Supplementary Information of

Iron-catalysed oxidative cleavage of lignin and β-O-4 lignin model compounds with peroxides in DMSO

Jakob Mottweiler,[+a] Torsten Rinesch,[+a] Claire Besson,[b] Julien Buendia[a,c] and Carsten Bolm*[a]

[a] Institute of Organic Chemistry, RWTH Aachen University, Landoltweg 1, D-52056 Aachen, Germany. E-mail: carsten.bolm@oc.rwth-aachen.de
[b] Institute of Inorganic Chemistry, RWTH Aachen University Landoltweg 1, D-52056 Aachen, Germany.
[c] New address: Institut de Chimie des Substances Naturelles, UPR 2301 CNRS, 1 Avenue de la Terrasse, F-91198 Gif-sur-Yvette, France.
[+] Both authors contributed equally.

TABLE OF CONTENT

1. General

1.1. Materials and methods

All reagents were acquired from commercial suppliers and used without further purification. THF was dried by distillation over Solvona® (sodium on molecular sieves) in the presence of benzophenone. Thin-layer chromatography (TLC) analysis was performed using Merck silica gel 60 F254 TLC plates, visualised by UV light irradiation (254 nm). Flash column chromatography was carried out with silica gel 60 (35-70 mesh).

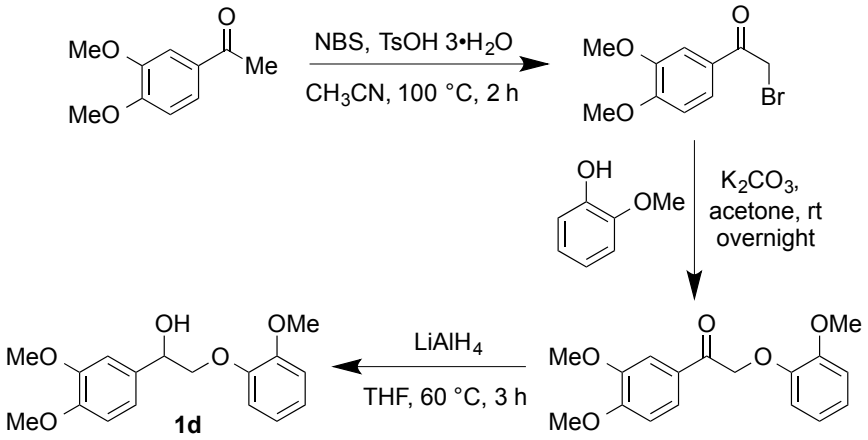
1.2. Instruments

NMR spectra were recorded on a Varian Inova 400 (^{1}H NMR: 400 MHz, ^{13}C NMR: 101 MHz) or Agilent VNMRS 600 (^{1}H NMR: 600 MHz, ^{13}C NMR: 151 MHz) spectrometer. Chemical shifts (δ) are given in ppm relative to the residual solvent peak ($CDCl_3$: δ = 7.26 ppm, DMSO-d_6: δ = 2.50 ppm). Spin-spin coupling constants (*J*) are given in Hz. Abbreviations are as follows: s (singlet), bs (broad singlet), d (doublet), t (triplet), m (multiplet), dd (doublet of doublets), ddd (doublet of doublet of doublets). Mass spectra were recorded on a Finnigan SSQ 7000 spectrometer (EI, CI). HPLC measurements were conducted on an Agilent Infinity 1260 HPLC apparatus using an Agilent Eclipse XDB-C18 (4.6 mm ID x 150 mm, 5 μm) column. H_2O/MeOH (60:40) or H_2O/MeOH (75:25) eluent and a flow rate of 1.0 mL/min were used for the measurements of all substrates and resulting products. X-band EPR spectroscopy was performed on a Bruker ESP 3220 spectrometer, with a non-saturating microwave power of 20 mW. Values of *g* were referenced against an external standard of 2,2-diphenylpicrylhydrazyl (*g* = 2.0036). Simulations of the spectra were performed with the easyspin software.[1]

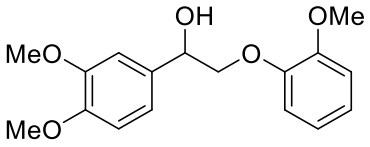
2. Preparation of starting materials and catalysts

2.1. Synthesis of lignin β-O-4 model compounds

Lignin model compounds **1a-c** and **1e-f**, which were used in the catalytic cleavage reactions, were synthesised following the reported procedure.[2] Monolignol **1d** was prepared in a 3 step synthesis in which the first two synthetic steps were in accordance to the protocol described by Picart *et al.* and the last step as described by Bolm and co-workers.[3,4]



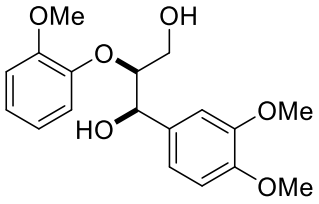
1-(3,4-Dimethoxyphenyl)-2-(2-methoxyphenoxy)ethan-1-ol (1d)[5]



$C_{17}H_{20}O_5$ (304.34 g/mol)

^{1}H-NMR (400 MHz, ($CDCl_3$)): δ = 7.04 – 6.88 (m, 6H), 6.86 (d, *J* = 8.2 Hz, 1H), 5.05 (dd, *J* = 9.4 Hz, 2.9 Hz, 1H), 4.17 (dd, *J* = 10.0 Hz, 3.0 Hz, 1H), 3.97 (t, *J* = 9.5 Hz, 1H), 3.90 (s, 3H), 3.89 (s, 3H) , 3.88 (s, 3H), 3.44 (bs, 1H).
^{13}C-NMR (101 MHz, ($CDCl_3$)): δ = 150.1, 149.1, 148.7, 147.9, 132.1, 122.6, 121.0, 118.6, 116.1, 111.9, 111.0, 109.3, 76.3, 72.1, 55.9, 55.8, 55.7.
MS (EI, 70 eV): *m/z* (%): 305 (48) $[M+1]^+$, 304 (90) $[M]^+$, 288 (14), 287 (58), 181 (10), 180 (56), 168 (18), 167 (100), 151 (73), 149 (28), 139 (90), 138 (80), 124 (43), 122 (16), 121 (15), 109 (19), 108 (11), 95 (11), 77 (30).

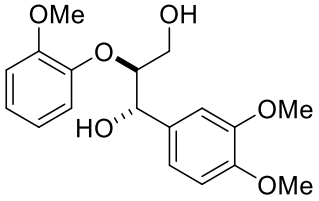
erythro 1-(3,4-Dimethoxyphenyl)-2-(2-methoxyphenoxy)propan-1,3-diol (1a)[2]



$C_{18}H_{22}O_6$ (334.37 g/mol)

^{1}H-NMR (400 MHz, ($CDCl_3$)): δ = 7.07 (ddd, *J* = 8.2 Hz, 7.2 Hz, 1.8 Hz, 1H), 6.99 – 6.89 (m, 5H), 6.84 (d, *J* = 8.3 Hz, 1H), 4.99 (d, *J* = 4.7 Hz, 1H), 4.16 (ddd, *J* = 6.0 Hz, 4.7 Hz, 3.4 Hz, 1H), 3.92 (m, 1H), 3.89 (s, 3H), 3.88 (s, 3H), 3.87 (s, 3H), 3.66 (dd, *J* = 12.1 Hz, 3.4 Hz, 1H), 2.79 (bs, 1H).
^{13}C-NMR (101 Hz, ($CDCl_3$)): δ = 151.7, 149.1, 148.6, 147.0, 132.5, 124.4, 121.8, 121.2, 118.5, 112.3, 111.1, 109.3, 87.6, 72.8, 60.9, 56.0 (3C).
MS (EI, 70 eV): *m/z* (%): 334 (31) $[M]^+$, 167 (16), 166 (12), 151 (17), 150 (100), 139 (20), 124 (11), 121 (12).

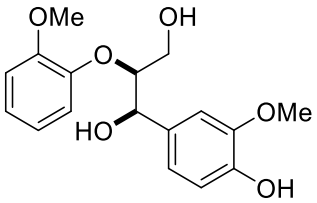
threo 1-(3,4-Dimethoxyphenyl)-2-(2-methoxyphenoxy)propan-1,3-diol (1b)[2]



$C_{18}H_{22}O_6$ (334.37 g/mol)

^{1}H-NMR (400 MHz, ($CDCl_3$)): δ = 7.13 (dd, *J* = 8.0 Hz, 1.6 Hz, 1H), 7.07 (ddd, *J* = 8.0 Hz, 7.2 Hz, 1.6 Hz, 1H), 7.01 – 6.96 (m, 2H), 6.95 (dd, *J* = 8.0 Hz, 1.6 Hz, 1H), 6.93 (ddd, *J* = 8.0 Hz, 8.0 Hz, 1.6 Hz, 1H), 6.85 (d, *J* = 8.0 Hz, 1H), 4.99 (d, *J* = 4.7 Hz, 1H), 4.03 (dt, *J* = 7.7 Hz, 3.7 Hz, 1H), 3.91 (s, 3H), 3.88 (s, 3H), 3.87 (s, 3H), 3.69 (br.d, *J* = 1.6 Hz, 1H), 3.63 (dt, *J* = 12.0 Hz, 3.7 Hz, 1H), 3.48 (ddd, *J* = 12.0 Hz, 7.7 Hz, 3.7 Hz, 1H), 2.72 (dd, *J* = 7.7 Hz, 4.7 Hz, 1H).
^{13}C-NMR (101 Hz, ($CDCl_3$)): δ = 151.5, 149.2, 149.1, 147.7, 132.2, 124.5, 121.9, 121.2, 119.8, 112.3, 111.2, 110.0, 89.7, 74.1, 61.2, 56.0 (3C).
MS (EI, 70 eV): *m/z* (%): 334 (30) $[M]^+$, 167 (15), 166 (12), 151 (17), 150 (100), 139 (20), 124 (11), 121 (12).

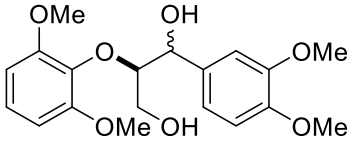
erythro 1-(4-Hydroxy-3-methoxyphenyl)-2-(2-methoxyphenoxy)propan-1,3-diol (1c)[2]



$C_{17}H_{20}O_6$ (320.34 g/mol)

^{1}H-NMR (400 MHz, ($CDCl_3$)): δ = 7,07 (ddd, *J* = 8.2 Hz, 7.2 Hz, 1.8 Hz, 1H), 6.93 (m, 5H), 6.83 (dd, *J* = 8.2 Hz, 1.8 Hz, 1H), 5.62 (s, 1H), 4.97 (m, 1H), 4.16 (ddd, *J* = 6.0 Hz, 4.7 Hz, 3.0 Hz, 1H), 3.92 (dd, *J* = 12.2 Hz, 5.6 Hz, 1H), 3.89 (s, 3H), 3.88 (s, 3H), 3.66 (ddd, *J* = 12.1 Hz, 7.7 Hz, 3.4 Hz, 1H), 3.48 (d, *J* = 3.3 Hz, 1H), 2.74 (dd, *J* = 7.7 Hz, 5.3 Hz, 1H).
^{13}C-NMR (101 Hz, ($CDCl_3$)): δ = 151.6, 146.8, 146.6, 145.1, 131.7, 124.3, 121.6, 121.1, 119.0, 114.2, 112.1, 108.6, 87.5, 72.7, 60.7, 55.9, 55.9.
MS (EI, 70 eV): *m/z* (%): 320 (1) $[M]^+$, 153 (16), 151 (15), 150 (100), 124 (15), 121 (15), 109 (17), 95 (10), 93 (19), 77 (15), 65 (15).

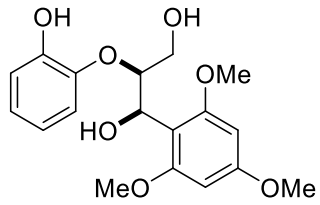
2-(2,6-Dimethoxyphenoxy)-1-(3,4-dimethoxyphenyl)propan-1,3-diol (1e)[6]



$C_{19}H_{24}O_7$ (364.39 g/mol) – 1.7:1 mixture of *erythro* and *threo* diastereoisomers

^{1}H-NMR (400 MHz, ($CDCl_3$)): δ = 7.11 – 6.94 (m, 5H), 6.87 – 6.80 (m, 3H), 6.65 (d, *J* = 8.4 Hz, 2H), 6.64 (d, *J* = 8.4 Hz, 2H), 5.07 (d, *J* = 8.7 Hz, 1H), 5.03 (d, *J* = 3.2 Hz, 1H), 4.36 (bs, 1H), 4.19 – 4.11 (m, 2H), 3.95 – 3.92 (m, 1H), 3.91 (s, 6H), 3.89 (s, 3H), 3.89 (s, 9H), 3.87 (s, 3H), 3.86 (s, 3H), 3.58 (dd, *J* = 10.8 Hz and 2.7 Hz, 1H), 3.50 (d, *J* = 10.8 Hz, 1H), 3.40 – 3.26 (m, 2H), 3.16 (bs, 1H).
^{13}C-NMR (101 Hz, ($CDCl_3$)): δ = 153.5 (2C), 153.2 (2C), 149.0, 148.9, 148.7, 148.2, 135.3, 135.0, 132.6, 132.0, 124.5, 124.5, 119.8, 118.1, 111.0, 111.0, 110.3, 109.0, 105.3 (2C), 105.3 (2C), 89.0, 87.0, 74.0, 72.5, 60.6, 60.5, 56.2 (4C), 55.9 (2C), 55.9 (2C).

erythro 2-(2-Methoxyphenoxy)-1-(2,4,6-trimethoxyphenyl)propan-1,3-diol (1f)[2]

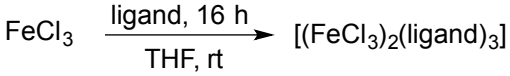


$C_{19}H_{24}O_7$ (364.39 g/mol)

^{1}H-NMR (400 MHz, ($CDCl_3$)): δ = 6.90 (ddd, *J* = 8.1 Hz, 7.4 Hz, 1.6 Hz, 1H), 6.84 – 6.70 (m, 2H), 6.65 (dd, *J* = 8.0 Hz, 1.6 Hz, 1H), 6.10 (s, 2H), 5.40 (dd, *J* = 11.1 Hz, 7.5 Hz, 1H), 4.45 (ddd, *J* = 7.4 Hz, 6.2 Hz, 3.9 Hz, 1H), 4.02 – 3.95 (m, 2H), 3.79 (s, 3H), 3.79 (s, 3H), 3.78 (s, 6H), 3.72 (d, J = 11.1 Hz, 1H), 3.18 (dd, J = 7.3 Hz, 6.1 Hz, 1H).
^{13}C-NMR (101 Hz, ($CDCl_3$)): δ = 160.9, 159.1 (2C), 150.9, 148.4, 122.8, 121.0, 119.6, 111.9, 109.0, 91.0 (2C), 85.5, 67.4, 63.0, 55.7 (3C), 55.3.
MS (EI, 70 eV): *m/z* (%): 364 (2) $[M]^+$, 198 (11), 197 (100), 150 (22), 109 (10), 77 (13).

2.2. Synthesis of the $FeCl_3$-derived catalysts

Anhydrous $FeCl_3$ (5 mmol, 1 eq.) was introduced into a flame-dried and argon-flushed 100 mL Schlenk flask and dissolved in dry THF (50 mL). Subsequently, the corresponding amine (7.5 mmol, 1.5 eq.) was added dropwise, and the reaction mixture was stirred for 16 h at room temperature. Afterwards the reaction mixture was filtered and the resulting solid was washed with THF (3 x 5 mL) and pentane (3 x 5 mL) and dried overnight under high vacuum.[7]



amine ligand	proposed catalyst formula	yield [%]
tetramethylethylenediamine (TMEDA)	$[(FeCl_3)_2(TMEDA)_3]$	91
1,4-diazabicyclo[2.2.2]octane (DABCO)	$[(FeCl_3)_2(DABCO)_3]$	97
pentamethyldiethylenetriamine (PMDTA)	$[(FeCl_3)_2(PMDTA)_2]$	98
hexamethylenetetramine (HMTA)	$[(FeCl_3)_2(HMTA)_3]$	93
1,4-dimethylpiperazine	$[(FeCl_3)_2(1,4\text{-dimethylpiperazine})_3]$	72

Following the protocol by Cahiez and co-workers, good to excellent product quantities were obtained of the iron complexes with regard to the proposed stoichiometry suggested for $[(FeCl_3)_2(TMEDA)_3]$.[7] However, Cahiez *et al.* did not provide any spectroscopic data for $[(FeCl_3)_2(TMEDA)_3]$ to verify its structure. Our attempts to characterize the complexes with ESI-MS did not provide any conclusive evidence. Elemental analyses and ICP-OES measurements showed that certain amounts of either solvent or water were most likely incorporated in the complexes. In the elemental analysis the carbon and nitrogen content was always lower and the hydrogen content slightly higher than expected. Furthermore, the ICP-OES measurements revealed that the iron content was always lower than the proposed stoichiometry would suggest.

Catalyst		Fe [%]	C [%]	H [%]	N [%]
$[(FeCl_3)_2(TMEDA)_3]$	Theo.	16.59	32.12	7.19	12.49
	Exp.	13.10	27.04	6.84	10.31
$[(FeCl_3)_2(DABCO)_3]$	Theo.	16.90	32.71	5.49	12.72
	Exp.	13.42	27.30	5.91	10.52
$[(FeCl_3)_2(HMTA)_3]$	Theo.	15.00	29.02	4.87	22.56
	Exp.	12.00	27.82	5.34	21.29
$[(FeCl_3)_2(PMDTA)_2]$	Theo.	16.65	32.22	6.91	12.52
	Exp.	9.92	30.78	7.52	11.85
$[(FeCl_3)_2(1,4\text{-dimethylpiperazine})_3]$	Theo.	16.75	32.42	6.35	12.60
	Exp.	11.47	28.11	7.494	10.83

Attempts to obtain single crystals for X-ray crystal structure analysis were not successful. X-Band EPR studies at room temperature of the catalyst powders incorporating TMEDA, DABCO, HMTA and PMDTA show a large signal centred around $g = 2$. The signal of the DABCO-based catalyst is given as an example (Figure S1a). While the signal is too featureless to provide any

information concerning the exact nature of the catalyst, it confirms the presence of Fe(III) while differing from the signal of $FeCl_3 \cdot 6H_2O$ (Figure S1b). In the case of the catalyst sample based on 1,4-dimethylpiperazine, an unexpected narrower signal superimposed with the large signal characteristic of Fe(III) was detected. Investigation at 115 K (Figure S1c) allowed the resolution of a sextuplet (A = 240 MHz) characteristic of a dilute Mn(II) species. An immediate control of the 1,4-dimethylpiperazine source (room temperature, neat sample) showed no signal, so that the source of the contamination remains unknown.

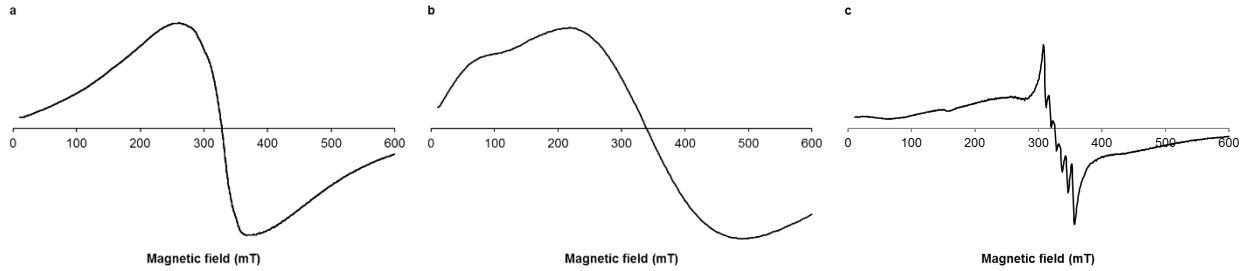
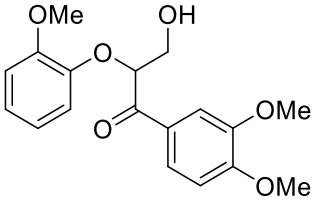


Fig. S1 EPR spectra of the iron catalysts: (a) DABCO-based catalyst (room temperature), (b) $FeCl_3 \cdot 6\ H_2O$ (room temperature), (c) 1,4-dimethylpiperazine (115 K).

2.3. Synthesis of *β*-O-4 hydroxy ketones

For the HPLC calibrations several *β*-hydroxy ketones were synthesised. The synthesis of 1-(3,4-dimethoxyphenyl)-3-hydroxy-2-(2-methoxyphenoxy)propan-1-one (**2a**) and 2-(2,6-dimethoxy-phenoxy)-1-(3,4-dimethoxyphenyl)-3-hydroxypropan-1-one was performed following the procedure described by Picart *et al.*.[3]

1-(3,4-Dimethoxyphenyl)-3-hydroxy-2-(2-methoxyphenoxy)propan-1-one (2a)[3]

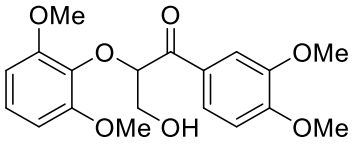


$C_{18}H_{20}O_6$ (332.35 g/mol)

^{1}H-NMR (600 MHz, ($CDCl_3$)): δ = 7.75 (dd, *J* = 8.4 Hz, 1.9 Hz, 1H), 7.62 (d, *J* = 1.9 Hz, 1H), 7.00 (td, *J* = 7.9 Hz, 1.4 Hz, 1H), 6.93 – 6.87 (m, 3H), 6.82 (td, *J* = 7.9 Hz, 1.2 Hz, 1H), 5.40 (t, *J* = 5.3 Hz, 1H), 4.07 (d, *J* = 5.3 Hz, 2H), 3.95 (s, 3H), 3.92 (s, 3H), 3.86 (s, 3H).
^{13}C-NMR (151 Hz, ($CDCl_3$)): δ = 195.0, 153.9, 150.5, 149.2, 146.9, 128.0, 123.7, 123.6, 121.2, 118.5, 112.2, 110.9, 110.1, 84.6, 63.7, 56.1, 56.0, 55.8.

MS (EI, 70 eV): *m/z* (%): 333 (44) $[M+1]^+$, 332 (75) $[M]^+$, 315 (28), 182 (23), 166 (21), 165 (100), 150 (57), 137 (10).

2-(2,6-Dimethoxyphenoxy)-1-(3,4-dimethoxyphenyl)-3-hydroxypropan-1-one[3]



$C_{19}H_{22}O_7$ (362.38 g/mol)

^{1}H-NMR (600 MHz, ($CDCl_3$)): δ = 7.69 (dd, *J* = 8.4 Hz, 1.8 Hz, 1H), 7.63 (d, *J* = 1.8 Hz, 1H), 6.98 (t, *J* = 8.4 Hz, 1H), 6.85 (d, *J* = 8.4 Hz, 1H), 6.54 (d, *J* = 8.4 Hz, 2H), 5.07 (dd, *J* = 7.8 Hz, 3.6 Hz, 1H), 4.01 – 3.92 (m, 2H), 3.91 (s, 3H), 3.91 (s, 3H), 3.83 – 3.77 (m, 1H), 3.69 (s, 6H).
^{13}C-NMR (151 Hz, ($CDCl_3$)): δ = 194.9, 153.4, 152.7 (2C), 149.0, 136.6, 128.6, 124.3, 123.4, 110.8, 110.0, 105.2 (2C), 87.4, 63.6, 56.0 (2C), 55.9 (2C).
MS (EI, 70 eV): *m/z* (%): 363 (12) $[M+1]^+$, 362 (43) $[M]^+$, 180 (44), 166 (10), 165 (100), 154 (43), 153 (21), 151 (13).

3. Catalysed cleavage of lignin and lignin β-O-4 model compounds

3.1. General procedure for the iron-catalysed cleavage of lignin β-O-4 model compounds

Reaction conditions for HPLC analysis

The model compound (0.250 mmol, 1.0 eq.) and the respective iron catalyst were introduced into a 25 mL round bottom flask equipped with a magnetic stirrer. The solvent (1 mL) was subsequently added, followed by the addition of either H_2O_2 (50 wt% in H_2O) or TBHP (70 wt% in H_2O) as oxidant and acetic acid as additive (0.5 eq.). The flask was then equipped with a reflux condenser, heated to the desired reaction temperature and stirred for the respective reaction time. Upon completion, the reaction mixture was cooled to room temperature and quenched with an aqueous HCl solution (c = 1 M, 20 mL). A standard solution of 3,4-dimethoxybenzylalcohol in methanol (1.000 mL, c = 0.2 mol/L) was added with an Eppendorf-pipette. The resulting aqueous phase was extracted with dichloromethane or ethyl acetate (3 x 20 mL). Next, the combined organic phases were washed with brine (2 x 50 mL) and water (50 mL), dried over $MgSO_4$, filtered and the solvent was removed under reduced pressure. A minimum of 2 samples containing 2-3 mg of the residue were prepared and dissolved in a mixture of 0.5 mL acetonitrile and 0.5 mL ethyl acetate. After all the products had gone into solution they were filtered into HPLC vials and subsequently measured by HPLC.

Reaction conditions for isolation of the cleavage products

The model compound (0.500 mmol, 1 eq.) and {Fe-DABCO} (16.5 mg, 0.025 mmol, 5 mol%) were introduced into a 25 mL round bottom flask. To the mixture, 2 mL of DMSO/H_2O (1:1), H_2O_2 (50 wt% in H_2O, 204 mg, 170.8 µL, 3.0 mmol, 6 eq.) and AcOH (15.0 mg, 14.2 µL, 0.250 mmol, 0.5 eq.) were added. The flask was then equipped with a reflux condenser and the mixture stirred for 16 h at 100 °C. Upon completion, the reaction was cooled to room temperature and quenched with an aqueous HCl solution (c = 1 M, 20 mL). The resulting aqueous phase was extracted with DCM (3 x 40 mL) and the combined organic phases washed sequentially with brine (40 mL), H_2O (40 mL) and additional brine (40 mL). The organic phase was then dried over $MgSO_4$, filtered and the solvent was removed under reduced pressure. The products were purified by column chromatography (gradient DCM pure to DCM/MeOH, 100:0.5).

Additional notes:

1. For the effect of the water quality on the reaction outcome, see footnote 18 in the manuscript.

2. The amount of DMSO could be reduced (from 28 eq. to 10 eq.), and a similar conversion of **1a** (95%) was observed. However, the yield of **4a** was lower (9% versus 32%).

3. The product extraction could also be done with ethyl acetate instead of DCM. Using the latter solvent, however, allowed a more precise yield determination of volatile products such as 2-methoxyphenol.

4. Using a DCM/MeOH mixture as eluent in the chromatography proved essential for achieving an optimal product separation.

3.2. General procedure for the iron-catalysed cleavage of organosolv and kraft lignin

A 25 mL round bottom flask was charged with 100 mg of the corresponding lignin sample **7**, **8**, or **9** and {Fe-DABCO} (5 mg, 5 wt%). Subsequently, 2 mL of DMSO or DMSO-d_6 (for the HSQC experiments) was added followed by the addition of H_2O_2 (50 wt% in H_2O, 150 μg, 125 μL) and AcOH (10 mg, 9.5 μL, 10 wt%). The flask was equipped with a reflux condenser and stirred at 100 °C for the desired reaction time. Upon completion, the reaction was cooled to room temperature. In the case of the HSQC experiments the solution was directly filtered into a NMR tube. For the GPC experiments the solvent was evaporated under high vacuum yielding a solid brown residue.

4. Studies on the involved radical species

Reaction conditions for the radical scavenging using TEMPO

The model compound (0.250 mmol, 1 eq.) and {Fe-DABCO} (8.3 mg, 0.0125 mmol, 5 mol%) were introduced into a 25 mL round bottom flask. To the mixture, 1 mL of DMSO/H_2O (1:1), H_2O_2 (50% in H_2O, 102 mg, 85.4 μL, 1.5 mmol, 6 eq.) and AcOH (7.5 mg, 7.1 μL, 0.125 mmol, 0.5 eq.) were added. Subsequently, TEMPO (195 mg, 1.250 mmol, 5 eq.) was added at the beginning, after 30 min. or after 1 h of reaction time. The reaction mixture was then stirred at 100 °C for a total reaction time of 16 h. The reaction was cooled to room temperature and quenched with an aqueous HCl solution (c = 1 M, 20 mL). A standard solution of 3,4-dimethoxybenzylalcohol in methanol (1.000 mL, c = 0.2 mol/L) was added with an Eppendorf-pipette to the reaction solution. Then, the aqueous phase was extracted with DCM (3 x 20 mL) and the combined organic phases washed sequentially with brine (20 mL), H_2O (20 mL) and additional brine (20 mL). The organic phase was then dried over $MgSO_4$, filtered and the solvent was removed under reduced pressure. A minimum of 2 samples containing 2-3 mg of the residue were prepared and dissolved in a mixture of 0.5 mL acetonitrile and 0.5 mL ethyl acetate. After all the products had gone into solution they were filtered into HPLC vials and subsequently measured by HPLC.

Reaction conditions for the radical trapping using PBN

Compound **1a** (0.250 mmol, 1 eq.) and {Fe-DABCO} (8.3 mg, 0.0125 mmol, 5 mol%) were introduced into a 25 mL round bottom flask. To the mixture, 1 mL of DMSO/H_2O (1:1), H_2O_2 (50% in H_2O, 102 mg, 85.4 μL, 1.5 mmol, 6 eq.) and AcOH (7.5 mg, 7.1 μL, 0.125 mmol, 0.5 eq.) were added. Then, *N-tert*-butyl-α-phenylnitrone (PBN, 4 mg) was added either immediately or after 45 min of heating the solution at 100 °C and subsequent cooling to room temperature. A small amount of the solution was introduced in an EPR flat cell. Spectra were measured ca. 15 min after the introduction of the PBN in the solution unless otherwise noted. Controls were performed (without heating) in the absence of substrate as well as in the absence of substrate and iron (but with the corresponding amount of DABCO). The latter showed no detectable signal.

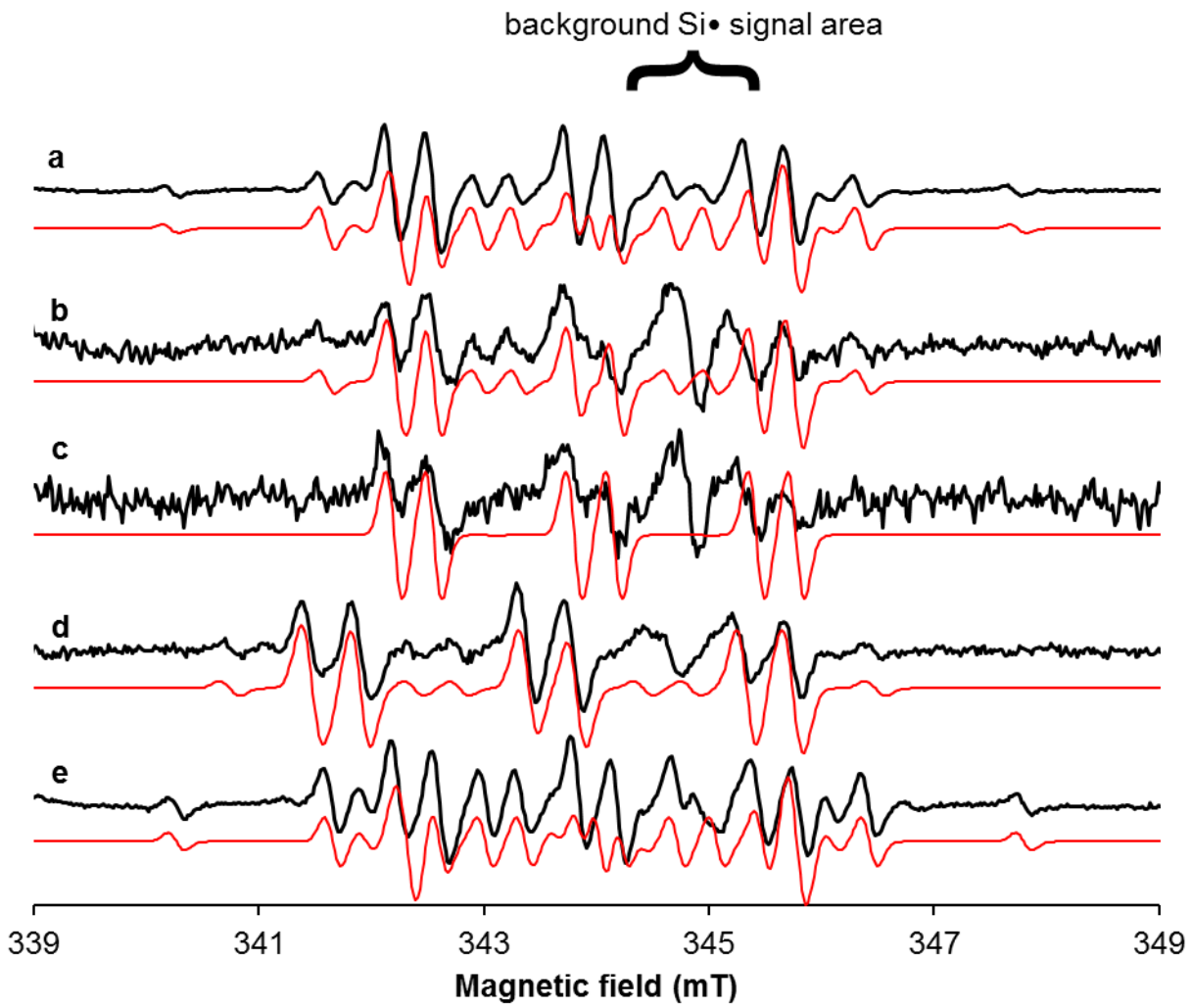


Fig. S2 Experimental (black) and simulated (red, see below for details) spectra of a) **1a**, catalyst, H_2O_2, AcOH and PBN in DMSO/H_2O; b) **1a**, catalyst, H_2O_2, AcOH and PBN in DMSO/H_2O, aged ca. 35 min.; c) **1a**, catalyst, H_2O_2 and AcOH in DMSO/H_2O, heated 45 min. before addition of PBN; d) catalyst, H_2O_2, AcOH and PBN in DMSO/H_2O; e) catalyst, H_2O_2, AcOH and PBN in DMSO/H_2O, aged ca. 30 min.

Spectrum	Conditions	Composition[a]	Proportions
a	**1a**, catalyst, H_2O_2, AcOH and PBN in DMSO/H_2O	CH_3-PBN• : H-PBN• : X•	45 : 50 : 5
b	**1a**, catalyst, H_2O_2, AcOH and PBN in DMSO/H_2O, aged ca. 35 min	CH_3-PBN• : H-PBN•	70 : 30
c	**1a**, catalyst, H_2O_2, AcOH in DMSO/H_2O, heated 45 min before addition of PBN	CH_3-PBN•	100
d	catalyst, H_2O_2, AcOH and PBN in DMSO/H_2O	CH_3-PBN• : H-PBN•	80 : 20
e	catalyst, H_2O_2, AcOH and PBN in	CH_3-PBN• : H-PBN• : X•	35 : 55 : 10

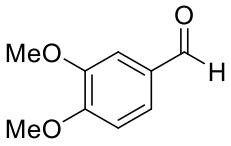
	DMSO/H_2O, aged ca. 30 min.		

[a] CH_3-PBN• : a_N = 45.2 MHz, a_H = 9.5 MHz; H-PBN• : a_N = 47.9 MHz, a_{2H} = 19.1 MHz: X• : a_N = 47.5 MHz, a_H = 116 MHz. Hyperfine coupling constants for the methyl and hydrogen adducts are in accordance with the literature.[8,9]

The reaction led to the formation of the methyl radical, which was trapped by PBN.[10] The hydrogen adduct of the nitrone was also observed (spectra d and e). Its formation, however, did not necessarily imply the presence of a hydrogen radical, as a one-electron reduction of PBN, followed or preceded by protonation was a more likely route. No additional signals were observed in the presence of the substrate (spectra a-c). However, traces of a compound, whose hydrogen hyperfine coupling (a_H = 116 MHz) seemed too large for a PBN derivative, have been observed in the presence and in the absence of the substrate (spectra a and e). A possible explanation for this signal would be a nitrogen-based radical, which was obtained by decomposition of the DABCO ligand of the catalyst. Therefore, we performed a control reaction with DABCO and H_2O_2 in DMSO/H_2O_2. No signal was observed, indicating that the presence of iron is necessary for the formation of this unidentified radical.

5. Spectroscopic data of the isolated products

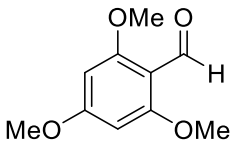
3,4-Dimethoxybenzaldehyde (3a)[5]



$C_9H_{10}O_3$ (166.18 g/mol)

^{1}H-NMR (600 MHz, ($CDCl_3$)): δ = 9.85 (s, 1H), 7.46 (dd, *J* = 8.2 Hz, 1.9 Hz, 1H), 7.41 (d, *J* = 1.8 Hz, 1H), 6.98 (d, *J* = 8.2 Hz, 1H), 3.96 (s, 3H), 3.94 (s, 3H).
^{13}C-NMR (150 Hz, ($CDCl_3$)): δ = 190.9, 154.5, 149.6, 130.1, 126.9, 110.4, 108.9, 56.2, 56.0.
MS (EI, 70 eV): *m/z* (%): 167 (15) $[M]^+$, 166 (100) $[M]^+$, 165 (75), 151 (12), 95 (20), 79 (12), 77 (15), 51 (11).

2,4,6-Trimethoxybenzaldehyde (4c)[11]

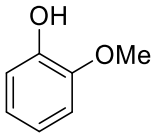


$C_{10}H_{12}O_4$ (196.20 g/mol)

^{1}H-NMR (400 MHz, ($CDCl_3$)): δ = 10.35 (s, 1H), 6.08 (s, 2H), 3.88 (s, 6H), 3.87 (s, 3H).

^{13}C-NMR (101 Hz, ($CDCl_3$)): δ = 187.7, 166.2, 164.1 (2C), 109.0, 90.1 (2C), 56.1 (2C), 55.6.
MS (EI, 70 eV): *m/z* (%): 197 (79) $[M+1]^+$, 196 (100) $[M]^+$, 195 (61), 180 (15), 179 (55), 178 (26), 167 (14), 165 (11), 152 (11), 151 (19), 150 (22), 139 (12), 137 (14), 135 (13), 121 (14), 106 (14), 69 (13).

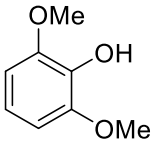
2-Methoxyphenol (3a)[12]



$C_7H_8O_2$ (124.14 g/mol)

^{1}H-NMR (600 MHz, ($CDCl_3$)): δ = 6.86 – 6.83 (m, 1H), 6.81 – 6.75 (m, 3H), 6.09 (s, 1H), 3.81 (s, 3H).
^{13}C-NMR (150 Hz, ($CDCl_3$)): δ = 146.7, 145.8, 121.2, 119.9, 114.6, 110.7, 55.6.
MS (EI, 70 eV): *m/z* (%): 125 (76) $[M+1]^+$, 124 (100) $[M]^+$, 123 (10), 109 (13), 81 (14).

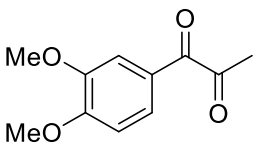
2,6-Dimethoxyphenol (3b)[13]



$C_8H_{10}O_3$ (154.17 g/mol)

^{1}H-NMR (400 MHz, $CDCl_3$): δ = 6.80 (dd, *J* = 8.7 Hz, 8.0 Hz, 1H), 6.59 (d, *J* = 8.3 Hz, 2H), 5.51 (s, 1H), 3.89 (s, 6H).
^{13}C-NMR (101 MHz, $CDCl_3$): δ = 147.4 (2C), 135.0, 119.2, 105.0 (2C), 56.4 (2C).
MS (EI, 70 eV): *m/z* (%): 155 (10) $[M+1]^+$, 154 (100) $[M]^+$, 139 (35), 111 (25), 96 (21), 93 (21), 68 (11), 65 (16).

1-(3,4-Dimethoxyphenyl)propane-1,2-dione (5a)[12]

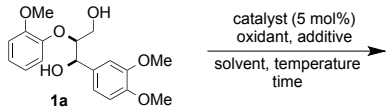


$C_{11}H_{12}O_4$ (208.21 g/mol)

^{1}H NMR (600 MHz, $CDCl_3$): δ = 7.66 (dd, *J* = 8.4, 1.8 Hz, 1H), 7.57 (d, *J* = 1.8 Hz, 1H), 6.91 (d, *J* = 8.4 Hz, 1H), 3.97 (s, 3H), 3.94 (s, 3H), 2.52 (s, 3H).

^{13}C NMR (151 MHz, $CDCl_3$): δ = 201.1, 190.2, 154.8, 149.4, 126.4, 124.7, 111.1, 110.3, 56.2, 56.0.
MS (EI, 70 eV): m/z (%) = 208 [M^+] (100), 166 (10), 165 (100), 137 (10), 79 (10).

6. Optimisation of the reaction conditions for the cleavage of dilignol 1a[a]

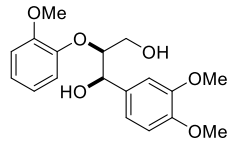
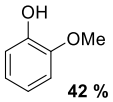
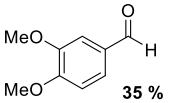
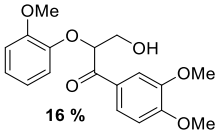
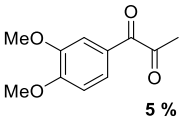
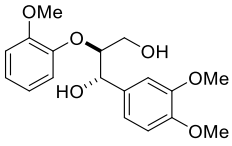
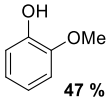
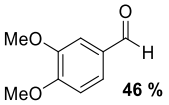
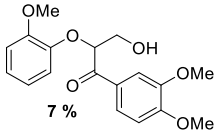
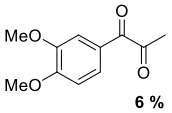
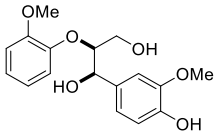
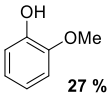
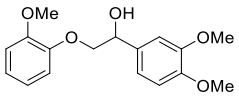
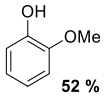
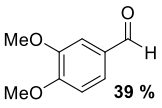
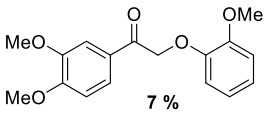
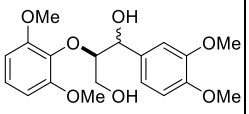
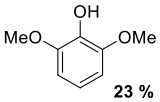
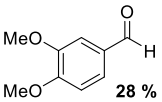
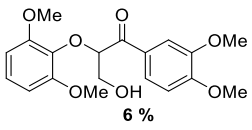
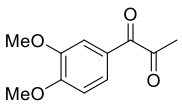
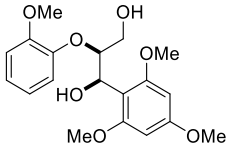
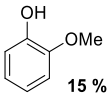
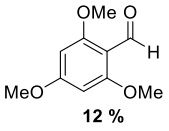


Entry	Oxidant	Catalyst	Additive [eq.]	Solvent	*t* [h]	T [°C]	Conv. [%]
1	-	-	-	pyridine	24	82	0
2	TBHP	-	-	pyridine	24	82	9
3	TBHP	$FeCl_3$	-	pyridine	24	82	43
4[b]	TBHP	$FeCl_3$	-	pyridine	24	82	45
5	TBHP	{Fe-TMEDA}	-	pyridine	24	82	48
6	TBHP	{Fe-DABCO}	-	pyridine	24	82	57
7	TBHP	{Fe-HMTA}	-	pyridine	24	82	52
8	TBHP	{Fe-PMDTA}	-	pyridine	24	82	48
9	TBHP	{Fe-1,4-dimethylpiperazine}	-	pyridine	24	82	48
10	-	-	-	DMSO	24	82	0
11	H_2O_2	-	-	DMSO	24	82	0
12	-	{Fe-DABCO}	-	DMSO	24	82	0
13	H_2O_2	{Fe-DABCO}	-	pyridine	24	82	10
14	H_2O_2	{Fe-TMEDA}	-	DMSO	24	82	30
15	H_2O_2	{Fe-HMTA}	-	DMSO	24	82	35
16	H_2O_2	{Fe-PMDTA}	-	DMSO	24	82	38
17	H_2O_2	{Fe-1,4-dimethylpiperazine}	-	DMSO	24	82	32
18	H_2O_2	{Fe-DABCO}	-	DMSO	24	82	41
19	H_2O_2	{Fe-DABCO}	-	DMSO/H_2O	24	82	74
20	H_2O_2	{Fe-DABCO}	-	DMSO/H_2O	72	100	>99
21	H_2O_2	{Fe-DABCO}	-	DMSO/H_2O	24	100	94
22	H_2O_2	{Fe-DABCO}	-	DMSO/H_2O	16	100	88
23	H_2O_2	{Fe-DABCO}	-	DMSO	24	100	84
24	H_2O_2	{Fe-DABCO}	-	DMSO	6	100	64
25	H_2O_2	{Fe-DABCO}	-	DMSO	6	90	58
26	H_2O_2	{Fe-DABCO}	-	DMSO	6	70	13
27	H_2O_2	{Fe-DABCO}	-	DMSO	6	50	1
28	H_2O_2	{Fe-DABCO}	-	DMSO	6	rt	0
29	H_2O_2	{Fe-DABCO}	AcOH [0.1]	DMSO/H_2O	16	100	90
30	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMSO/H_2O	16	100	97
31	H_2O_2	{Fe-DABCO}	AcOH [5.0]	DMSO/H_2O	16	100	88
32	H_2O_2	{Fe-DABCO}	boric acid [0.5]	DMSO/H_2O	16	100	86
33	H_2O_2	{Fe-DABCO}	benzoic acid [0.5]	DMSO/H_2O	16	100	91
34	H_2O_2	{Fe-DABCO}	H_3PO_4 [0.5]	DMSO/H_2O	16	100	61
35	H_2O_2	{Fe-DABCO}	NaOH [0.5]	DMSO/H_2O	16	100	72
36	H_2O_2	{Fe-DABCO}	Cs_2CO_3 [0.5]	DMSO/H_2O	16	100	0
37	H_2O_2	{Fe-DABCO}	AcOH [0.5]	THF	16	100	2
38	H_2O_2	{Fe-DABCO}	AcOH [0.5]	NMP	16	100	10
39	H_2O_2	{Fe-DABCO}	AcOH [0.5]	1,4-dioxane	16	100	0
40	H_2O_2	{Fe-DABCO}	AcOH [0.5]	toluene	16	100	29
41	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMF	16	100	27
42	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMC	16	100	8
43[c]	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMSO/H_2O	16	100	88
44[b]	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMSO/H_2O	16	100	86
45[d]	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMSO/H_2O	16	100	92
46[e]	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMSO/H_2O	16	100	90
47	H_2O_2	$FeCl_3{\cdot}6H_2O$	AcOH [0.5]	DMSO/H_2O	16	100	65
48	H_2O_2	$FeCl_3$	AcOH [0.5]	DMSO/H_2O	16	100	81

49	H_2O_2	$FeCl_2 \cdot 4H_2O$	AcOH [0.5]	DMSO/H_2O	16	100	54
50	H_2O_2	$Fe(NO_3)_3$	AcOH [0.5]	DMSO/H_2O	16	100	82
51	H_2O_2	$Fe(acac)_3$	AcOH [0.5]	DMSO/H_2O	16	100	76
52	H_2O_2	$CuBr_2$	AcOH [0.5]	DMSO/H_2O	16	100	52
53	H_2O_2	$Mn(OAc)_3 \cdot 2H_2O$	AcOH [0.5]	DMSO/H_2O	16	100	25
54	H_2O_2	$Co(OAc)_3 \cdot 4H_2O$	AcOH [0.5]	DMSO/H_2O	16	100	10
55	TBHP	{Fe-DABCO}	AcOH [0.5]	DMSO/H_2O	16	100	68
56	H_2O_2	{Fe-TMEDA}	AcOH [0.5]	DMSO/H_2O	16	100	90
57[f]	H_2O_2	{Fe-DABCO}	AcOH [0.5]	DMSO/H_2O	16	100	95
58	H_2O_2	-	AcOH [0.5]	DMSO	16	100	16

[a] Reaction conditions: substrate (0.25 mmol), catalyst (5 mol%), DMSO/H_2O (0.5 mL/0.5 mL), AcOH (0.5 eq.), H_2O_2 (6 eq.), conversion determined by HPLC analysis. [b] Use of 10 mol% catalyst. [c] Use of 2.5 mol% catalyst. [d] Reaction performed under Ar-atmosphere. [e] Reaction performed under O_2-atmosphere. [f] Reaction performed on a 1 mmol scale; conversion determined by column chromatography.

7. Products formed by cleavage of various β-O-4 model compounds[a]

model compound	conversion	methoxy phenol derivatives	benzaldehyde derivatives	ketone products[b]	diketone product
	95	 42 %	 35 %	 16 %	 5 %
	97	 47 %	 46 %	 7 %	 6 %
	95	 27 %	-	-	-
	97	 52 %	 39 %	 7 %	-
	96	 23 %	 28 %	 6 %	 9 %
	95	 15 %	 12 %	-	-

[a] Reaction conditions: substrate (0.5 mmol), catalyst (5 mol%), DMSO/H_2O (1.0 mL/1.0 mL), AcOH (0.5 eq.), H_2O_2 (6 eq.); yields after purification with column chromatography in DCM/MeOH (100:0.5). [b] Yields of ketones determined by HPLC.

8. Analytic data concerning the iron-catalysed cleavage of lignin samples 7-9

8.1. Lignin pre-treatment conditions

Organosolv lignin samples **7** and **8** were extracted from beech wood chips using an ethanol-based organosolv process. Sample **7** was extracted with aqueous ethanol (50% w/w) without the addition of an acid catalyst. The lignin was precipitated with water and afterwards washed with water to remove the residual carbohydrates. Sample **8** (supplied by Hybrid Catalysis) was extracted with aqueous ethanol (60-40% w/w). The Lignin was precipitated from both the organosolv liquor and the pulp washing liquor by adding these liquors to an excess of water. The lignin precipitate was sedimented by centrifugation and the liquor above decanted. Finally, the lignin was dried and pulverized. Kraft lignin #370959 (Sample **9**) was purchased from Sigma Aldrich and used without further purification.

8.2. 2D-NMR HSQC measurements

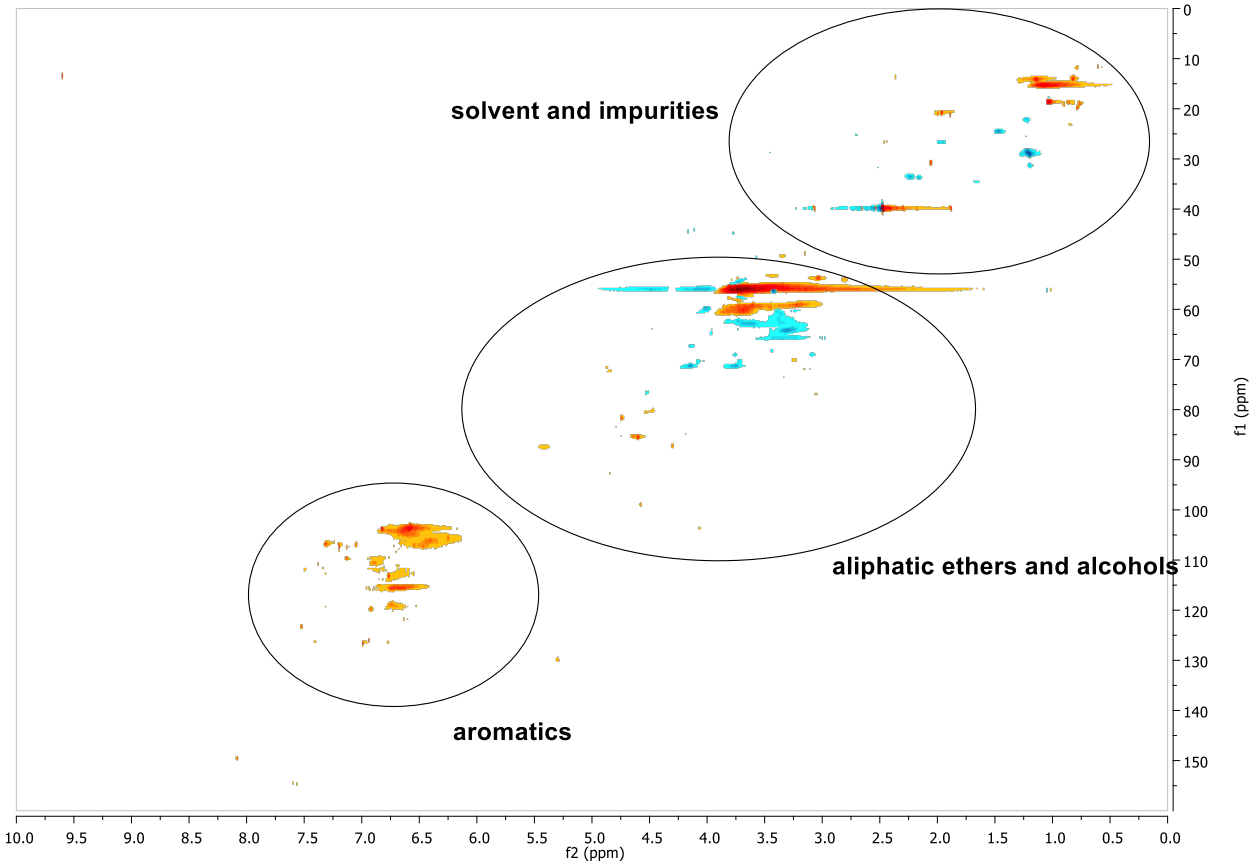


Fig. S3 2D-NMR HSQC spectrum of organosolv beech lignin sample **8** in DMSO-d_6 before the reaction.

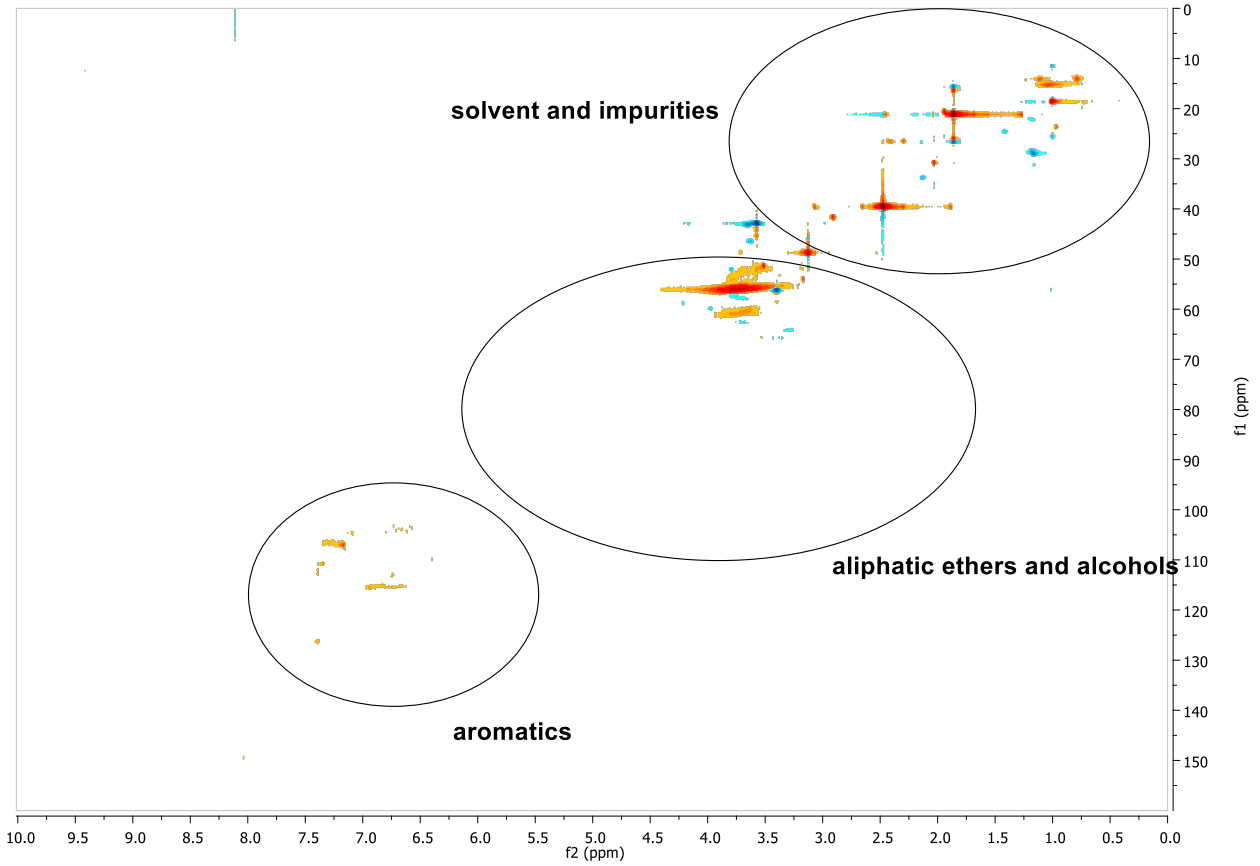


Fig. S4 2D-NMR HSQC spectrum of organosolv beech lignin sample **8** in DMSO-d_6 after the reaction.

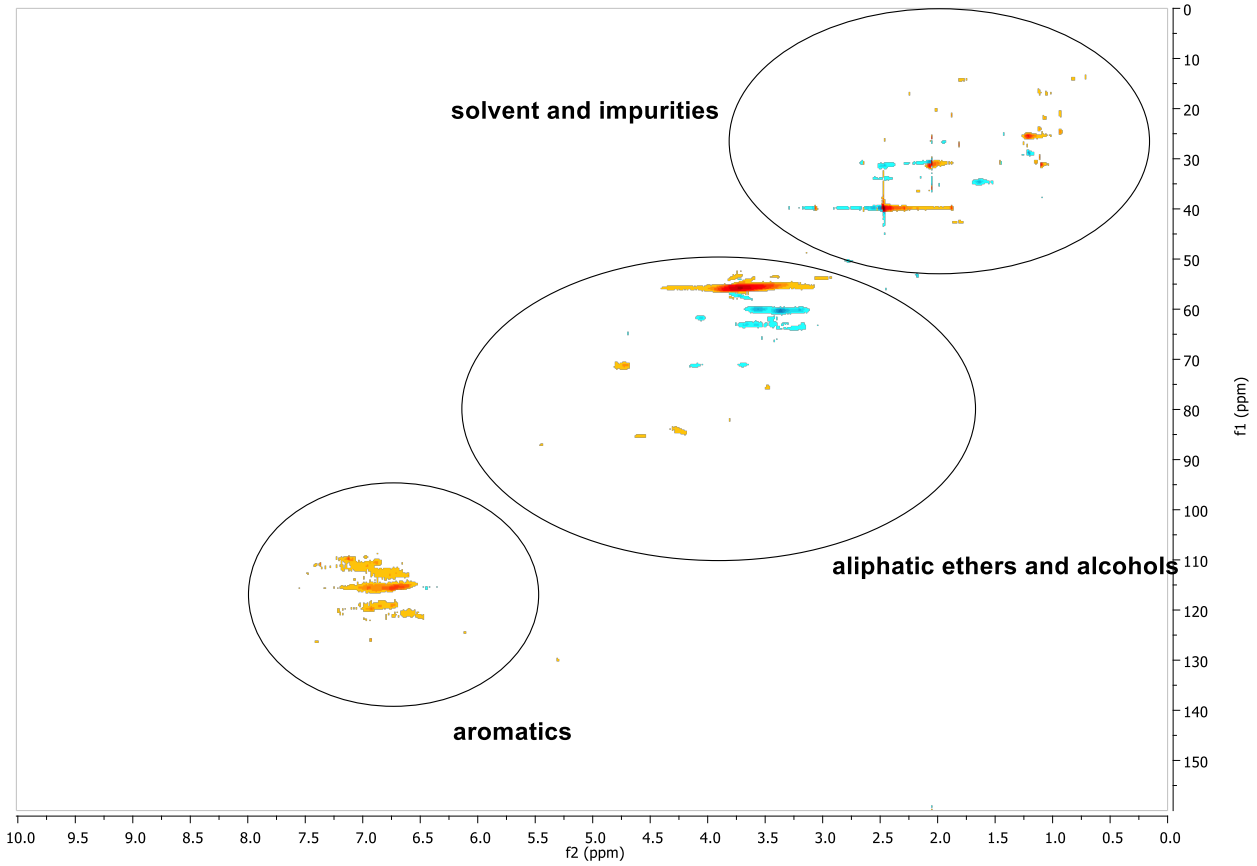


Fig. S5 2D-NMR HSQC spectrum of organosolv beech lignin sample **7** in DMSO-d_6 before the reaction.

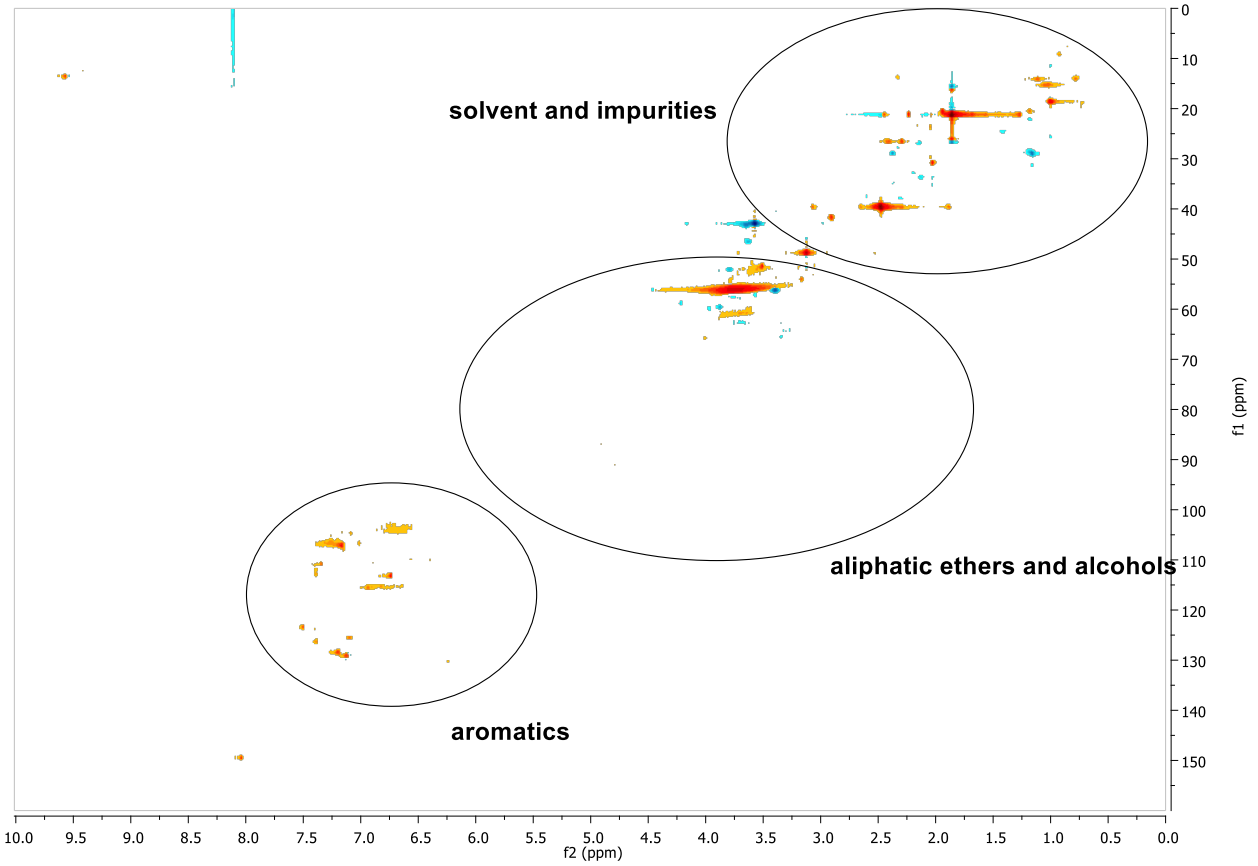


Fig. S6 2D-NMR HSQC spectrum of organosolv beech lignin sample **7** in DMSO-d_6 after the reaction.

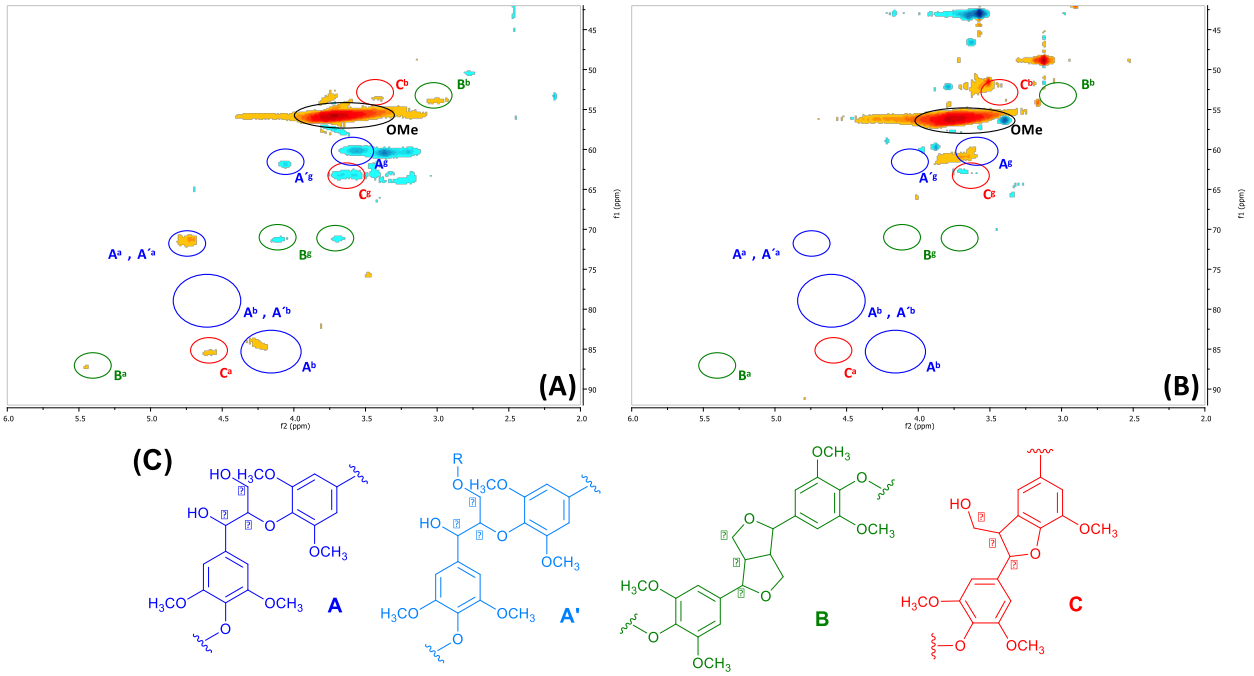


Fig. S7 Comparison of the aliphatic ether and alcohol region of organosolv beech lignin sample **7** in DMSO-d_6 before (A) and after the reaction (B).

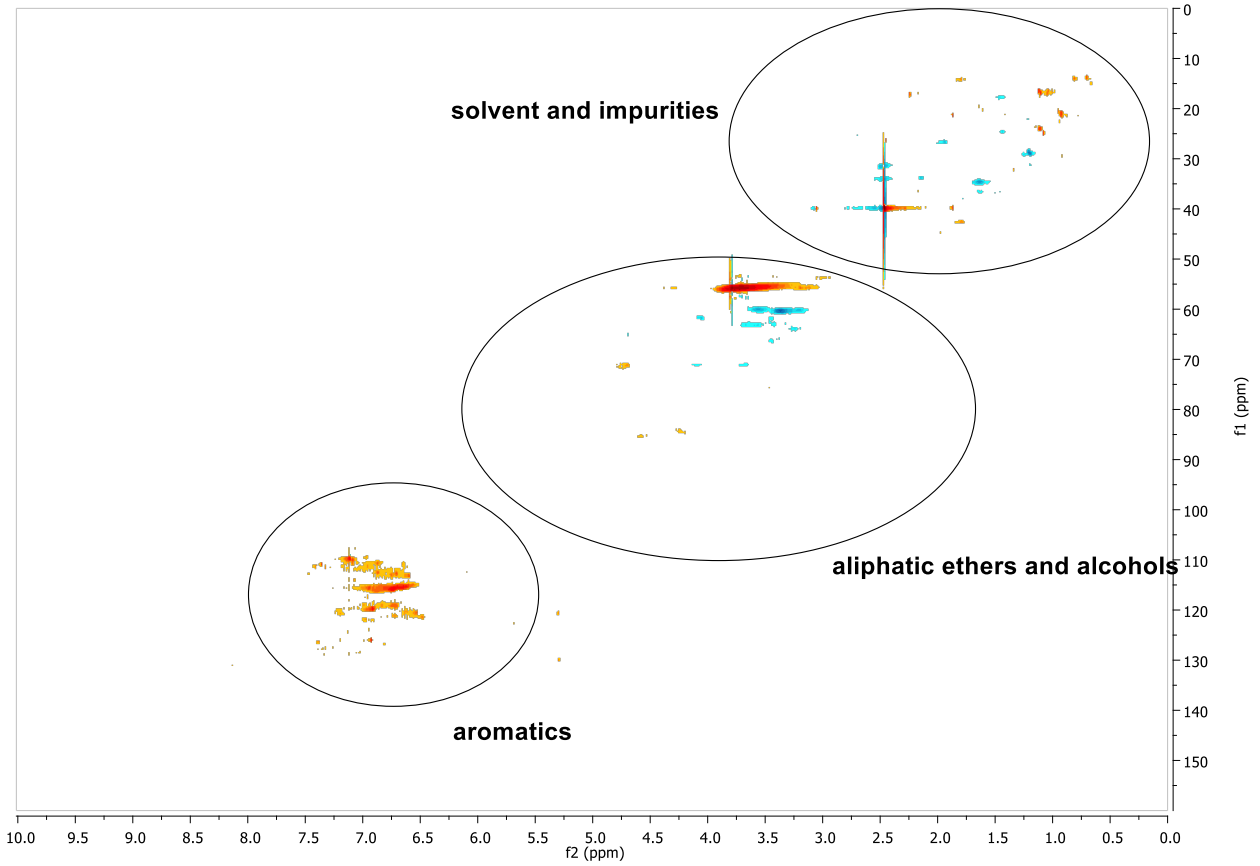


Fig. S8 2D-NMR HSQC spectrum of kraft lignin sample **9** in DMSO-d_6 before the reaction.

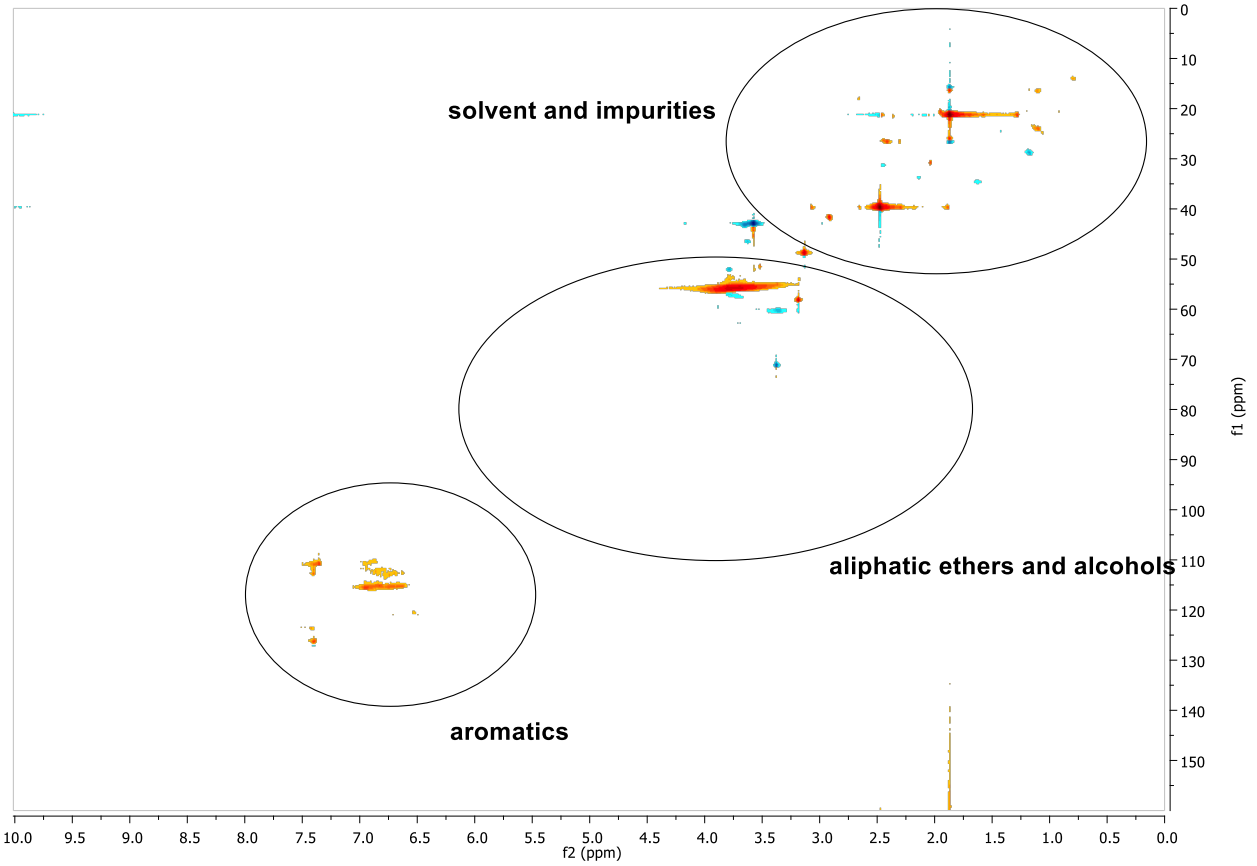


Fig. S9 2D-NMR HSQC spectrum of kraft lignin sample **9** in DMSO-d_6 after the reaction.

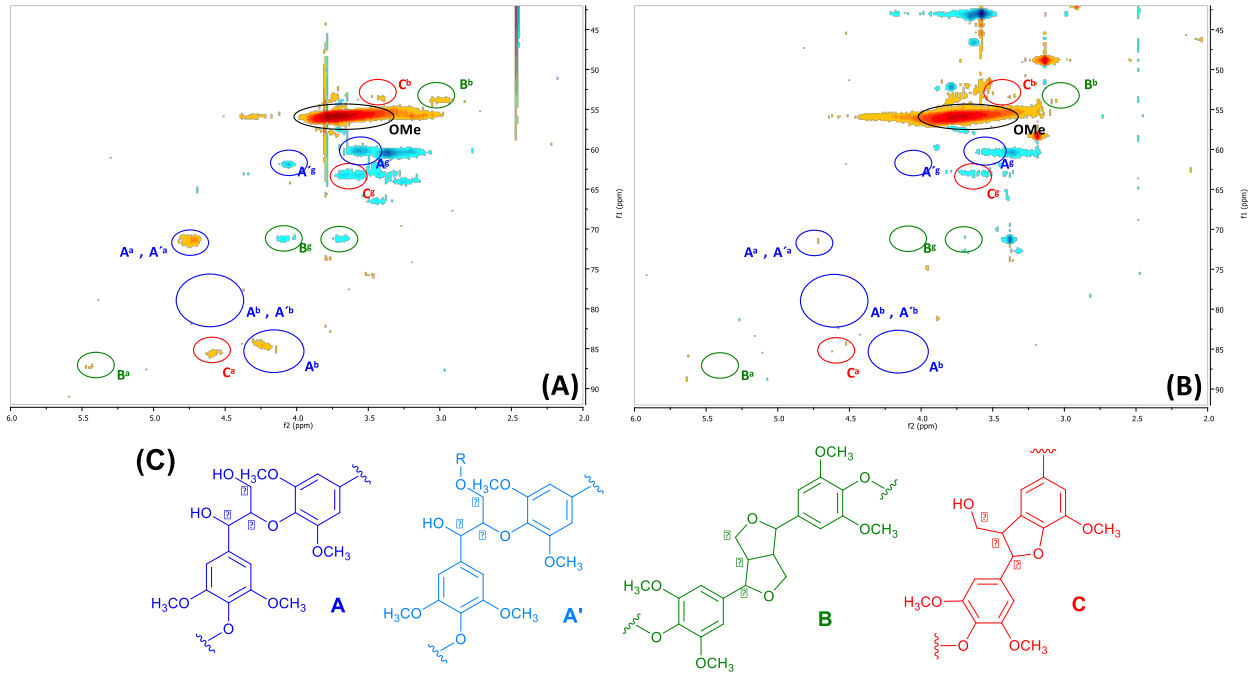


Fig. S10 Comparison of the aliphatic ether and alcohol region of kraft lignin sample **9** in DMSO-d_6 before (A) and after the reaction (B).

8.3. GPC measurements

The GPC measurements were performed on an ECO Sec System apparatus (HLC-8320GPC) from TOSOH-Bioscience LLC Company. It was equipped with one pre-column PSS Suprema (50 x 8 mm, 100 Å) and three columns PSS Suprema (300 x 8 mm, 100 Å). Measurements were conducted with a flow rate of 1 mL/min. and an injection volume of 20 μL. A Na_2HPO_4 buffer solution (pH 12) with 0.5 g PEG 6000 was used as solvent, and the signals were detected with an ECO Sec RI and/or UV-detector. The elugrams show the detector response of the RI-detector.

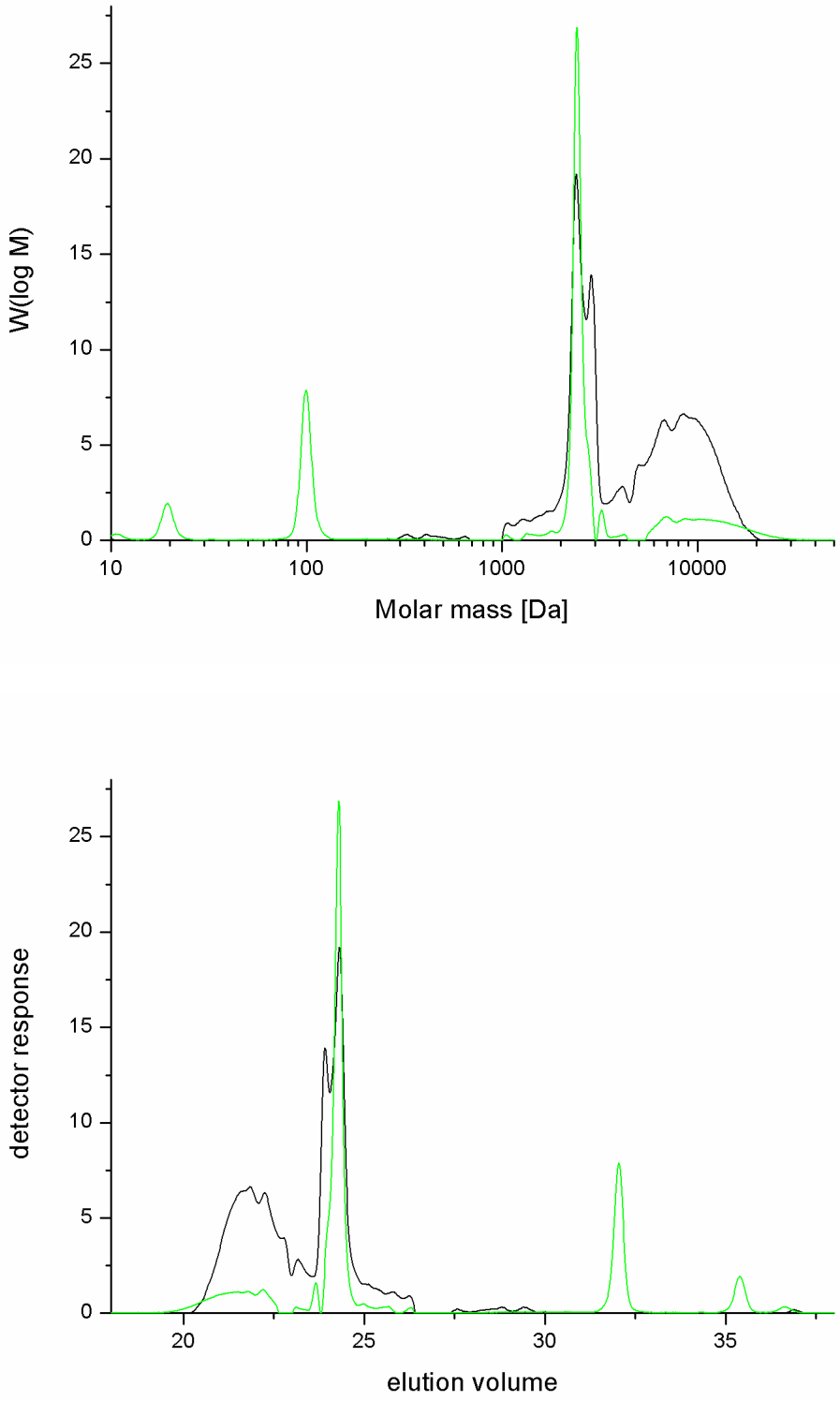


Fig. S11 GPC mass distribution of organosolv lignin sample **7** (top) and elugram (bottom) after a reaction time of 8 h under standard conditions; spectrum before treatment in black, after treatment in green.

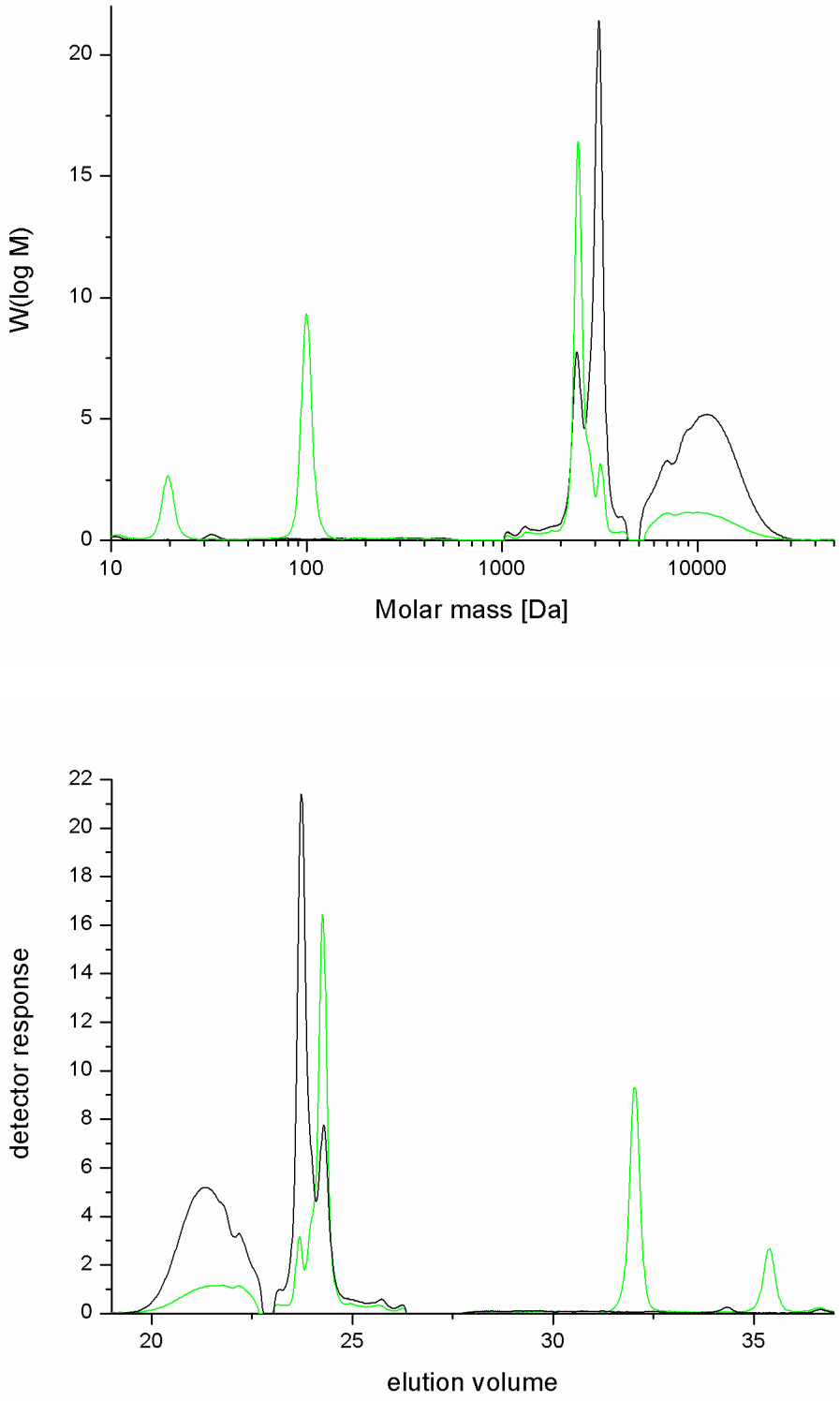


Fig. S12 GPC mass distribution of organosolv lignin sample **8** (top) and elugram (bottom) after a reaction time of 8 h under standard conditions; spectrum before treatment in black, after treatment in green.

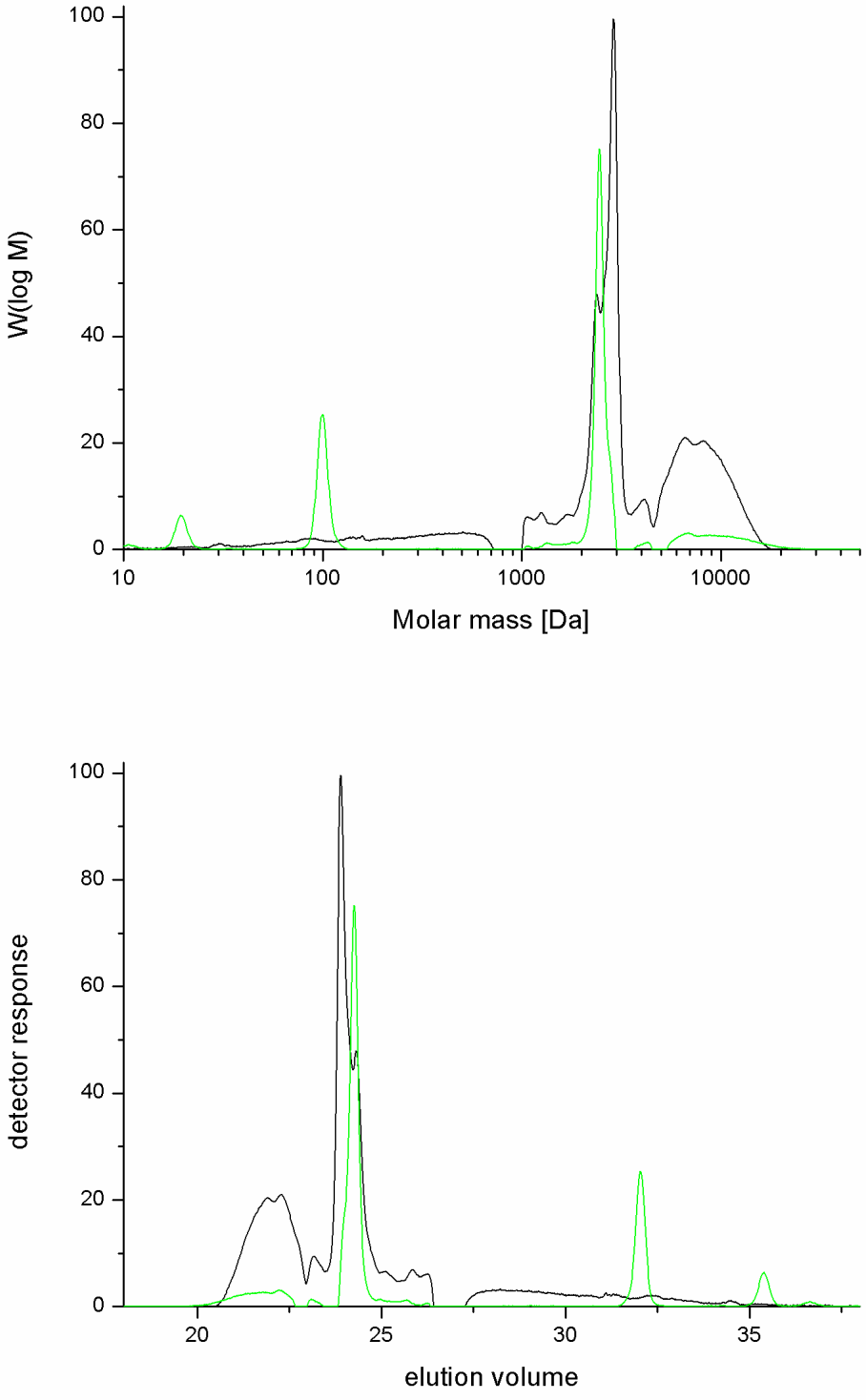


Fig. S13 GPC mass distribution of kraft lignin sample **9** (top) and elugram (bottom) after a reaction time of 8 h under standard conditions; spectrum before treatment in black, after treatment in green.

9. References

[1] S. Stoll and A. Schweiger, *J. Magn. Reson.*, 2006, **178**, 42–55.

[2] J. Buendia, J. Mottweiler and C. Bolm, *Chem. Eur. J.*, 2011, **17**, 13877–13882.

[3] P. Picart, C. Müller, J. Mottweiler, L. Wiermans, C. Bolm, P. Domínguez de María and A. Schallmey, *ChemSusChem.,* 2014, **7**, 3164–3171.

[4] S. Dabral, J. Mottweiler, T. Rinesch and C. Bolm, *Green Chem.*, DOI: 10.1039/C5GC00186B.

[5] A. Rahimi, A. Azarpira, H. Kim, J. Ralph and S. S. Stahl, *J. Am. Chem. Soc.*, 2013, **135**, 6415−6418.

[6] T. Kleine, J. Buendia and C. Bolm, *Green Chem*., 2013, **15**, 160–166.

[7] G. Cahiez, V. Habiak, C. Duplais and A. Moyeux, *Angew. Chem.,* 2007, **119**, 4442–4444; *Angew. Chem. Int. Ed.*, 2007, **46**, 4364–4366.

[8] a) H. Kosaka, Y. Katsuki and T. Shiga, *Arch. Biochem. Phys.*, 1992, **293**, 401–408; b) A. F. Carley, H. A. Edwards, B. Mile, M. W. Roberts, C. C. Rowlands, S. D. Jackson and F. E. Hancock, *J. Chem. Soc., Chem Commun.*, 1994, 1407–1408; c) K. R. Maples, F. Ma and Y.-K. Zhang, *Free Rad. Res.*, 2001, **34**, 417–426; d) W. Imaram, R. J. Johnson and A. Angerhofer, *Appl. Magn. Reson.*, 2010, **37**, 463–472 and references cited therein.

[9] NIH Spin Trap database, available online at http://tools.niehs.nih.gov/stdb/

[10] a) W. T. Dixon, R. O. C. Norman and A. L. Buley, *J. Chem. Soc.*, 1964, 3625–3634; b) B. C. Gilbert, R. O. C. Norman and R. C. Sealy, *J. Chem. Soc., Perkin Trans. 2*, 1975, 303–308; c) T. M. Santosusso and D. Swern, *J. Org. Chem.*, 1976, **41**, 2762–2768.

[11] M. Tobisu, S. Yamaguchi and N. Chatani, *Org. Lett.*, 2007, **9**, 3351–3353.

[12] A. Rahimi, A. Ulbrich, J. J. Coon and S. S. Stahl, *Nature*, 2014, **515**, 249–252.

[13] T. Ritter, K. Stanek, I. Larrosa and E. M. Carreira, *Org. Lett.*, 2004, **6**, 1513–1514.