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1. Introduction

Lignin, a heterogeneous aromatic biopolymer, is one of the main constituents of lignocellulosic biomass, comprising roughly 30% on a weight basis and 40% on an energy basis.^{1,2} It is constructed by three main phenyl propane units, namely *p*-coumaryl (H), coniferyl (G), and sinapyl (S).^{3–5} The aromatic structure offers the potential to convert it into commodity chemicals and high-quality fuels, which exhibits bright prospects for sustainable development given the concerns at present over limited fossil resource reserves.^{1,6}

However, these phenyl propane units are linked *via* various C– O and C–C bonds, including β -O-4, β -1, β - β , 4-O-5, α -1, 5–5' and so on.^{3–5,7} Among these linkages, the β -O-4 structure accounts for approximately 43% to 65% of all the bonds in softwood and hardwood native lignin.^{1,2,8} Therefore, the efficient cleavage of the

Mild selective oxidative cleavage of lignin C–C bonds over a copper catalyst in water[†]

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The conversion of lignin into aromatics as commodity chemicals and high-quality fuels is a highly desirable goal for biorefineries. However, the presence of robust inter-unit carbon–carbon (C–C) bonds in natural lignin seriously impedes this process. Herein, for the first time, we report the selective cleavage of C–C bonds in β -O-4 and β -1 linkages catalyzed by cheap copper and a base to yield aromatic acids and phenols in excellent yields in water at 30 °C under air without the need for additional complex ligands. Isotope-labeling experiments show that a base-mediated C_{β}-H bond cleavage is the rate-determining step for C_{α}-C_{β} bond cleavage. Density functional theory (DFT) calculations suggest that the oxidation of β -O-4 ketone to a key intermediate, *i.e.*, a peroxide, by copper and O₂ lowers the C_{α}-C_{β} bond dissociation energy and facilitates its subsequent cleavage. In addition, the catalytic system could be successfully applied to the depolymerization of various authentic lignin feedstocks, affording excellent yields of aromatic compounds and high selectivity of a single monomer. This study offers the potential to economically produce aromatic chemicals from biomass.

 β -O-4 linkage is the major challenge for producing aromatic chemicals from lignin.⁷ In targeting its cleavage, researchers have developed pyrolysis,^{9–12} acid or alkali hydrolysis,^{13–16} reduction^{17–20} and oxidation^{21–27} methods, each with its own advantages and limitations. From a chemical point of view, oxidative conversion of lignin has several attractive advantages, including but not limited to, the relatively low conversion temperatures and pressures, and the production of highly functional aromatic compounds (such as aldehydes, esters and organic acids), which can be directly used as fine and platform chemicals.^{1,2,7}

The oxidative depolymerization of β -O-4 linkages can be achieved by breaking the C-O or C-C bonds. Much current research has focused on their depolymerization through the cleavage of C-O bonds.^{22,23,28-32} Inter-unit C-C bonds have higher dissociation energies and the selective cleavage of these bonds remains a significant challenge.3,33 Therefore, an efficient catalytic system that can selectively break C-C linkages in lignin should be developed. Rossi and colleagues had previously shown that a copper system (composed of CuCl and pyridine) catalyzed the aerobic oxidation of diols, highlighting the potential of copper to catalyze C-C bond cleavage.34 Recent work showed that copper-based catalytic systems, such as CuCl/TEMPO/2,6-lutidine/toluene,³⁵ Cu(OAc)₂/1,10-phenanthroline/methanol,³⁶ Cu (OAc)₂/BF₃·OEt₂/methanol,³⁷ CuBr₂/*N*-methyl TBD/DMSO,³⁸ CuCl₂/N-iodosuccinimide/DMSO,³⁹ etc., were efficient in cleaving C–C bonds in β -O-4 ketones, affording acids, esters and phenols.

However, organic solvents (such as methanol, pyridine, toluene, acetonitrile, DMSO, *etc.*) and complex ligands (such as

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the abovementioned 2,6-lutidine, 1,10-phenanthroline, N-methyl TBD, etc.) are usually indispensable for increasing the solubility and generating active copper complex cores.33,35-43 From the atom-economical and green chemistry viewpoint, the copper-catalyzed aerobic oxidation of lignin linkages in water and without any additional complex ligands would be more ideal, as it avoids the use of toxic organic solvents, which are often hazardous and generate waste.^{1,44-48} Besides, it is known that phenols are easily oxidized or undergo repolymerization reactions under oxidative conditions to create products that are not desirable.49 Previous work on the oxidative cleavage of lignin models usually showed low yields for phenols.^{36,50-52} Thus, if the oxidative cracking of lignin linkages can be carried out at mild ambient temperature and pressure, the yield of the desired monomers could be fully maximized.

Herein we report a mild aerobic lignin depolymerization system based on an inexpensive commercially available copper salt and a base. The catalytic system can selectively cleave the C–C bonds of a series of β -O-4 and β -1 lignin model compounds into acids, phenols and aldehydes under ambient conditions in water (Scheme 1). The mechanism for the cleavage of C–C bonds was studied *via* isotope-labeling experiments and DFT calculations. Encouraged by the success of the reaction system in the cleavage of the model compounds, the applicability of both CuCl and NaOH in the degradation of real lignin raw materials was studied, affording excellent yields of aromatic compounds and high selectivity of a single monomer. This study provides an attractive option for producing value-added chemicals from renewable lignin with a simple and economical catalyst under mild conditions.

2. Experimental

2.1 Procedure for the synthesis of β-O-4 model compounds

All β-O-4 dimeric lignin model compounds were prepared based on previously reported procedures.⁵³ The structures of

these compounds were confirmed by 1 H-NMR and 13 C-NMR (Fig. S1–S6†).

2.2 General procedure for the cleavage reaction

2.2.1 Procedure for the cleavage reaction of the \beta-O-4 and \beta-1 model compounds. A pressure tube was equipped with a magnetic stir bar and was charged with the model compound (0.1 mmol), catalyst (0.05 mmol), NaOH (0.4 mmol) and H₂O (2.5 mL). The tube was sealed and then heated at 30 °C for 5.5 h. After the reaction, the mixture was acidified with hydrochloric acid solution to pH = 2 and extracted with dichloromethane (3 × 5 mL). The organic layers were combined and dried over anhydrous Na₂SO₄. The products were subsequently characterized and quantified using gas chromatography/mass spectrometry (GC-MS) and gas chromatography (GC).

2.2.2 Procedure for the cleavage reaction of the authentic lignin material. Oxidation experiments were performed in a 50 mL autoclave (type 316 stainless steel, Anhui Kemi Machinery Technology Co., Ltd) charged with 0.5 g of authentic lignin sample, catalyst (0.5 mmol), and NaOH (15 mmol) and H₂O (25 mL) as the solvent. The reactor was pressurized with 5 bar of air, and heated to the desired reaction temperature. After the reaction, 5 mL of the reaction solution was added to a 15 mL glass vial, acidified with hydrochloric acid solution to pH = 2 and extracted with dichloromethane (3 × 10 mL). The organic layers were combined and dried over anhydrous Na₂SO₄. The products were subsequently characterized and quantified using GC-MS and GC.

2.3 Density functional theory (DFT) calculations

The C_{α} - C_{β} , C_{β} -O and C_{β} -H bond dissociation energies (BDE) were calculated using the DFT method.^{54,55} The geometry optimizations of the lignin model compounds used in this article were performed using DFT with the M06-2X hybrid exchange–correlation functional and the 6-311 basis set using the Gaussian 09 suite of programs.⁵⁶



Scheme 1 The C–C bond cleavage of β -O-4 and β -1 ketone linkages to benzoic acid, phenol, and benzaldehyde.

3. Results and discussion

3.1 Model compound studies

The initial reactions were performed using a typical and widely used lignin β-O-4 model compound, 2-phenoxy-1-phenylethanone (1a), as the starting material under air conditions at room temperature (30 °C) for 5.5 h in the presence of CuCl. Reports^{46,57,58} in the literature have indicated that lignin tends to be partly soluble in alkaline solution. Therefore, a range of bases was screened to potentially enhance the conversion of the lignin model compound 1a in water over a CuCl catalyst (Table 1, entries 3-8). The product distribution analysis shows that two kinds of typical products can be obtained in parallel from the oxidation of **1a**: benzoic acid (**c**) and phenol (**d**). The bases showed an obvious effect on the reaction. The reaction could not proceed without adding a base (Table 1, entry 2), indicating the crucial role of the alkaline conditions. The activity increased with the base strength. The weak bases, such as NH₃·H₂O and NaOAc, showed little effect on the reaction (Table 1, entries 7 and 8). NaOH and KOH were favored for oxidative cleavage reaction (Table 1, entries 3 and 4), and NaOH showed the best performance with 96.96% conversion of 1a (Table 1, entry 3). Therefore, NaOH was chosen as the base due to its excellent performance and cheaper price than KOH.

Table 1 Catalyst and base screening for the cleavage of $\beta\text{-}O\text{-}4$ lignin model compound 1a

		Air(1 atr	$(m)/30 ^{\circ}C$ /Base/H ₂ O	O H + H	
	1a			c	d
				Yields (mol%)	
Entry	Catalyst	Base	Conversion (%)	c (benzoic acid)	d (phenol)
1	None	NaOH	8.07	0.16	1.73
2	CuCl	None	0.75	0	0
3	CuCl	NaOH	96.96	85.12	89.03
4	CuCl	KOH	83.55	67.33	70.02
5	CuCl	Na_2CO_3	49.18	2.62	5.51
6	CuCl	$CsCO_3$	18.52	1.82	2.33
7	CuCl	$NH_3 \cdot H_2O$	23.32	0.89	2.98
8	CuCl	NaOAc	27.86	1.11	2.56
9	CuO	NaOH	49.13	19.94	16.41
10	$Cu(OAc)_2$	NaOH	49.83	8.53	6.12
11	$Cu(OH)_2$	NaOH	17.99	10.78	7.45
12	CuCl ₂	NaOH	80.23	51.04	45.22
13	$CuSO_4$	NaOH	71.15	60.01	55.14
14	Cu_2O	NaOH	49.81	22.48	19.53
15	CuBr	NaOH	71.03	48.55	42.9
16	$MnCl_2$	NaOH	35.26	2.39	4.56
17	$AlCl_3$	NaOH	45.78	9.54	7.20
18	FeCl ₃	NaOH	38.23	8.56	6.39
19	$ZnCl_2$	NaOH	12.37	0	0
20^a	CuCl	NaOH	7.64	0.54	2.73

General conditions: **1a** (0.1 mmol), catalyst (0.05 mmol), base (0.4 mmol), water solvent (2.5 mL), air (1 atm), 30 °C for 5.5 h. a Ar atmosphere (1 atm) instead of air.

Optimization of the amount of NaOH for the cleavage of **1a** is given in the ESI (see Table S1[†]).

In addition to the alkali, the copper catalyst also plays an important role in the cleavage of 1a. Only a small amount of the desired products c and d (<2%) were obtained without adding copper (Table 1, entry 1). Then, numerous copper salts or oxides were screened to potentially enhance the conversion of 1a. Among the Cu(II) catalysts (Table 1, entries 9–13), CuO and Cu(OAc)₂ showed moderate activity with 49% conversion of 1a, while $Cu(OH)_2$ was ineffective for the 1a oxidation. Regarding CuCl₂ and CuSO₄, about 80% and 71% of 1a were converted, respectively. Unexpectedly, Cu(I) performed much better than Cu(II). Over CuCl, almost complete conversion of model 1a could be achieved with 85.12% yield of benzoic acid and 89.03% yield of phenol even under 1 atm aerobic environment at 30 °C for 5.5 h (Table 1, entry 3). However, Cu₂O and CuBr showed lower activities (Table 1, entries 14 and 15), possibly due to poor solubility in water. In addition to copper catalysts, various other commonly used metal salt catalysts in the literature^{26,28,43,44,46} were tested for the conversion of 1a (Table 1, entries 16–19). $ZnCl_2$ had no activity for β -O-4 linkage cleavage. Regarding MnCl₂, AlCl₃ and FeCl₃, about 40% of 1a was converted, however, and only low yields of the desired product benzoic acid and phenol (<10%) were obtained, suggesting that 1a was possibly transformed into (unidentified) byproducts, e.g., polymers according to previous reports.^{7,37,50} Moreover, poor product yields were detected under an Ar atmosphere with a pronouncedly decreased conversion (Table 1, entry 20), confirming the necessity of atmospheric oxygen in the cleavage of the β -O-4 linkage.

Further insight into the reaction conditions was obtained using 1a. Fig. 1(I) shows that with the reaction time increased from 0.5 to 5.5 h, the yields of c and d at 30 °C increased from 1.99% and 4.54% to the maximum yields of 85.12% and 89.03%, respectively. A further increase in the reaction time to 10 h led to a significant decrease in yields, although 100% conversion of 1a could be achieved. Fig. 1(I) also shows that reactant 1a was rapidly transformed within 10 min at higher temperatures. A conversion of 62.36% was obtained after 10 min of reaction at 60 °C. Further increasing the temperature enhanced the conversion of 1a but also led to a notable decline in yields and selectivity of c and d (see Table S2[†]), probably due to degradation or repolymerization at high temperatures according to previous reports.42,50 These results demonstrate the importance of mild conditions in avoiding unnecessary condensation and decomposition and provide strong motivation to develop milder lignin oxidation methods.

Natural lignin usually contains various substituted functional groups (especially OMe, phenolic OH, and γ -CH₂OH groups), which may affect the activation of linkages.^{1,7} A series of other lignin β -O-4 model substrates **2–5a** was then tested in this catalytic system, and all of them could be almost completely converted within 4 to 18 h with high yields of aromatic acids, phenols or aromatic aldehydes (see Fig. 1(II)). Conversion of 97.42% of **2a** was obtained at 30 °C after 4 h, and generated corresponding acid and phenol in high yields (I) Optimization of Reaction Conditions

(II) Substrate Scope





Fig. 1 (I) Optimization of reaction conditions for 1a conversion. (II) Exploration of substrate scope. General conditions: Substrate (0.1 mmol), CuCl catalyst (0.05 mmol), NaOH (0.4 mmol), solvent (2.5 mL), air (1 atm).

of 85.56% and 91.28%, respectively, while **3a** and **4a** possessing two or three methoxy groups in the aromatic units were oxidized more slowly, probably owing to the steric hindrance effect.^{7,50} The β -O-4 lignin model with phenolic OH and γ -CH₂OH (1-(4-hydroxy-3,5-dimethoxyphenyl)-2-(2-methoxyphenoxy)propane-1,3-diol, **5a**) was also successfully broken down to guaiacol and syringaldehyde in 83.57% and 76.06% yields, respectively. But a higher reaction temperature (50 °C) was required. Except for β -O-4 compounds, β -1 ketone lignin model (1,2-diphenylethanone, **1b**) was also successfully broken down into benzoic acid (**c**) and benzaldehyde (**e**) with 94.38% conversion under air conditions at 50 °C for 10 h in the presence of Cu(1), and the third product was a trace amount (3.02%) of the C-H bond oxidation product diphenylethane-dione (**f**).

3.2 Mechanism study

Mechanistic insights into the depolymerization process are discussed below. It is apparent that benzoic acid **c** and phenol **d** were generated from the breakage of the C_{α} - C_{β} and/or C_{β} -O bonds in models **1–3a**. To investigate the cleavage mechanism of the chemical bonds in lignin β -O-4 and β -1 ketone, DFT calculations were initially performed with Gaussian 09. The calculated bond dissociation energies of the C α -C β , C β -O and C $_{\beta}$ -H bonds from the optimized geometries of lignin model com-

pounds are listed in Table 2. Optimized structures for the lignin model compounds are provided in the ESI Fig. S8–S13.†

The BDEs of the C–O and C–C bonds in models **1–4a** are approximately 60–65 and 81–86 kcal mol⁻¹ (Table 2, entries 1–4), respectively while the β -1 linkage has a moderate C–C BDE of 76 kcal mol⁻¹ (Table 2, entry 5). Breaking the C_{β}–H bonds in the β -O-4 ketone and β -1 ketone require approximately 90 kcal mol⁻¹ and 106 kcal mol⁻¹, respectively. Combining the above experimental results that the complete conversion of **1b** requires a higher temperature (50 °C) than the conversion of **1–4a**, it is speculated that C_{β}–H may have played an important role in the first reaction step (see also discussion below).

Then, the ¹H-NMR analysis was performed to elucidate the structural transformation of model compound **1a** before and after oxidative reaction (Fig. S15†). The strong signal corresponded to C_{β} -H (δ = 5.58) of substrate **1a** disappeared completely after 5.5 h of reaction, demonstrating the effective breakage of the C_{β} -H bond. Together with other significant changes of the ¹H-NMR signals, it is considered that the main structure of **1a** was significantly changed due to the breaking of the specific bonds over CuCl and NaOH. To verify this conclusion, the ¹H-NMR analysis was conducted using compounds **1a** and **1a-d**₂ (hydrogen atoms in C_{β} -H substituted by deuterium) as the substrates. The signals before and 4 h after the reaction are shown in Fig. 2. The ¹H spectra of the main

Table 2 Bond dissociation energies of $C_{\alpha}-C_{\beta},\ C_{\beta}-O$ and $C_{\beta}-H$ in lignin compounds

		Dissociation energy (kcal mol^{-1})		
Entry	Compound	C_{α} - C_{β}	C_{β} –O	C_{β} –H
1		81.09	64.51	89.57
2		84.49	61.12	90.09
3		83.54	64.34	90.38
4		86.63	59.77	91.90
5	(4a)	76.35	_	106.38

Bond dissociation energies (BDEs) of lignin model compounds determined by density functional theory (DFT).



Fig. 2 1 H NMR spectra of 1a and 1a-d₂ before and after 4 h reaction in 0.6 mL of DMSO as the solvent. Conditions: Substrate (0.1 mmol), CuCl catalyst (0.05 mmol), NaOH (0.4 mmol), water solvent (2.5 mL), air (1 atm), 30 °C, 4 h.

cleavage products benzoic acid c and phenol d standards are also provided for reference. As shown in Fig. 2, the characteristic peaks of c and d signal appeared in the 4 h reaction mixture from both **1a** and **1a-d**₂. No other products were detected, indicating that no stable intermediates were formed during the β -O-4 ketone oxidative cleavage reaction. Furthermore, the product signals of **1a-d**₂ were obviously weaker than that of **1a**.

Then the isotope effect was investigated. The time-oncourse process for **1a** and **1a-d**₂ fragmentation at the abovementioned conditions were recorded in Fig. 3. Different from **1a** fragmentation, products **c** and **d** were formed slower when **1a-d**₂ was the substrate. This phenomenon is caused by the difference of H and D species.⁶¹ When the independent reactions of substrates **1a** and **1a-d2** were compared, a primary kinetic isotope effect (KIE) was obtained with a $k_{\rm H}/k_{\rm D} = 2.2$, indicating that the cleavage of C_β-H is the rate-limiting step during the cleavage of the β-O-4 linkages. As mentioned above, the reaction could not proceed without adding a base. Then we infer that NaOH played a significant role in the first reaction step, *i.e.*, C_β-H cleavage. Thereafter, CuCl and O₂ were indispensable for the next steps.

Due to the huge difference (approximately 20 kcal mol^{-1}) in dissociation energy between the C_{α} - C_{β} and C_{β} -O bonds, it was speculated that the C_{β} -O bond in β -O-4 ketone linkages is broken first to form 2-hydroxy-1-phenylethanone and sodium phenolate as reported.⁴⁰ However, 2-hydroxy-1-phenylethanone was not detected as a product in the present catalytic system. When it was used as a substrate, only 9.75% conversion was obtained, affording a 2.02% yield of benzoic acid over the CuCl catalyst after 5.5 h at the identical conditions as the abovementioned conditions for compounds 1-4a conversion (Scheme 2, eqn (1)), suggesting that phenols and benzoic acids were not formed via the C_{β} -O ether bond direct cleavage. Instead, it appears more likely that the two phenyl units were generated from the breakage of C_{α} - C_{β} bonds. Thus, phenyl formate was speculated as a transient intermediate result from the breakage of the C_{α} - C_{β} bond and was facilely converted to phenol and formic acid in the presence of NaOH and CuCl (Scheme 2, eqn (2)). Regarding the β -5 model compound conversion, diphenylethanedione (f) was observed as a minor product, but cannot be converted to benzoic acid and benzaldehyde (Scheme 2, eqn (3)), indicating that it was not the reaction intermediate, but a by-product.

In order to determine whether the aerobic breakage of **1a** undergoes a free radical process or not, 0.1 mmol (1.0 equiv.) TEMPO (2,2,6,6-tetramethyl-1-piperidinyloxy) was added as a radical scavenger before the oxidation reaction. It was found that the yields of **c** and **d** significantly reduced from 85.12 and 89.03% to 21.63 and 15.32%, respectively (Table 3). If the amount of TEMPO was reduced to 0.05 mmol (0.5 equiv.), the yields of **c** and **d** can be restored to a certain extent, reaching 43.95 and 36.45%, respectively. Similar results were obtained when using **1b** as the substrate (Table 3). Therefore, it was considered that the reaction was significantly inhibited but not completely hindered, suggesting that the C_{α} - C_{β} cleavage reaction involves a free radical mechanism, which may be the dominant path.

On the basis of the above-described explorations combined with the knowledge in the literature, two plausible reaction



Fig. 3 Kinetic Isotope Effects (KIEs) with deuterium labelled compound **1a-d**₂ (I), the linear fit of concentration against the reaction time of models **1a** (II) and **1a-d**₂ (III). Conditions: Substrate (0.1 mmol), CuCl catalyst (0.05 mmol), NaOH (0.4 mmol), water solvent (2.5 mL), air (1 atm), 30 °C.



Scheme 2 Control experiments of the possible intermediates or side products.

Table 3 Oxidation o	f lignin model	compounds w	ith TEMPO
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			Yield (%)	
Substrate	Quantity (equiv.)	Conversion (%)	с	d(e)
1a	_	96.96	85.12	89.03
	1.0	40.02	21.63	15.32
	0.5	69.30	43.95	36.45
1b	_	94.38	82.53	76.65
	1.0	36.02	14.26	15.35
	0.5	55.65	32.38	24.11

Conditions: Lignin model (0.1 mmol), CuCl (0.1 mmol), NaOH (0.4 mmol), 2.5 ml $\rm H_2O,$ 30 °C and 5.5 h for 1a, 50 °C and 10 h for 1b.

pathways are proposed for aerobic oxidative cleavage of the lignin β -O-4 and β -1 linkages (Scheme 3). The initial step involves a base-catalyzed enolization reaction of ketone 1a (or **1b**) to form enolate **g** and hydrogen oxide, the rate-limiting step in the reaction pathway. In the presence of a base, the enolization reaction can quickly reach equilibrium, which is why the cleavage of β -O-4 and β -1 ketone can occur even under mild room temperature conditions. The enolate g may subsequently undergo aerobic oxidation via a copper-catalyzed single electron transfer (SET) route.⁶² Meanwhile, Cu(I) ion is also easily oxidized to $Cu(\pi)$ ion by atmospheric oxygen, and Cu(II) in turn is an effective single-electron oxidant.^{39,62} Considering that both Cu(I) and Cu(II) salts had induced the cleavage of **1a** to **c** and **d** (see Table 1, *e.g.*, entries 3 and 12), the main role of the copper in the early reaction stages might be to oxidize the enolate g to the peroxide intermediate h. Such peroxide intermediates are often related to aerobic oxidation reactions according to previous studies.^{59,60} In pathway A (the radical pathway), the peroxide intermediate h might be homolytically cleaved into the oxygen-centered radical i catalyzed by copper, which could undergo rapid C-C fragmentation according to previous reports by Wang et al.63 and Schoenebeck et al.⁶² The benzaldehyde radical j is then oxidized to final benzoic acid product \mathbf{c} in the presence of Cu(I)and O₂. While another C-C fragmentation product is ester k or benzaldehyde e (for β -O-4 and β -1, respectively). In the presence of a base, ester k is facilely converted to final product phenol **d** and small molecule carboxylic acid via hydrolysis (Scheme 2, eqn (2)). In pathway B (the anionic path), h could generate dioxetane I, which could further proceed ring-



Scheme 3 Possible mechanism of the copper(i) and base catalyzed oxidative cleavage of β -O-4 and β -1 lignin linkages. The bond dissociation energy (BDE) values of $C_{\alpha}-C_{\beta}$ refer to the compounds with R = phenoxy, X = H, obtained with the M06-2X.

opening to generate benzoic acid **c** and ester **k** or benzaldehyde **e** (for β -O-4 and β -1, respectively).³⁹ The ester **k** is readily converted to the final product **d** as mentioned above. The whole mechanism shows that the role of NaOH in activating the substrates and the role of copper in electron transfer and oxygen transfer are the key points in this mild aerobic C–C cleavage.

DFT calculations (see Scheme 3) show that the BDEs of the C_{α} - C_{β} bond from substrate **1a** to intermediate **h** (X = H) significantly decrease from 81.09 kcal mol⁻¹ to 31.38 kcal mol⁻¹. The subsequent C–C fragmentation from the corresponding oxygen-centered radical **i** in pathway **A** can be very easy, requiring less than 10 kcal mol⁻¹ dissociation energy. The dissociation energy of C–C cracking from the dioxetane **l** in pathway **B** was calculated to be much higher (22.05 kcal mol⁻¹). Thus the above calculations suggest that the radical route is more favorable than the anionic route.

3.3 The conversion of authentic lignin feedstocks

The results obtained with the lignin model compounds encouraged us to apply the methodology to the conversion of real lignin. Lignocellulosic feedstocks, *viz*. hardwood eucalyptus, softwood pine, herb corn stover, bamboo, pennisetum and bagasse, were subjected to alkaline aerobic oxidation with CuCl. Due to the inherent complexity of the real lignin structure and the variety of different linkages and subunits depending on plant type and high temperature (typically \geq 160 °C) together with proper O₂ or air pressure must be taken to partially dissolve lignin into small pieces to maximize the yield of

the desired monomers.⁶⁴ Therefore, compared with the model compounds, higher temperature and pressure are required in the cleavage reaction of the authentic lignin. Thus, the oxidative depolymerization of the authentic lignin was performed at optimized conditions at 160 °C under 5 bar air pressure for 60 min according to Fig. S16-18.† The oxidation of corn stover lignin mainly yielded the aromatic aldehydes vanillin and syringaldehyde, along with other compounds such as vanillic acid and syringic acid. According to the typical functional groups, products can be divided into three categories: aromatic aldehydes, acids and ketone compounds. The monomer yields and selectivity of the main product vanillin and syringaldehyde from different substrates are illustrated in Fig. 4. The oxidation of pine yielded only G-type aromatics (vanillin, vanillic acid and acetovanillone), which is consistent with the intrinsic nature of softwoods, with high selectivity towards vanillin (73.66%). From eucalyptus, an excellent (38.61 wt%) monomer yield was obtained, comprising 23.96 wt% single product syringaldehyde. Fig. S19† shows a gas chromatogram of the monomeric products after eucalyptus conversion.

To explain the structural changes occurring, eucalyptus and the oxidative depolymerization products (the organic oil) were analysed through two-dimensional heteronuclear single quantum coherence nuclear magnetic resonance (2D HSQC-NMR, Fig. 5). In the aliphatic regions (Fig. 5(I) and (II)), the native lignin consists of abundant β -O-4 linkages (A), calculated as 51.2/100 C₉,⁶⁶ along with relatively small amounts of β - β (B) and β -5 (C). After oxidative depolymerization, the signals of these linkages were extremely small, demonstrating



Fig. 4 Monomer yields (on lignin basis) from CuCl catalyzed oxidation of various lignocellulosic feedstocks. Reaction conditions: 0.5 g wood, 0.5 mmol CuCl, NaOH (15 mmol) and H₂O (25 mL) as the solvent, 160 °C, 5 bar air (at RT), 60 min.

that these bonds have been successfully disrupted, especially for β -O-4 linkages. From the aromatic region (Fig. 5(III) and (IV)), the S and G peaks reduced and the S' became the most prominent signals in the organic oil, supporting that the eucalyptus lignin was mainly degraded into large amounts of benzylic ketone analogs by this catalytic system.



Fig. 6 The FTIR spectrum of the residue after mild alkaline aerobic oxidation. Reaction conditions: 0.5 g wood, 0.5 mmol CuCl, NaOH (15 mmol) and H₂O (25 mL) as the solvent, 160 °C, 5 bar air (at RT), 60 min.

The Fourier transformation infrared spectrum (FTIR, Fig. 6) of the residue after the reaction exhibited several functional groups commonly found in cellulose and hemicellulose^{67,68} (Table S4†), indicate that most of the cellulose and part of the hemicellulose may be still in the residue. Then the compositional analysis of the residue was conducted based on the Laboratory Analytical Procedure (LAP)⁶⁹ of the National Renewable Energy Laboratory (NREL). Delignification (%) and



Fig. 5 2D HSQC-NMR spectra of eucalyptus wood lignin sample before (I and III) and after (II and IV) aerobic oxidation. Cross peaks are assigned according to the previous literature.^{65,66} Reaction conditions: 0.5 g eucalyptus wood, 0.5 mmol CuCl, NaOH (15 mmol) and H₂O (25 mL) as the solvent, 160 °C, 5 bar air (at RT), 60 min.

hemicellulose dissolution (%) of different biomass sources in mild alkaline oxidation reaction are illustrated in Table S5.[†] More than 80% of lignin and 60% of hemicelluloses can be extracted at quite a short time of 1 h and a very low degree of cellulose solubilisation. The mild alkaline aerobic oxidation process simultaneously realizes the valorisation of lignin and biological pretreatment, which reduced the recalcitrance of lignocellulosic biomass. After the reaction, cellulose and hemicellulose sediments can be separated by acidification and subsequent filtration. The lignin-free cellulose is a good starting material for biochemical processes.¹⁷ These promising results provide an attractive option for a truly integrated and economically viable lignocellulosic biorefinery in the years to come.⁷⁰

4. Conclusion

In conclusion, we report a useful method for a facile cleavage of lignin β -O-4 and β -1 linkages in water without extra ligands under mild conditions such as an air atmosphere and ambient pressure and temperature. The effective selective cleavage of C-C bonds could be achieved through either a free-radicalmediated or anionic pathway with high yields of benzoic acid and phenol derivative products. Isotope-labeling experiments show that C₆-H bond activation is the rate-determining step. The mechanistic studies showed that an activated hydroperoxide intermediate is generated after a series of activation steps, whose target bond has lower energy and easily breaks in the subsequent transformations. The roles of a base, a catalyst, and atmospheric oxygen were illustrated. Most importantly, the catalytic system can cleave a series of raw lignocellulose samples into aromatic aldehydes and acids under mild conditions in water. These promising results provide an attractive option for the cost-efficient production of aromatic chemicals from biomass.

Conflicts of interest

There are no conflicts to declare.

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