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Copper- and Vanadium-Catalyzed Oxidative Cleavage of Lignin using Dioxygen

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Transition-metal-containing hydrotalcites (HTc) and $V(acac)_3$/$Cu(NO_3)_2 \cdot 3H_2O$ (acac = acetylacetonate) mixtures were tested for their catalytic activity in the cleavage of the lignin model compound *erythro*-1-(3,4-dimethoxyphenyl)-2-(2-methoxyphenoxy)-l,3-propanediol (**1**) with molecular oxygen as oxidant. Both catalytic systems displayed high activity and good selectivity and afforded veratric acid as the main product. The catalyst behavior was studied by EPR spectroscopy, XRD, and Raman spectroscopy. After the catalysts were established for the model system, lignin depolymerization studies were performed with various organsolv and kraft lignin sources. The oxidative depolymerization and lignin bond cleavage were monitored by gel permeation chromatography (GPC), MALDI MS, and 2D-NMR (HSQC). Irrespective of the lignin pretreatment, both HTc-Cu-V and $V(acac)_3$/$Cu(NO_3)_2 \cdot 3H_2O$ were able to cleave the β-O-4 linkages and the resinol structures to form dimeric and trimeric products.

Introduction

In recent years, biomass valorization has received increased attention.[1] Lignin is one of the three main components of the lignocellulosic biomass, and as the petroleum reserves of the world depletes, it is envisaged that lignin will become a viable source for energy, chemicals, and fuels.[2] Despite groundbreaking advances, lignin degradation is still in its infancy.[3] The main challenges arise from the rather complex structure of lignin, which is an amorphous three-dimensional polymer. It contains methoxylated phenylpropane units,[4] which are linked by a variety of interconnecting bonds. Among those bonds, β-O-4 linkages are predominant and range from 45 to 60 %, depending on the wood type.[3,4] The cleavage of such β-O-4 linkages has been the focus of several investigations over recent decades.[5] In many of those examples, model compounds with β-O-4 linkages[6] were used because native lignin was considered too structurally complex.[3]

The development of catalytic methods for lignin degradation has become a central goal, and both heterogeneous and homogeneous transition-metal catalysts have proven useful in this context.[3,7] The former found many applications in reductive lignin conversions, as exemplified by the work of Pepper and co-workers, who were among the first to describe the use of supported noble metals as catalysts for such reactions.[8] Their pioneering work has been extended in recent years to provide access to a broad range of phenolic, phenyl, and cyclohexyl derivatives.[9] The use of homogenous nickel-, iridium-, rhenium-, or ruthenium-based catalysts allows the reductive and redox-neutral cleavage of lignin model compounds.[6,10]

Homogenous transition-metal catalysts have also been applied in oxidative lignin studies.[11] Very promising results have recently been achieved in the cleavage of β-O-4 dilignol model compounds with vanadium[11n,q] (Scheme 1) and cobalt complexes.[11r] However, heterogeneous catalysts have been used rarely for such reactions.[12,13] Most frequently, peroxides serve as oxidants that lead to only moderate product selectivities. Furthermore, the model compounds used for such studies often lack key structural features of lignin (e.g., ferulic acid or veratryl alcohol).[13] Most reports focus on the nonselective removal of lignin and lignin derivatives in pulping and waste water.[3,12a–c]

For any future large-scale oxidative lignin conversion, dioxygen will most likely be the oxidant of choice.[5e] Along those lines, Sales et al. described catalytic wet aerobic lignin oxidation in alkaline solutions with Pd/γ-Al_2O_3 catalysts to form aromatic aldehydes.[14a] Lin and co-workers obtained analogous products under similar conditions with manganese, copper, and cobalt Perovskite-type oxides as catalysts.[14b–e] Under optimized conditions, 66.6 % of their lignin source was converted after 3 h.[15] Vanillin was isolated as the main product from the oxidative cleavage reactions of lignin alkaline solutions under a dioxygen atmosphere.[16]

Here, we show the selective aerobic cleavage of lignin (and model compounds thereof) to afford products of a mass of ap-

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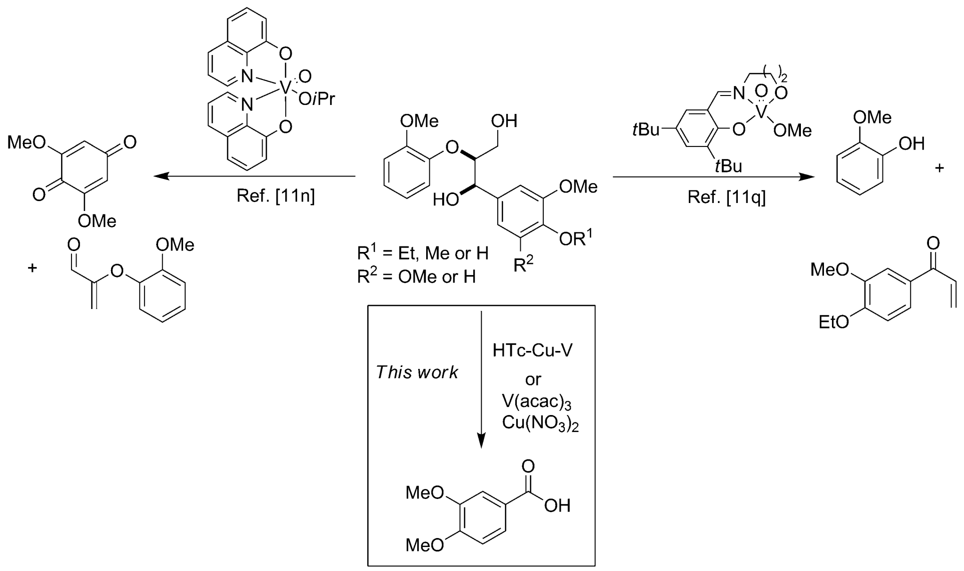


Scheme 1. Previous reports on vanadium-catalyzed oxidative cleavage of β-O-4 dilignol model compounds and the current work.

proximately 300 Da by using copper–vanadium double-layered hydrotalcites or combined V(acac)$_3$ and Cu(NO$_3$)$_2$·3H$_2$O as catalysts.

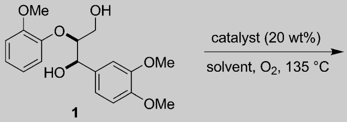
Results and Discussion

Considering their basic properties and oxidation potentials,[17] transition-metal-containing hydrotalcites (HTc) were chosen as catalysts (Table 1). The HTcs were prepared by coprecipitation synthesis[18] and characterized by inductively couple plasma optical emission spectroscopy (ICP-OES) and XRD (see Supporting Information). The cleavage of *erythro*-dilignol **1**, which is readily accessible in larger quantities as a diastereomerically pure model compound with a β-O-4 linkage,[6] was selected as a test reaction. Unfortunately, initial reaction attempts with 20 wt% of HTc containing cobalt, iron, zinc, or copper in toluene under dioxygen (6 bar) at 130 or 135 °C led to only trace conversions of **1** (Table 1, entries 1–5). To our delight, the situation changed with pyridine as the solvent. Then, the copper-containing HTc (HTc-Cu) became catalytically active, and 77% conversion of dilignol **1** was observed after 72 h (Table 1, entry 6). Ketone **2**, veratraldehyde (**4**), and veratric acid (**5**) were identified as the products (Scheme 2). However, no increased activity was observed for cobalt-, iron-, and zinc-containing HTc in pyridine (not shown). The role of copper was further confirmed through reactions with the metal-free hydrotalcite (HTc) in toluene or pyridine under otherwise identical conditions, which did not lead to significant conversions of **1** (Table 1, entries 7 and 8).

On the basis of these initial findings and acknowledging the catalytic power of vanadium in other oxidative lignin cleavage reactions of model compounds (Scheme 1),[11n,q] the initial catalysts were further modified by the introduction of vanadate into the interlayer of the hydrotalcite. As hypothesized, the newly prepared copper–vanadium and iron–vanadium hydrotalcite-like catalysts (HTc-Cu-V and HTc-Fe-V) showed a much higher catalytic activity than the previously applied catalysts and led to very high conversions of **1** (>99%) in toluene after a reaction time of only 13 h (Table 1, entries 9 and 10). Cobalt–vanadium hydrotalcite and vanadium hydrotalcite (HTc-Co-V and HTc-V) proved less active and resulted in 72 and 71% conversion of **1**, respectively (Table 1, entries 11 and 12).

Although these catalysts were highly active, the reactions in toluene were rather unselective and afforded numerous products. Once more, the switch from toluene to pyridine led to a remarkable improvement with a significant enhancement in product selectivity. Excellent conversions of **1** (>99%) to veratric acid (**5**) as the main product were now achieved with HTc-Cu-V and HTc-Zn-Cu-V as catalysts under a dioxygen pressure of 5 bar for 17 h (Table 1, entries 13 and 14). A vanadium-con-

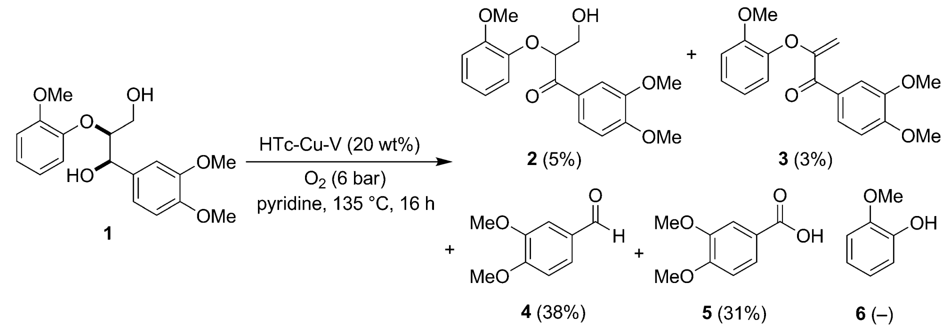
Table 1. Catalyst screening for the oxidative cleavage of dilignol **1**.[a]



1

Entry	Catalyst	*t* [h]	Solvent	Conversion [%][b]
1	HTc-Co	72	toluene	traces
2	HTc-Zn-Co	72	toluene	traces
3[c]	HTc-Fe	40	toluene	traces
4	HTc-Zn	72	toluene	traces
5	HTc-Cu	72	toluene	traces
6	HTc-Cu	72	pyridine	77
7	HTc	72	toluene	traces
8	HTc	40	pyridine	traces
9	HTc-Cu-V	13	toluene	>99
10	HTc-Fe-V	13	toluene	>99
11	HTc-Co-V	13	toluene	71
12	HTc-V	13	toluene	72
13[d]	HTc-Cu-V	17	pyridine	>99
14[d]	HTc-Zn-Cu-V	17	pyridine	>99
15	HTc-V	17	pyridine	98
16	HTc-Cu-V	17	dimethyl carbonate	92
17[e]	HTc-Cu-V	17	pyridine	92
18[f]	HTc-Cu-V	17	pyridine	83
19[d,g]	HTc-Cu-V	17	pyridine	89
20[g]	HTc-Cu-V	17	pyridine	98

[a] Reaction conditions: **1** (0.25 mmol), catalyst (20 wt%), O$_2$ (6 bar), solvent (1.25 mL), 135 °C, stirring rate 600 rpm. [b] Conversions were determined by HPLC with 3,4-dimethoxybenzylalcohol as internal standard. [c] Performed at 130 °C. [d] 5 bar of O$_2$. [e] Air (5 bar) instead of O$_2$. [f] 5 wt% of catalyst. [g] 10 wt% of catalyst.



Scheme 2. Cleavage of dilignol **1** under the optimized reaction conditions (1 mmol scale; yields after column chromatography).

taining HTc without copper was also active (Table 1, entry 15), but the selectivity towards the cleavage products was lower. Similar observations were made for HTc-Cu-V in dimethyl carbonate as the solvent instead of pyridine (Table 1, entry 16). Air was also suitable as an oxidant, albeit slightly lower conversions of **1** were obtained (Table 1, entry 17). The influence of the catalyst loading and O_2 pressure was studied, and it was possible to achieve a high conversion (98%) of **1** with 10 wt% of HTc-Cu-V under 6 bar of O_2. From a catalysis performed on a 0.25 mmol scale with a reaction time of 17 h (Table 1, entry 13), 8% of veratraldehyde (**4**) and 64% of veratric acid (**5**) were obtained (as determined by HPLC).

To enable the isolation and identification of the minor cleavage components, the HTc-Cu-V catalyst was used in a larger-scale reaction, and veratraldehyde (**4**) and veratric acid (**5**) were again the major cleavage products (see Scheme 2). However, they were now obtained (after isolation by column chromatography) in almost equimolar amounts (38 and 31% yield, respectively). As byproducts, 5% of ketone **2** and 3% of enol ether enone **3** were isolated. We attributed the altered selectivity for the formation of **4** and **5** to the change of the reaction scale and assumed that the outcome of the catalysis was affected by the respective dioxygen uptake. Consequently, the stirring rate was varied, but no general trend could be deduced from the observed data (for details, see Supporting Information).[19] During the optimization process, 2-methoxyphenol (**6**) was not detected in any reactions, although we initially expected it be to formed in substantial amounts from the concomitant formation of **4** and **5** upon cleavage of **1**.

In light of the results of Alejandre et al., who reported that copper hydrotalcite-like catalysts oxidized phenol derivatives to organic acids and CO_2 with benzoquinone derivatives as intermediates,[20] a control experiment was performed, in which **6** was subjected to the aforementioned standard reaction conditions with HTc-Cu-V as the catalyst. As hypothesised **6** was degraded rapidly to a complex mixture of unidentifiable products.[21]

To test catalyst recyclability and to facilitate the detection of catalyst modifications upon recycling, the reaction conditions were slightly changed to avoid the full conversion of **1**. HTc-Zn-Cu-V was selected as the catalyst, and, as shown in Table 2, its activity remained almost the same during the first two runs, as indicated by the 89 and 91% conversions of dilignol **1** (Table 2, entries 1 and 2). However, in the third catalytic cycle, the conversion of **1** decreased to 76% (Table 2, entry 3). In all three runs, products **2**–**5** were isolated, and the latter two were predominantly formed as before. As a possible cause of the decrease in catalyst activity upon recycling, we considered metal leaching. To verify that hypothesis, the reaction in the presence of HTc-Cu-V was interrupted after 2 h, and the solids were collected filtered off from the hot reaction solution. The XRD patterns of the fresh and reacted HTc-Cu-V samples showed no appreciable structural modifications of the solid catalyst (Figure 1). These findings were further validated by Raman spectroscopy measurements of the HTc-Cu-V sample before and after the reaction (see Supporting Information).

Table 2. Catalyst recycling experiments.[a]

Entry	Run	Yield [%][b]				
		1[c]	2	3	4	5
1	first	11	8	2	30	22
2	second	9	5	2	26	32
3	third	24	7	3	22	14

[a] Reaction conditions: **1** (1 mmol), HTc-Zn-Cu-V (20 wt%), O_2 (5 bar), pyridine, 135 °C, 16 h. [b] After column chromatography. [c] Reisolated starting material.

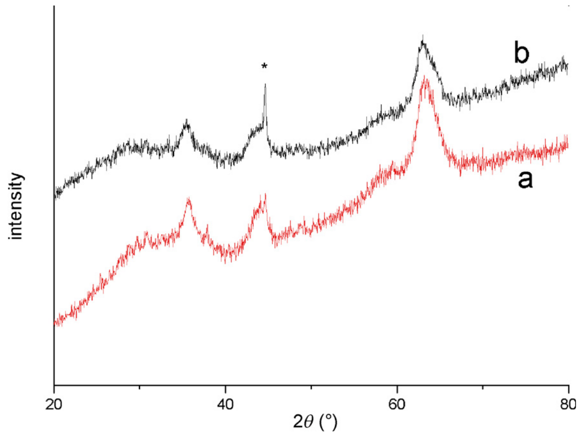


Figure 1. XRD spectra of HTc-Cu-V a) before the reaction and b) after a reaction time of 17 h; * peak caused by the sample holder.

After the solid had been removed by filtration, the resulting clear solution of the 2 h reaction was left to react for additional 15 h. The reaction still occurred after catalyst separation, and 82% conversion was achieved. This indicated that catalytically active species had leached into solution. However, those homogeneous catalysts appeared to be less active than their heterogeneous counterparts or they deactivated over the course of the reaction. The amounts of copper and vanadium in solution after filtration (111.9 and 251.0 mg L^{-1}, respectively, correspond to 10 and 6.4 % of the copper and vanadium present in the heterogeneous HTc-Cu-V sample) were quantified by ICP-OES measurements.

A series of analyses were conducted to determine whether HTc-Cu-V served as a heterogeneous catalyst or acted as a dispenser of the catalytically active homogeneous species, which were slowly deactivated over time, possibly owing to agglomeration. Thus, we analyzed the copper and vanadium species in the solution over the course of the reaction by ICP-OES after the solids were filtered off from the hot reaction mixture (Figure 2). The amount of leached copper increased faster during the first 4 h of the reaction and continuously rose during the entire reaction. However, a high initial leaching of homogeneous vanadium species was observed. After the initial leaching, the vanadium concentration remained more or less constant with a slight decrease at the end of the reaction, which can potentially be attributed to agglomeration.

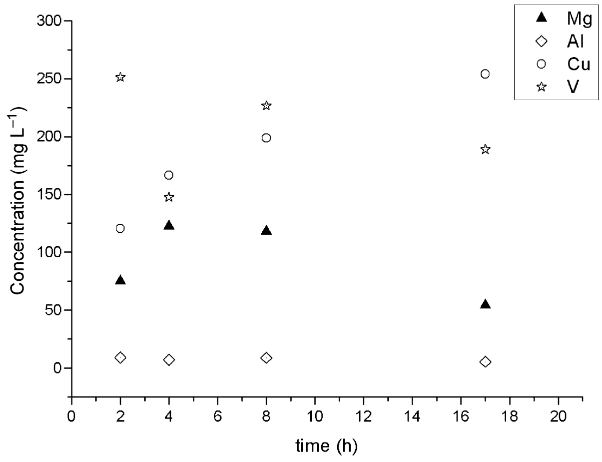


Figure 2. ICP measurements of leached metal species from HTc-Cu-V over the course of the reaction under the following conditions: **1** (0.25 mmol), HTc-Cu-V (20 wt %), O_2 (5 bar), pyridine (1.25 mL), 135 °C, stirring rate 600 rpm.

Then, to study the general catalytic activity of the homogeneous vanadium and copper species, both together and individually, $V(acac)_3$ was chosen as the vanadium source, and $Cu(NO_3)_2{\cdot}3\,H_2O$ was chosen as the copper source. With 2.5 mol % of $V(acac)_3$ and 1 mol % of $Cu(NO_3)_2{\cdot}3\,H_2O$, 97 % conversion was achieved after a reaction time of 17 h, and veratric acid (**5**) and veratraldehyde (**4**) were the main products in 39 and 26 % yield, respectively. $V(acac)_3$ (2.5 mol %) remained very active without a copper source and afforded 96 % conversion, but the yield for veratraldehyde (**4**) decreased to 15 %, and the yield of veratric acid (**5**) stayed at 39 %. However, $Cu(NO_3)_2{\cdot}3\,H_2O$ by itself was significantly less active, even with a catalyst loading of 5 or 10 mol %, and resulted in only 20 % conversion after 17 h. To achieve complete conversion with $V(acac)_3$ and $Cu(NO_3)_2{\cdot}3\,H_2O$, the reaction time had to be extended to 20 h. A catalyst loading of 5 mol % $V(acac)_3$ and 5 mol % $Cu(NO_3)_2{\cdot}3\,H_2O$ furnished veratric acid (**5**) in 62 % yield and veratraldehyde (**4**) in 25 % yield.

Next, we determined whether there was a correlation between the nature of the active homogeneous copper and vanadium species in the $V(acac)_3/Cu(NO_3)_2{\cdot}3\,H_2O$ catalyst and the leached metal species that had gone it into solution from the HTc-Cu-V catalyst. For this investigation, EPR spectroscopy was used. The leached species from HTc-Cu-V were studied first. After a reaction time of 2 h, the catalyst was removed by hot filtration. The analysis of the resulting solution showed a strong signal typical of copper with an oxidation state of +2, and no signal typical of vanadium with an oxidation state of +4 was present (Figure 3).This reaction solution was subjected to the original reaction conditions for additional 15 h, and a distinct signal for vanadium(IV) was observed. Then, EPR spectroscopy measurements with the $V(acac)_3/Cu(NO_3)_2{\cdot}3\,H_2O$ catalyst system and a catalyst loading of 5 mol % were conducted. Within the first 2 h of the reaction, similar to the results with HTc-Cu-V, a very strong signal for copper(II) and only a very weak signal for vanadium(IV) were detected (see Supporting Information). After 17 h of reaction, however, a strong increase in the vanadium(IV) signal occurred, as for the reaction with HTc-Cu-V after an additional reaction time of 15 h. Therefore, we conclude that the homogeneous copper and vanadium species from $V(acac)_3/Cu(NO_3)_2{\cdot}3\,H_2O$ and the leached HTc-Cu-V are most likely very similar in nature.

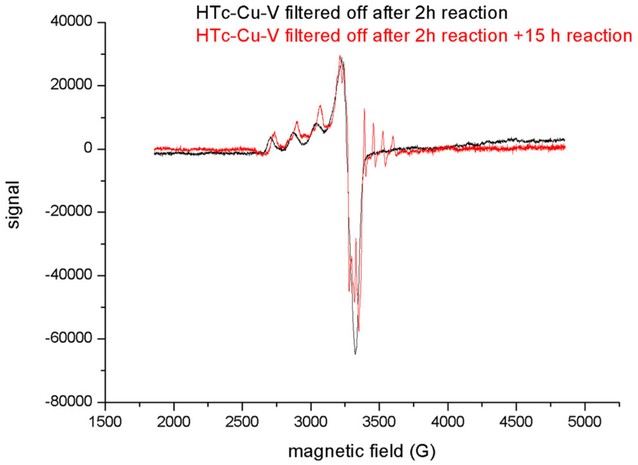


Figure 3. EPR spectra of the reaction solution after the HTc-Cu-V had been removed by hot filtration; the reaction conditions were those summarized in Figure 2.

In light of all of these findings and considering the substantial progression of the reaction after the HTc-Cu-V was removed by filtration (38 % conversion after 2 h and 82 % after an additional 15 h reaction time), we assume that HTc-Cu-V acts to a significant degree as a dispenser of the catalytically active homogeneous species, which are continuously released. In turn, these leached catalytically active species are deactivated over time, possibly through agglomeration or a resting state of the catalyst. Vanadium(IV) could represent such a resting state because it is only present in very low concentrations at the beginning of the reaction when the homogeneous catalyst is most active and increases in quantity over the course of the reaction as the reactivity of the system decreases. This also means that the catalytically active species does not contain a vanadium(IV) center.

The fundamental understanding of the reaction and catalyst behavior in the conversion of the model compound **1** containing a β-O-4 linkage was essential for the subsequent studies of lignin degradations. Lignin model compounds represent a very valuable tool to assess the preliminary catalytic activity and selectivity of reaction systems for prominent bonds within lignin. However, a direct correlation or comparison of the results obtained with model compounds and actual lignin is difficult, as the higher complexity and the presence of impurities in natural and extracted lignin frequently lead to a reduction in catalyst activity.[3c] The utilized lignin samples were analyzed and characterized by calibrated gel permeation chromatography (GPC). Initial experiments with organsolv beech lignin **7** and **8** (for the pretreatment conditions of the lignin sources, see Supporting Information) showed that more dilute reaction solutions than those used previously for the cleavage of the model compound were necessary to improve the solubility of the lignin. Furthermore, longer reaction times and higher dioxygen pressures were needed. Gratifyingly, with a reaction time of 40 h and 10 bar of dioxygen pressure, up to 86 % of the original mass of lignin was isolated after work-up, and more than 80 % of this lignin sample was degraded to products of a reduced size. Excellent selectivities were observed, and the maximum of the mass peak shifted from approximately 1400 Da before the reaction to 300 Da after the reaction, and this mass corresponds to dimeric lignin fragments (Figure 4).[22] In addition to the depolymerization, small amounts of lignin were converted to masses of 4000 to 6000 Da. Whether these were polymerization products or agglomerates of products with lower masses could not be determined with absolute certainty. The depolymerization of lignin to lower molecular masses was further proven by MALDI MS measurements (see Supporting Information).

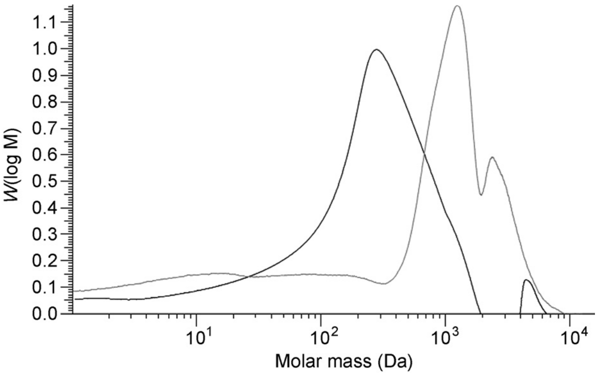


Figure 4. GPC mass distributions of organosolv beech lignin **8**. The mass distribution of **8** before the reaction is shown in gray, and that after the reaction is shown in black. For additional information on the use of different lignin sources and catalysts, see Supporting Information.

With the optimized reaction conditions in hand, the generality of the approach was demonstrated by the conversions of other lignin samples that had undergone different pretreatment conditions (Sigma–Aldrich kraft lignin #471003 and Sigma–Aldrich kraft lignin #370959). In all cases, the main products had masses of approximately 300 Da or lower (see Supporting Information). Notably, the impurities in both kraft lignin sources did not affect the activity of the catalyst, which underlines the robustness of the system. A control experiment with organosolv beech **7** confirmed the key role of the catalyst. Without catalyst, no depolymerization occurred, and the formation of products of 4000 Da and greater was enhanced significantly.

Finally, with 5 wt % of $V(acac)_3$ and $Cu(NO_3)_2{\cdot}3\,H_2O$ as the catalyst, similar results were obtained, and cleavage products with a mass of less than 300 Da were formed. To the best of our knowledge, this is the first example in which the size reduction of lignin to such a high degree through selective catalytic oxidative depolymerization is reported and has been quantified by both calibrated GPC and MALDI MS measurements.

To determine the extent of the cleavage of the β-O-4 and other characteristic lignin linkages, 2D NMR (HSQC) spectroscopy measurements before and after the reaction with deuterated pyridine as the solvent were performed (Figure 5). The interpretation of the spectra followed the method outlined by Sun and co-workers.[23] Accordingly, in both organosolv beech lignins **7** and **8** as well as Sigma–Aldrich kraft lignin #370959, the β-O-4 linkages, acetylated β-O-4 linkages, resinol structures and *p*-hydroxycinnamyl alcohols identified in the starting material were completely degraded during the reaction. Especially the cleavage of the resinol structures is noteworthy because previous NMR-monitored lignin studies by us[5c] and Westwood and co-workers[24] have shown that the resinol structure is actually more prominent in pretreated lignin sources than its natural abundance in native lignin would suggest. To the best of our knowledge we report the first transition metal system using dioxygen as oxidant that is able to cleave the resinol structure in its entirety independently of which pretreatment technology was used. Other structural modifications of lignin could not be specified by this NMR technique although they must have occurred as revealed by the degradation of Sigma–Aldrich kraft lignin #471003, where β-O-4 linkages, for example, are absent owing to the pretreatment process. Consequently, it can be concluded that the newly devised catalyst systems are active for the cleavage of not only β-O-4 linkages but also other significant bonds that contribute to the original molecular size of lignin.

Conclusions

We have investigated the oxidative cleavage of lignin with dioxygen as the oxidant and inexpensive transition-metal-containing hydrotalcites (HTc) or combinations of $V(acac)_3$ and $Cu(NO_3)_2{\cdot}3\,H_2O$ as catalysts. In both the conversion of a model

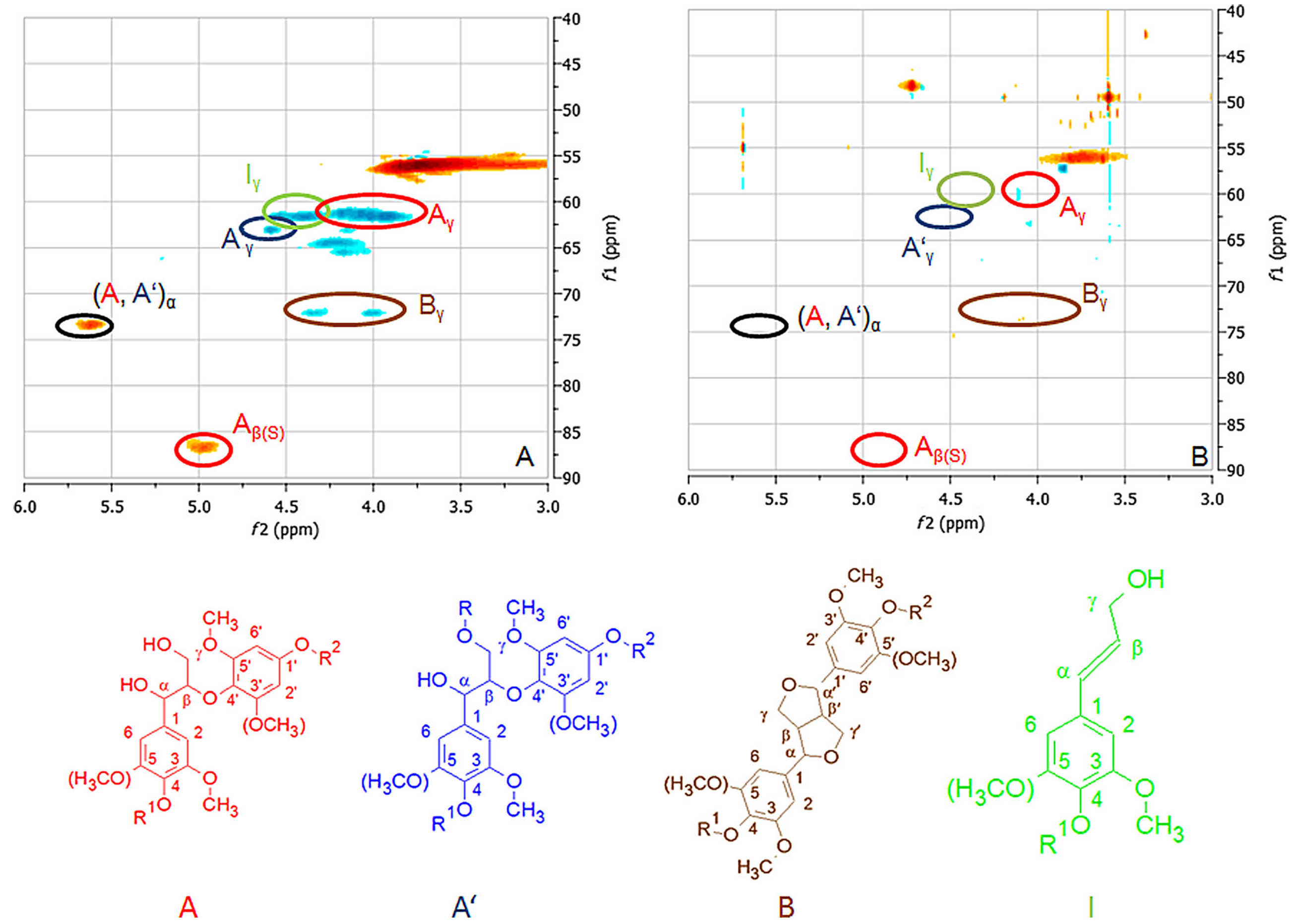


Figure 5. 2D HSQC NMR spectra ([D_5]pyridine) of organosolv beech lignin **7** A) before the reaction and B) after the reaction. For additional information on organosolv beech lignin **8**, Sigma–Aldrich kraft lignin #370959, and the cleavage of organosolv lignin **7** with $V(acac)_3$ and $Cu(NO_3)_2{\cdot}3H_2O$, see Supporting Information.

compound and the degradation of four different lignin sources, the catalysts showed high activity and good selectivity. We are conducting further studies of alternative lignin cleavage reactions in our laboratories.

Experimental Section

General procedure for the oxidative cleavage of dilignol 1 with HTc catalysts

A 25 mL glass autoclave was charged with dilignol **1** (83.6 mg, 0.250 mmol, 1.0 equiv.), the corresponding HTc catalyst (16.7 mg, 20 wt%), and a magnetic stirrer. Subsequently, pyridine (1.25 mL) was added. The autoclave was purged three times with oxygen and charged with 5 bar of oxygen, and the mixture was stirred at 600 rpm in a preheated oil bath at 135 °C. After the desired reaction time, the autoclave was taken out of the oil bath and cooled to room temperature. The remaining oxygen pressure was released, and the autoclave was opened. A standard solution (3,4-dimethoxybenzylalcohol in methanol, 1.000 mL, $c = 0.2\ \mathrm{mol\,L^{-1}}$) was added to the reaction solution with an Eppendorf pipette. The reaction mixture was filtered into a 1 M HCl solution (50 mL), the autoclave was rinsed with dichloromethane (10 mL), and the catalyst was washed with dichloromethane (20 mL). The aqueous phase was then extracted with dichloromethane (4×20 mL). Next, the combined organic phases were washed with 1 M HCl (1×50 mL) and brine (1×50 mL), dried with $MgSO_4$, filtered, and the solvent was removed under reduced pressure. A minimum of three samples were taken from each reaction mixture for HPLC measurements. For each sample, the reaction product (2.0–3.0 mg) was weighed into a vial. Then, ethyl acetate (0.5 mL) and acetonitrile (0.5 mL) were added to the vial, and after the complete dissolution of all products, the solution was filtered into a HPLC vial.

General procedure for the oxidative cleavage of dilignol 1 with $V(acac)_3$ and $Cu(NO_3)_2{\cdot}3H_2O$

A 25 mL glass autoclave was charged with dilignol **1** (83.6 mg, 0.250 mmol, 1.0 equiv.), the corresponding amount of $V(acac)_3$ and $Cu(NO_3)_2{\cdot}3H_2O$, and a magnetic stirrer. Subsequently, pyridine (1.25 mL) was added. The autoclave was purged three times with oxygen and charged with 5 bar of oxygen, and the mixture was stirred at 600 rpm in a preheated oil bath at 135 °C. After the desired reaction time, the autoclave was taken out of the oil bath and cooled to room temperature. The remaining oxygen pressure was released, and the autoclave was opened. A standard solution (3,4-dimethoxybenzylalcohol in methanol, 1.000 mL, $c = 0.2\ \mathrm{mol\,L^{-1}}$) was added to the reaction solution with an Eppendorf pipette. The reaction mixture was added to a 1 M HCl solution (50 mL), and the autoclave was rinsed with dichloromethane (10 mL). The aqueous phase was then extracted with dichloromethane (4×20 mL). Next, the combined organic phases were washed with 1 M HCl (1×50 mL) and brine (1×50 mL), dried with MgSO$_4$, filtered, and the solvent was removed under reduced pressure. A minimum of three samples were taken from each reaction for HPLC measurements. For each sample, the reaction product (2.0–3.0 mg) was weighed into a vial. Then, ethyl acetate (0.5 mL) and acetonitrile (0.5 mL) were added to the vial, and after the complete dissolution of all products, the solution was filtered into a HPLC vial.

General procedure for the oxidative cleavage of lignin

A 20 mL steel autoclave was charged with the lignin source (100 mg) and either HTc-Cu-V (20 mg, 20 wt%) or V(acac)$_3$ (5 mg, 5 wt%) and Cu(NO$_3$)$_2$·3H$_2$O (5 mg, 5 wt%). Subsequently, pyridine (4.5 mL) was added. The autoclave was purged three times with oxygen and charged with 10 bar of oxygen, and the mixture was stirred at 600 rpm in a preheated oil bath at 135 °C. After 40 h, the autoclave was taken out of the oil bath and cooled to room temperature. The residual pressure was released, the reaction mixture was filtered, and the autoclave and catalyst were washed with pyridine (20 mL). Under reduced pressure, the pyridine was removed. The reaction mixture was dissolved in methanol (20 mL), and the solvent was evaporated to remove residual pyridine. This process was repeated twice (2×20 mL). Afterwards, the product was dried under high vacuum. The product was characterized by GPC, MALDI MS, and elemental analysis.

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