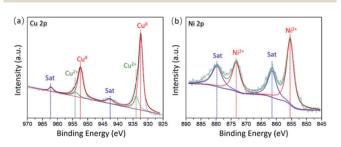


Fig. 3 XPS spectra of (a) Cu 2p core level and (b) Ni 2p core level for ${\rm Cu_4Ni_1Al_4O_x}.$

BAF *via* direct amination of 5-HMF with NH₃ over bifunctional CuNiAlO_x catalyst using two-stage reaction process. By tuning the Cu/Ni molar ratio, Cu₄Ni₁Al₄O_x exhibited excellent catalytic performance in the direct amination of 5-HMF to BAF, affording the desired product in 85.9% yield. Experimental results suggested that the reaction proceeded *via* reductive amination of aldehyde group of 5-HMF with NH₃ at 90 °C, followed by hydrogen-borrowing reaction of hydroxyl of 5-HMF with NH₃ at 210 °C. This work offers an effective methodology for the controlled synthesis of biomass-derived diamines monomers.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

- 1 (a) E. Karsten, H. Erhard, R. Roland and H. Hartmut, Amines, Aliphatic in Ullmann's Encyclopedia of Industrial Chemistry, Wiley-VCH, Weinheim, 2005; (b) A. Ricci, Amino group chemistry: from synthesis to the life sciences, John Wiley & Sons, 2008.
- 2 (a) D. K. Chattopadhyay and K. V. S. N. Raju, *Prog. Polym. Sci.*, 2007, 32, 352–418; (b) J. M. García, F. C. García, F. Serna and L. D. L. P. José, *Prog. Polym. Sci.*, 2010, 35, 623–686.
- 3 (a) A. Corma, S. Iborra and A. Velty, *Chem. Rev.*, 2007, **107**, 2411–2502; (b) D. Li, W. Ni and Z. Hou, *Chin. J. Catal.*, 2017, **38**, 1784–1793.
- 4 (a) I. Delidovich, P. J. Hausoul, L. Deng, R. Pfutzenreuter, M. Rose and R. Palkovits, *Chem. Rev.*, 2016, 116, 1540–1599; (b) V. Froidevaux, C. Negrell, S. Caillol, J. P. Pascault and B. Boutevin, *Chem. Rev.*, 2016, 116, 14181–14224; (c) M. Pelckmans, T. Renders, S. Van de Vyver and B. F. Sels, *Green Chem.*, 2017, 19, 5303–5331; (d) M. Pera-Titus and F. Shi, *ChemSusChem*, 2014, 7, 720–722.
- (a) P. Pal and S. Saravanamurugan, *ChemSusChem*, 2019, 12, 145–163; (b) H. Yuan, J.-P. Li, F. Su, Z. Yan, B. T. Kusema, S. Streiff, Y. Huang, M. Pera-Titus and F. Shi, *ACS Omega*, 2019, 4, 2510–2516; (c) F. Gao, J. Chen, Z. Huang and C. Xia, *J. Mol. Catal.*, 2018, 32, 276–293.
- 6 N.-T. Le, A. Byun, Y. Han, K.-I. Lee and H. Kim, *Green Sustainable Chem.*, 2015, **05**, 115–127.
- 7 T. Komanoya, T. Kinemura, Y. Kita, K. Kamata and M. Hara, J. Am. Chem. Soc., 2017, 139, 11493–11499.
- 8 X. Wang, W. Chen, Z. Li, X. Zeng, X. Tang, Y. Sun, T. Lei and L. Lin, *J. Energy Chem.*, 2018, **27**, 209–214.
- 9 Y. Xu, X. Jia, J. Ma, J. Gao, F. Xia, X. Li and J. Xu, *Green Chem.*, 2018, **20**, 2697–2701.

Paper

10 D. Pingen, J. B. Schwaderer, J. Walter, J. Wen, G. Murray, D. Vogt and S. Mecking, *ChemCatChem*, 2018, **10**, 3027–3033.

- 11 K. Zhou, H. Liu, H. Shu, S. Xiao, D. Guo, Y. Liu, Z. Wei and X. Li, *ChemCatChem*, 2019, 11, 2649–2656.
- 12 K.-I. Shimizu, Catal. Sci. Technol., 2015, 5, 1412-1427.
- 13 X. Cui, X. Dai, Y. Deng and F. Shi, *Chem.-Eur. J.*, 2013, **19**, 3665–3675.
- 14 (a) J. Aston, T. Peterson and J. Holowchak, J. Am. Chem. Soc.,
 1934, 56, 153–154; (b) T. Yamakawa, I. Tsuchiya,
 D. Mitsuzuka and T. Ogawa, Catal. Commun., 2004, 5, 291–295; (c) Y. Wu, H. Huang, X. Dai and F. Shi, ChemSusChem,
 2019, 12, 3185–3191.