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Environmentally-friendly and sustainable synthesis of bimetallic NiCo-based carbon nanosheets for catalytic cleavage of lignin dimers

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ABSTRACT

This paper reports on a study of 2D metal-based (Ni-, NiCo-) carbon nanosheet (CNs) material that were synthesized via a template method and the synthetic materials showed an ultra-thin lamellar structure. The structures were characterized using different analytical methods including XRD, SEM, EDX, TEM, XPS, NH₃-TPD. The synthesized NiCo-based CNs are ultrathin sheet shape with good crystallinity and uniform particle distributions. In the synthetic route of NiCo-based CNs, sodium lignosulfonate was employed as carbon and sulfur source and boric acid was used as 2D template to form a perfect lamellar structure. It manifested an environmentally-friendly and sustainable concept for preparation of the 2D NiCo-CNs. Although simple CNs was a poor catalyst, after Ni and NiCo doping, it became highly active in cleavage of β -O-4 ether bond in lignin through a catalytic transfer hydrogenation process and led to very high product yields.

1. Introduction

Sustainable utilization of lignin, especially waste sodium lignosulfonate from pulp and paper making, has attracted lots of attention [1-5]. While the employment of lignin could not only provide renewable carbon resource, but also solve the problem of environmental waste utilization [6-8]. However, due to the three-dimension amorphous polymer structure of lignin, the degradation of real lignin substantially restricted [9–10]. In the past few years, tremendous efforts to the depolymerization of lignin have been implemented in particularly using lignin β -O-4 model compounds as a research material over heterogeneous catalysts [11–15]. Generally, lignin β -O-4 ether bond could be cleaved via hydrogenolysis using high H₂ pressure over different noble metal-based catalysts (e.g., Pt, Ru, Pd) [13-15]. For example, Han et al. found Ru/C and Ru/hydroxyapatite could efficiently catalyze the cleavage of aromatic ether bond in various lignin-derived compounds via catalytic transfer hydrogenation employing isopropanol as hydrogen source [16-17]. Wei et al. reported Ru/AC exhibited a high activity for converting lignin model compounds into cyclohexanol and cyclohexane under extra H_2 [18]. Although these noble metal-based catalysts witnessed considerable success, it still faced many challenges, such as high prices, environmental pollution, employment of extra H_2 as hydrogen source and so on [19]. Therefore, catalytic transfer hydrogenation for the transformation of lignin model compounds to value-added products over transition metal-based catalysts is a tendency of lignin conversion in the future [20].

As well-known, 2D CNs materials were employed in vast fields such as biotechnology, energy storage and catalytic reactions, and it has the advantages of both unique electronic properties in confined dimension of nanophase sp²-hybridized carbon [21] and endowing more active sites as well as facilitating better contact with the reaction substrates in catalytic reaction [22]. On the basis of the traditional impregnated synthesis of NiCo-based heterogeneous catalysts [23], NiCo-loaded carbon nanosheets with ultrathin layers was synthesized using sodium lignosulfonate from pulp and paper making as carbon and sulfur source and boric acid as 2D template in one-step. The obtained 2D materials were calcined under 700 °C for 2 h, which provided a sustainable, green, energy-saving, and time-saving method. Thus, the synthesized NiCo-

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Fig. 1. (a) photograph of as-prepared NiCo-CNs; (b) SEM images of CNs; (c) SEM image of Ni-CNs; (d) SEM image of NiCo-CNs (e) EDX spectrum of NiCo-CNs. (f-j) element mapping of NiCo-CNs.

based carbon nanosheet was then used in the catalytic cleavage of β -O-4 ether bond through a catalytic transfer hydrogenation process and achieved a good result, indicating that catalysts with good crystallinity and uniform particle distributions have good application prospects in catalytic degradation of lignin model compounds and lignin. According to this, various advantages of the as-prepared 2D NiCo-CNs could be found as follows: (1) transition metals nickel and cobalt were cheap and easy to get, (2) boric acid was used as 2D template, and it could be recycled for repeated use by evaporative crystallization from the waste liquid [24], (3) waste reaction product of wood pulp lignosulfonate was calcined as support was in line with the concept of green chemistry. Therefore, we wish to report a new alternative method for catalytic transfer hydrogenation of lignin model compounds to corresponding aromatics over an environmentally-friendly and sustainable NiCo-CNs catalyst.

2. Experimental details

2.1. Materials

 $Ni(NO_3)_2 \cdot 6H_2O$ and $Co(NO_3)_2 \cdot 6H_2O$ were obtained from Aladdin Industrial Inc. Shanghai, China. Sodium lignosulfonate and boric acid was provided from Sigma-Aldrich. Phenyl benzyl ether (>99%), diphenyl ether (>99%), phenethoxybenzene, 2-phenoxy-1-phenylethan-1-one, 2-phenoxy-1-phenylethan-1-ol, 2-(2-methoxyphenoxy)-1phenylethan-1-ol and 2-(2-methoxyphenoxy)-1-(4-methoxyphenyl)propane-1,3-diol was provided from Leyan.com. N₂ was supplied by local gas factory. Deionized water and isopropanol were employed for all experiments.

2.2. General procedures for the preparation of CNs and NiCo-CNs

CNs was prepared by an impregnation method using boric acid as templet. 8 g boric acid was added into water at 80 °C, followed by adding 1 g sodium lignosulfonate under magnetic stirring. The dark mixture solution was remained at 80 °C under stirring until the water was evaporated. Then, the evaporated solid was then calcined under 700 °C for 2 h, obtaining a black powdery product. In the end, the obtained black powdery product was washed with water to wash off boric acid and dried at 80 °C for 12 h to yield desired CNs.

Ni-CNs and NiCo-CNs were prepared in the same method. 8 g boric acid, 1 g sodium lignosulfonate, 0.4 g nickel nitrate hexahydrate and 0.1 g cobalt nitrate hexahydrate were added in the water at 80 °C under magnetic stirring, followed by evaporation, calcination and washing with water. In the end, the desired Ni-CNs and NiCo-CNs were obtained.

2.3. General procedure for the reactions

The reaction was carried in a 25 mL high pressure reactor (Instrument model: YZPR-25) which was purchased from Beijing Yanzheng Biotechnology Co., Ltd. In a typical run, 100 mg of lignin β -O-4 substrate (2-phenoxy-1-phenylethan-1-ol was selected as model compounds) and 20 mg of NiCo-CNs catalyst in 10 mL of iPrOH were charged into a 25 mL stainless Parr autoclave. The reaction was then heated at 240 °C for 4 h with stirring at 800 rpm under 2 MPa N₂. When the reaction terminated, NiCo-CNs could be removed by a centrifugal process and reused in the next run. The obtained colorless mixture was followed analyzed by GC/MS using n-dodecane as the internal standard. The reaction conversion rate and yield of the aromatic monomer were calculated according to the following Eqs. (1)–(3):

$$Conversion = \frac{mole \ of \ reacted \ substrate}{total \ mole \ of \ substrate \ feed} *100\%$$
(1)



Fig. 2. XPS spectra of as-prepared NiCo-CNs: (a) survey; (b) C 1s; (c) S 2p; (d) Ni 2p; (e) Co 2p; (f) TEM image of NiCo-CNs.

Yield of ethylbenzene =
$$\frac{mole \ of \ ethylbenzene}{total \ mole \ of \ substrate \ feed} *100\%$$
 (2)

$$Yield of phenol = \frac{mole of phenol}{total mole of substrate feed} *100\%$$
(3)

After the reaction, the used catalyst after each run was washed with *i*PrOH for three times and dried overnight in the oven at 90 °C. Repeated experiment was carried out under the optimal reaction condition.

2.4. Characterization

Powder X-ray diffraction (XRD) patterns of the catalysts were performed on a Bruker D8 Advance X-ray powder diffractometer using Ni filtered Cu K\alpha radiation ($\lambda = 1.5406$ Å) with a scan speed of 2° min⁻¹ and a scan range of 10–80° at 30 kV and 15 mA. Scanning electron microscopy (SEM) was studied by using a TESCAN-VEGA3 instrument. Transmission electron microscopy (TEM) images were collected using a TEM Tecnai G2 20. The acidity of catalysts was detected by NH₃-TPD on a Micromeritics AutoChem 2920 instrument. The X-Ray photoelectron spectroscopy (XPS) was examined on an ESCALAB-250 (Thermo-VG Scientific, USA) spectrometer with Al K α (1486.6 eV) irradiation source.

3. Results and discussion

The 2D lamellar NiCo-CNs was synthesized by an impregnation method using sodium lignosulfonate as carbon and sulfur source, boric acid as templet. The samples were then calcined and dried. The photograph of the as-prepared NiCo-CNs was recorded, and the uniform black powder could be clearly seen in Fig. 1a. SEM images in Fig. 1b-d indicated a perfect ultra-thin lamellar structure of CNs, Ni-CNs and NiCo-CNs. It also revealed that the introduction of different metals would not destroy the excellent lamellar structure. As shown in the insert diagram of Fig. 1e, the Ni:Co weight ratio was around 4:1, which was close to the theoretical calculation in the preparation of NiCo-CNs. Additionally, the element mapping result in Fig. 1f-j suggested that Ni, Co, S were all presented in the surface of CNs with distinct morphology of nanoparticles. The XRD patterns of Ni-CNs showed diffraction peaks with 20 values of 31.104°, 38.271°, 44.330°, 49.733° and 55.161°, which were indexed to the (110), (021), (202), (113) and (122)



Fig. 3. NH₃-TPD of the Ni-CNs and NiCo-CNs samples.

planes of Ni_3S_2 [25]. No diffraction peaks of Co and/or CoS was observed. It was probably owing to good crystallinity or low content of Co introduced in NiCo-CNs (Fig. S1).

XPS survey spectra in Fig. 2a proved the presence of C, O, S, Ni and Co in NiCo-CNs material. In C 1s spectra (Fig. 2b), three distinct peaks at 284.20 eV, 285.50 eV and 287.20 eV were corresponding to C—C, C—S, and C—O [26]. For S2p spectra (Fig. 2c), the peak at 162.20 eV and 164.25 eV were corresponded to Ni-S in NiCo-CNs [12]. The main peaks of the XPS spectrum of Ni2p (Fig. 2d) around 855.05 eV and 857.40 eV were indexed to Ni2p3/2, whereas the peaks at 873.50 eV and 874.90 eV were indexed to Ni2p1/2, which all corresponded to Ni₃S₂ [27]. In Co2p spectra (Fig. 2e). The content of the Co 2p spectrum was complicated due to the presence of various species at surface level. The Co 2p2/3 spectrum has binding energies at 780.10 and 784.50 eV that could be attributed to CoS. The peaks between 797.20 and 803.05 eV belonged to Co 2p1/2 signals of their Co 2p3/2 counterparts and the satellite signal [28]. It was consistent with the results in XRD patterns (Fig. S1). TEM image in Fig. 2f could clearly discover the presence of nano Ni₃S₂ and

Table 1

Evaluation of the NiCo-CNs in cleavage of phenoxy-1-phenylethan-1-ol over different catalysts.^a

$ \underbrace{\operatorname{Catalyst}}_{iPrOH, 2 \text{ MPa } N_2} \underbrace{\operatorname{Catalyst}}_$					
Entry	Cat.	Conv. (%) ^b	Yield(%) ^b		
			2	3	4
1	_	0	0	0	0
2	CNs	0	0	0	0
3	Ni powder	5	3	2	2
4	Ni powder and CNs	6	3	2	3
5	Ni-CNs	70	16	44	42
6	NiCo-CNs	99	5	90	89

 $^a\,$ Reaction conditions: substrate (100 mg), Cat. (20 mg), iPrOH (10 mL), 2.0 MPa $N_2,$ 240 $^\circ C,$ 4 h;

^b Conversion and yields were determined by GC/MS with n-dodecane as the internal standard.

CoS metal particles over the lamellar nanosheets, suggesting a uniform particle distribution.

In addition, the acidity of Ni-CNs and NiCo-CNs was investigated using NH₃-TPD, as shown in Fig. 3. It was found that Ni-CNs showed a broad NH₃ desorption peak at 300–400 °C and NiCo-CNs showed a broad NH₃ desorption peak at 350–450 °C. It indicated the presence of medium strong acid site in Ni-CNs and NiCo-CNs catalysts. It could also be found that NH₃ desorption peak in NiCo-CNs shifted to high temperature compared with Ni-CNs. This phenomenon indicated an acidity enhancement after the introduction of element Co in Ni-CNs catalyst. Thus, it resulted in a better catalytic activity in the cleavage of lignin β -O-4 ether bond over NiCo-CNs.

The acidity information in Table S3 confirmed the synergy between Ni and Co. The total acidity for Ni-CNs increased gradually with the addition of Co in catalysts, while the acidity for NiCo-CNs improved to 3.6221 mmol/g NH₃, in comparison with Ni-CNs catalyst (0.4604 mmol/g NH₃). Apart from the improvement in total acidity, pyridine-IR analysis was also conducted to understand the Bronsted acid and Lewis

acid distributions in Ni-CNs and bimetallic NiCo-CNs catalysts. Interestingly, the improvement in both total acidity and Bronsted acid site in NiCo-CNs was observed during the pyridine-IR analysis, which was in accordance with the NH_3 -TPD analysis results.

4. Catalytic cleavage of lignin β-O-4 ether bond

Blank experiment with no catalyst or CNs as catalyst failed to transformed 2-phenoxy-1-phenylethan-1-ol to ethylbenzene and phenol (Table 1 entries 1–2). When Ni powder was employed in the reaction, nearly 95% substrate was recovered in the catalytic system (Table 1 entry 3). Mechanical mixture of nickel powder and CNs also could not be converted 2-phenoxy-1-phenylethan-1-ol into ethylbenzene and phenol (Table 1 entry 4). Ni-CNs showed better catalytic performances in the cleavage β -O-4 ether bond (Table 1 entries 5), producing 3 and 4 in moderate yield (44% and 42% yield of ethylbenzene and phenol, respectively). It could come to a conclusion that Ni₃S₂ on the surface of CNs played a catalytic role in the cleavage of β -O-4 ether bond compared



Fig. 4. Cleavage of 2-phenoxy-1-phenylethan-1-ol over NiCo-CNs (a) effect of reaction time, (b) effect of reaction temperature, (c) effect of N₂ pressure, (d) and effect of solvents.



Fig. 5. Cleavage of various lignin derived dimers over optimal NiCo-CNs catalyst.

with the results in entry 4. Interestingly, introducing Co into Ni-CNs dramatically improved the catalyst activity and the NiCo-CNscatalyzed reaction of **1** led to **3** and **4** in almost quantitative yield (Table 1 entry 6). It was probably owing to more active sites in lamellar structure facilitated better contact with the reaction substrates and the enhancement acidity of NiCo-CNs after the introduction of Co. The result in Table 2 entry 6 could be repeated three times and it could be seen in Table S2. The cleavage of β -O-4 ether bond was a catalytic transfer hydrogenation process, in which isopropanol served as a good H-donner and provided a large amount of active hydrogen to promote the cleavage of C—O bond [29]. Of note is the mass balance of these reactions. The hydrogenolysis product was obtained as phenethoxybenzene, ethylbenzene and phenol. And nearly no starting materials could be recovered by GC/MS when the product yield is very high in Fig. S5. The representative chromatogram could be seen in Fig. S3.

In order to determine the optimized reaction condition for the cleavage of β -O-4 ether bond, the effect of reaction condition such as reaction time, reaction temperature, N2 pressure, solvent on the catalytic cleavage of 2-phenoxy-1-phenylethan-1-ol were studied. As shown in Fig. 4a-4c, as the reaction time, reaction temperature and N₂ pressure increased, the conversion of 2-phenoxy-1-phenylethan-1-ol and the yield of aromatic monomers continue to increase. Although isopropanol could replace extra hydrogen source to provide hydrogen, it could only provide a small amount of hydrogen compared with extra H₂. So, we added 2 MPa N2 in the catalytic system for total conversion of 2-phenoxy-1-phenylethan-1-ol. It was probably owing to that the existence of high N2 pressure could lower too high catalyst surface coverage of H2 or ease the dispersion of the gas phase in the liquid, which resulted in a good conversion and yields of target products. Similar reaction condition (reaction condition: NiCu/C, 270 $^\circ\text{C}$, 4 h, 1 MPa N_2 pressure) was reported by Cheng et al [30]. When the reaction time, temperature and

N2 pressure reach 4 h, 240 °C and 2 MPa, the conversion and yield reached the highest value (99% conversion of 2-phenoxy-1-phenylethan-1-ol, 90% and 89% yield of ethylbenzene and phenol respectively). It was interesting to find that the yield of phenethoxybenzene decreased with the increase of the reaction time, reaction temperature and N₂ pressure. It indicated that phenethoxybenzene was a key intermediate state in the transformation of 2-phenoxy-1-phenylethan-1-ol. From the result detected in the GC/MS, we could also find the existence of phenethoxybenzene (Fig S3). When three types of hydrogen donor solvent were employed as solvent in the catalytic process, moderate to high yield of ethylbenzene and phenol was obtained in Fig. 4c. Cyclohexane, compared with methanol, ethanol and isopropanol, was carried out as solvent in the cleavage of 2-phenoxy-1-phenylethan-1-ol. It failed to convert 2-phenoxy-1-phenylethan-1-ol to aromatic monomers, which confirmed that methanol, ethanol and isopropanol served as hydrogen donor solvent in the catalytic reaction. This is consistent with our previous research [30].

Inspired by the excellent performance of NiCo-CNs catalyst for the efficient cleavage of the β -O-4 bond. Then the cleavage of C—O bond was further studied in more detail by varying substituent groups on the benzene ring in Fig. 5. Generally, it could be verified that the NiCo-CNs catalyst was highly efficient for the transfer hydrogenolytic cleavage of ether bond in a variety of lignin derived model compounds. Substrate with no substituent group on α -C could be cracked to obtain 85% and 83% yield of ethylbenzene and phenol in Entry 1b, respectively. When α -C was substituted with carbonyl, better yield of ethylbenzene and phenol was achieved in Entry 1c. It was probably owing to lower bond dissociation energy of β -O-4 ketone (227.8 kJ/mol) than β -O-4 alcohol (274.0 kJ/mol), which led to C—O bond in β -O-4 ketone is easier to break [31]. Thus, substitutions at the α -C atom have a great effect on bond dissociation energy of C β -OPh bond and the activation of the β -O-4



BDE=336.3 kJ/mol

Fig. 6. Possible pathway for the conversion of 2-phenoxy-1-phenylethan-1-ol over NiCo-CNs.

lignin linkage. In addition, methoxy substituted β-O-4 dimer model compounds was carried out in the catalytic process and moderate conversion and yield of corresponding aromatic monomers were obtained. For example, 2-(2-methoxyphenoxy)-1-phenylethan-1-ol could generate 72% yield of ethylbenzene and 69% guaiacol (Entry 1d). it was not easy to find that substituent groups on benzene ring led to a negative effect on the cleavage of lignin derived β-O-4 dimer model compounds. It was consistent with our previous research. We all know that β -O-4 dimer model compounds with γ -OH lignin typical realistic segment [32]. Therefore, 2-(2-methoxyphenoxy)-1-(4-methoxyphenyl)propane-1,3diol was charged in the optimal catalytic system. However, it failed to obtain 1-ethyl-4-methoxybenzene (Entry 1d). Additionally, two kinds of C—O bond dimers of lignin (4-O-5 and α -O-4) were investigated in the optimal reaction condition. Moderate yield of benzene and phenol was achieved in Entry 1f compared with relative high yield of toluene and phenol in Entry 1 g. This is mainly due to high bond dissociation energy of 4-O-5 ether bond (314.0 kJ/mol) than α-O-4 (245.0 kJ/mol) [33–34]. Generally. all these examples above demonstrated that NiCo-CNs catalyst showed good to excellent catalytic cleavage of different substrates containing lignin ether bonds to generate corresponding aromatic monomers, which could provide a novel route for the generation of aromatic hydrocarbons and aromatic alcohols by catalytic hydrotreatment of lignin dimeric model compounds. Finally, the recycled sustainable NiCo-CNs catalysts could also be carried out in the next five runs with only slight decrease in the conversion (Fig. S2). It was probably owing to the metal leaching from the surface of the catalyst (Table S1).

Three different types of intermediate state were proposed, including 2-phenoxy-1-phenylethan-1-one, phenethoxybenzene and (2-phenoxyvinyl)benzene. It could be clearly seen in Fig. 6 that the order of C-O bond dissociated energy is as follows: (2-phenoxyvinyl)benzene > phenethoxybenzene > 2-phenoxy-1-phenylethan-1-one, which indicated that 2-phenoxy-1-phenylethan-1-ol need to overcome the energy of 62.3 kJ/mol to convert into (2-phenoxyvinyl)benzene [31]. It was quite difficult to achieve this goal in our catalytic system. So, (2-phenoxyvinyl)benzene was not a key intermediate and no (2-phenoxyvinyl) benzene was detected in time conversion curve. It was surprising to find that the C-O bond dissociated energy of 2-phenoxy-1-phenylethan-1one was lower than 2-phenoxy-1-phenylethan-1-ol. However, no oxidant was added in the reaction and we did not observe 2-phenoxy-1phenylethan-1-one in the GC/MS. So, route 1 is not a possible reaction pathway for the conversion of 2-phenoxy-1-phenylethan-1-ol. From the GC/MS result in the Fig. S3 the possible intermediate was phenethoxybenzene, and ethylbenzene and phenol were generated after the cleavage of C-O bond over NiCo-CNs. In addition, the reaction circumstance is not for the dehydrogen or oxygenation. In general, route 2 was the main pathway in the conversion of 2-phenoxy-1-phenylethan1-ol over NiCo-CNs catalyst.

The detailed pathway was discussed, and it could be seen in Fig. S4. The isopropanol was adsorbed and dissociated on NiCo sites to form H⁺. firstly, the metal NiCo and the formed H⁺ enhanced the hydrodeoxygenation of C α -OH to produce phenethoxybenzene. The H⁺ subsequently reacted with oxygen atom in phenethoxybenzene to produce phenol via the cleavage of C—O ether bond. Finally, C₆H₅-CH₂-CH₂⁺ abstracted H⁻ from the C α -H⁻ of isopropanol to produce ethylbenzene. The GC–MS results in Fig S3 also confirmed the pathway in Fig S4.

5. Conclusion

In conclusion, we discovered that the CNs exhibited excellent catalytic activities in cleavage of lignin β -O-4 ether bond after NiCo doping, because of the ultrathin lamellar structure that led to endowing more active sites to facilitate better contact with the reaction substrates. The catalyst could also be easily removed and recycled in the next run with only slight decrease. In comparison with the previously reported NiCobased catalyst, the lamellar NiCo-CNs was fabricated from cheap and abundant waste residue of pulp sodium lignosulfonate in one step through very simple immersing processes. It provided an environmentally-friendly method for lignin dimers hydrotreatment and further hydrotreatment of realistic lignin would be carried out in our next work.

CRediT authorship contribution statement

Changzhou Chen: Conceptualization, Writing – original draft. **Dichao Wu:** Methodology. **Jurong Ren:** Software. **Peng Liu:** Validation, Formal analysis, Investigation. **Haihong Xia:** Resources, Data curation. **Minghao Zhou:** Visualization, Supervision, Project administration. **Jianchun Jiang:** Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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References

- M. Ghadiryanfar, K.A. Rosentrater, A. Keyhani, M. Omid, Renewable Sustainable Energy Rev. 54 (2016) 473–481.
- [2] C.O. Tuck, E. Perez, I.T. Horvath, R.A. Sheldon, M. Poliakoff, Science 237 (2012) 695–699.
- [3] F. Gao, J.D. Webb, J.F. Hartwig, Angew. Chem.; Int. Ed. 55 (2016) 1474-1478.
- [4] L. Dong, L. Lin, X. Han, X. Si, X. Liu, Y. Guo, F. Lu, S. Rudić, S.F. Parker, S. Yang, Y. Wang, Chem 5 (2019) 1521–1536.
- [5] Z. Sun, B. Fridrich, A. de Santi, S. Elangovan, K. Barta, Chem. Rev. 118 (2018) 614–678.
- [6] Z. Zhang, J. Somg, B. Han, Chem. Rev. 117 (2017) 6834-6880.
- [7] H. Zeng, Z. Qiu, A. Domínguez-Huerta, Z. Hearne, Z. Chen, C.-J. Li, ACS Catal. 7 (2017) 510–519.
- [8] A. Procentese, E. Johnson, V. Orr, A.G. Campanile, J.A. Wood, A. Marzocchella, L. Rehmann, Bioresource Technol. 192 (2015) 31–36.
- [9] P. Liu, C. Chen, M. Zhou, H. Xia, J. Li, B.K. Sharma, J. Jiang, New J. Chem. 45 (2021) 8258–8268.
- [10] C. Chen, P. Liu, M. Zhou, B.K. Sharma, J. Jiang, Energies 13 (2020) 846.
- [11] C. Chen, P. Liu, H. Xia, M. Zhou, J. Zhao, B.K. Sharma, J. Jiang, Molecules 25 (2020) 2019.
- [12] C. Chen, P. Liu, H. Xia, M. Zhou, J. Jiang, J. Chin, Chem. Soc. 68 (2021) 582–591.
- [13] J. Zhang, Z. Su, Z. Wu, P. Wang, F.-S. Xiao, Catal. Today 365 (2021) 193–198.
- [14] D. Ma, S. Lu, X. Liu, Y. Guo, Y. Wang, Chin. J. Catal. 40 (2019) 609-617.
- [15] C. Zhang, J. Qi, J. Xing, S.-F. Tang, L. Song, Y. Sun, C. Zhang, H. Xin, X. Li, RSC Adv. 6 (2016) 104398–104406.

- [16] H. Wu, J. Song, C. Xie, C. Wu, C. Chen, B. Han, ACS Sustainable Chem. Eng. 6 (2018) 2872–2877.
- [17] M. Hua, J. Song, C. Xie, H. Wu, Y. Hu, X. Huang, B. Han, Green Chem. 21 (2019) 5073–5079.
- [18] J.-P. Cao, T. Xie, X.-Y. Zhao, C. Zhu, W. Jiang, M. Zhao, Y.-P. Zhao, X.-Y. Wei, Fuel 284 (2021), 119027.
- [19] F. Mauriello, E. Paone, R. Pietropaolo, A.M. Balu, R. Luque, ACS Sustainable Chem. Eng. 6 (2018) 9269–9276.
- [20] M. Zhou, C. Chen, P. Liu, H. Xia, J. Li, B.K. Sharma, J. Jiang, ACS Sustainable Chem. Eng. 8 (2020) 14511–14523.
- [21] P.C. Gao, W.Y. Tsai, B. Daffos, P.L. Taberna, C.R. Pérez, Y. Gogotsi, P. Simon, F. Favier, Nano Energy 12 (2015) 197–206.
- [22] D. Wu, C. Chen, J. Li, X. Jian, A. Wang, K. Sun, J. Jiang, New J. Chem. 44 (2020) 21271–21278.
- [23] C. Chen, M. Zhou, P. Liu, K. Sharma, J. Jiang, New J. Chem. 44 (2020) 18906–18916.
- [24] Z. Ling, Z. Wang, M. Zhang, C. Yu, G. Wang, Y. Dong, S. Liu, Y. Wang, J. Qiu, Adv. Funct. Mater. 26 (2016) 111–119.
- [25] Z. Wang, W. Song, W. Yan, W. Zhang, Y. Liu, X. Hao, G. Guan, Mater. Lett. 238 (2019) 81–84.
- [26] C. Chen, D. Wu, P. Liu, J. Li, H. Xia, M. Zhou, J. Jiang, Green. Chem. 23 (2021) 3090–3103.
- [27] Q. Zhang, G. Peng, J.P. Mwizerwa, H. Wan, L. Cai, X. Xu, X. Yao, J. Mater. Chem. A 6 (2018) 12098–12105.
- [28] Q. Xu, D. Jiang, T. Wang, S. Meng, M. Chen, RSC Adv. 6 (2016) 55039-55045.
- [29] X. Lin, L. Chen, H. Li, Y. Lv, Y. Liu, X. Lu, Bioresource Technol. 333 (2021), 125136.
- [30] C. Chen, P. Li, W. Yu, D. Shen, S. Gu, Bioresource Technol. 319 (2021), 124238.
- [31] C. Zhang, J. Liu, X. Zhang, K. MacArthur, M. Heggen, H. Li, F. Wang, Green Chem. 18 (2016) 6545–6555.
- [32] F. Zhang, J. Zhang, S. Guo, Inorg. Chem. Commun. 100 (2019) 105–109.
- [33] C. Chen, D. Wu, P. Liu, H. Xia, M. Zhou, X. Hou, J. Jiang, React, Chem. Eng. 6 (2021) 559–571.
- [34] A. Bjelić, B. Likozar, M. Grilc, Chem. Eng. J. 399 (2020), 125712.