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JOURNAL OF THE AMERICAN CHEMICAL SOCIETY
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Aromatic Monomers by in Situ Conversion of Reactive Intermediates in the Acid-Catalyzed Depolymerization of Lignin

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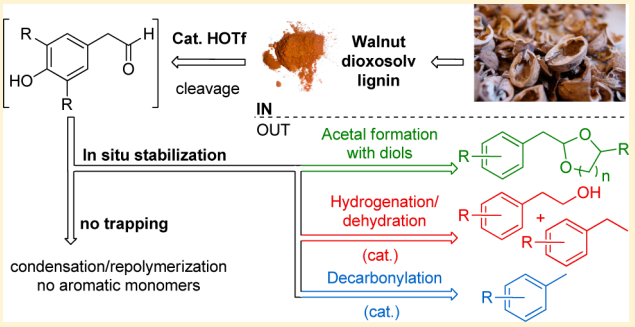
Supporting Information

ABSTRACT: Conversion of lignin into well-defined aromatic chemicals is a highly attractive goal but is often hampered by recondensation of the formed fragments, especially in acidolysis. Here, we describe new strategies that markedly suppress such undesired pathways to result in diverse aromatic compounds previously not systematically targeted from lignin. Model studies established that a catalytic amount of triflic acid is very effective in cleaving the β-O-4 linkage, most abundant in lignin. An aldehyde product was identified as the main cause of side reactions under cleavage conditions. Capturing this unstable compound by reaction with diols and by in situ catalytic hydrogenation or decarbonylation lead to three distinct groups of aromatic compounds in high yields acetals, ethanol and ethyl aromatics, and methyl aromatics. Notably, the same product groups were obtained when these approaches were successfully extended to lignin. In addition, the formation of higher molecular weight side products was markedly suppressed, indicating that the aldehyde intermediates play a significant role in these processes. The described strategy has the potential to be generally applicable for the production of interesting aromatic compounds from lignin.



INTRODUCTION

Lignin is the richest source of renewable aromatic compounds on the planet and harbors great potential for the production of industrially relevant aromatic bulk and fine chemicals.[1] However, the efficient catalytic conversion of lignin to well-defined aromatics still represents a key challenge due to the robust and amorphous structure of this highly oxygenated biopolymer.[1,2] The development of new approaches is very important, as these will play a crucial role in the implementation of lignocellulose as a renewable alternative to fossil carbon resources.[1,2a,3] In particular, methods that enable efficient depolymerization and subsequent defunctionalization of the formed fragments are desired.[1a,2a,4] At the same time, competing recondensation reactions that lead to higher molecular weight side products should be minimized.[5] A number of innovative approaches both in homogeneous[6] as well as heterogeneous[7] catalysis exist and have been summarized in recent reviews.[2a,3c,4,8] Methods in homogeneous catalysis are generally limited to selective bond cleavage in model compounds, although some protocols have been tested on lignin.[9] Approaches using higher temperatures often suffer from low product selectivity due to overreduction of the aromatic rings or formation of biochar.[1a,2a,8a,b] Recently, breakthroughs were achieved in the mild depolymerization of lignin. Mixtures of aromatic compounds were obtained in high yield through a unique approach developed by Stahl and co-workers.[10] Furthermore, single aromatic compounds were isolated upon catalytic depolymerization of lignin under low severity conditions.[11] Here we present a new concept that affords three distinctly different classes of aromatic compounds from lignin, relying on acidolysis.

Acidolysis is one of the most widely used methods for the fractionation of lignocellulose into its main components[1a,2,12] and will regain importance if the implementation of the biorefinery concept is to be financially viable.[13] Historically, acid pulping was mainly used for isolation of reduced molecular weight lignin fractions from the lignocellulose matrix.[14] Although distinct aromatic compounds have been found upon acidolysis of lignin in early studies, these were mainly used in the context of structural elucidation, rather than in designing the depolymerization of lignin into valuable aromatic monomers.[15] In fact, prolonged treatment of lignin with mineral acids in aqueous/organic media typically leads to

Received: April 9, 2015
Published: May 22, 2015

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456−7467

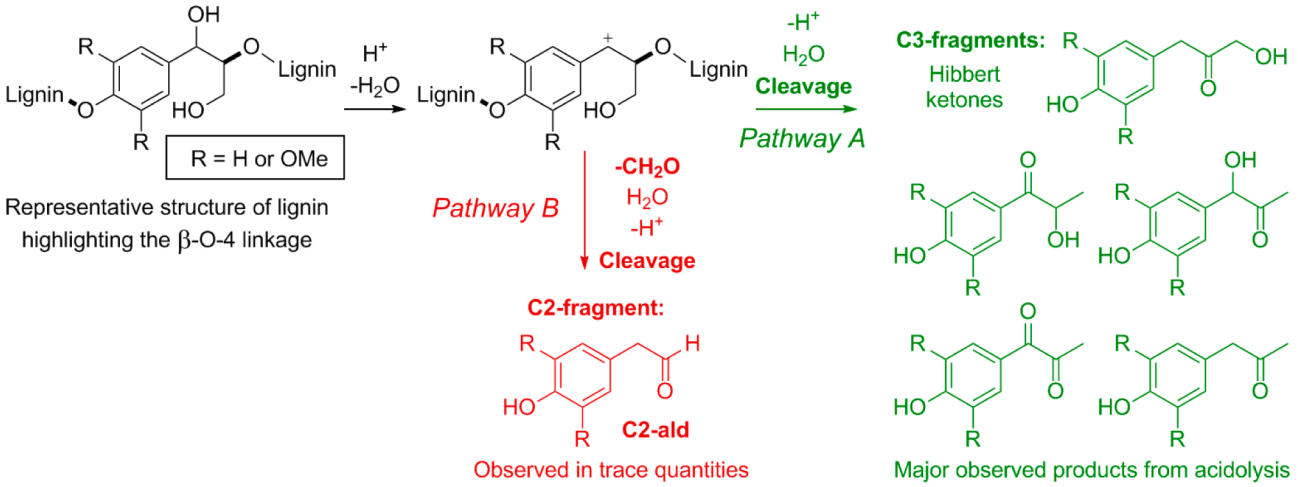


Figure 1. Major identified cleavage pathways and products from lignin β-O-4 linkage acidolysis indicating C2- and C3-fragments.

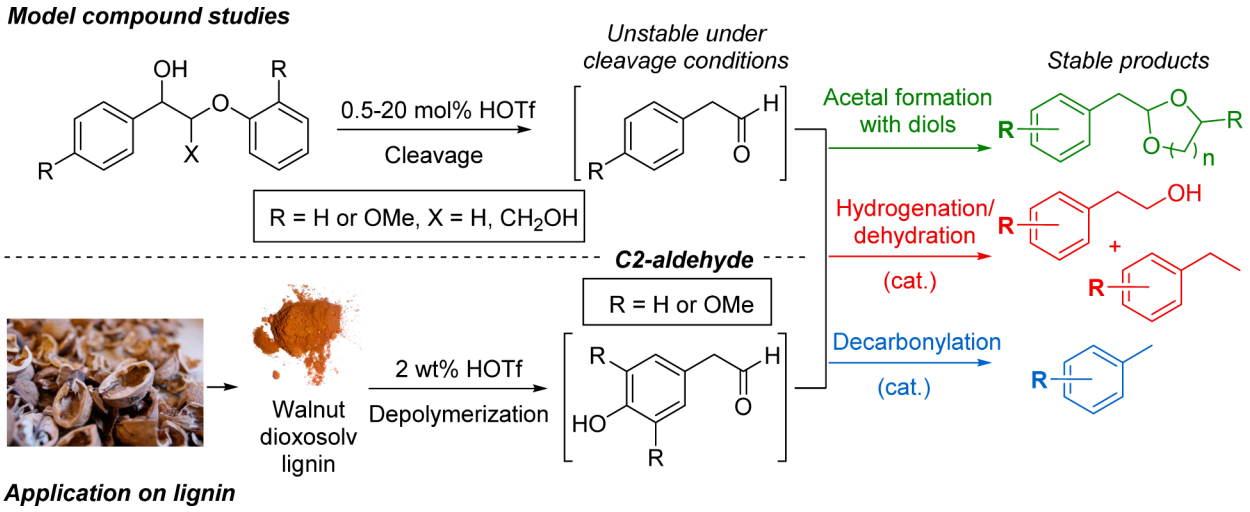
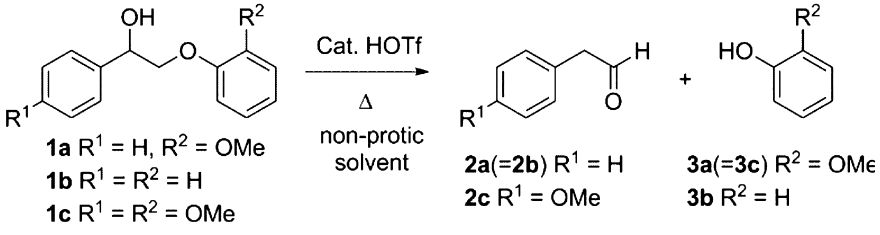


Figure 2. Overview of the work presented in this manuscript showing the C2-aldehydes targeted for stabilization.

Scheme 1. Triflic-Acid-Catalyzed Cleavage of β-O-4 Model Compounds 1a–c



substantial amounts of insoluble material and low monomer yields.[14,16] Surprisingly, the specific causes of these recondensation phenomena, first observed decades ago,[17] have remained largely unanswered, despite extensive mechanistic studies elucidating cleavage pathways.

Building on earlier reports,[16,18] interesting recent mechanistic studies[19] conducted with model compounds that mirror the most abundant β-O-4 linkage in lignin have established that the phenyl-ether bond readily undergoes acidolysis at temperatures up to 150 °C and that two main cleavage pathways exist (Figure 1). Pathway A leads to C3-fragments typically referred to as Hibbert ketones, while Pathway B involves the loss of formaldehyde, leading to C2-fragments.[16,19b,c] In model studies, up to 50% of the products can correspond to cleavage via Pathway B.[19a,d] Interestingly, however, the monomeric products observed after acidolysis of lignin almost exclusively consist of phenolic-C3-ketones (Hibbert ketones).[15c] We noted, that the apparent lack of C2-products upon acidolysis of lignin likely indicates involvement of these fragments in recondensation reactions.

Using model compounds we have revisited cleavage reactions related to Pathway B[19a,20] applying catalytic amounts of acid and confirmed the involvement of the unstable C2-aldehyde in recondensation processes. We anticipated that immediate conversion of these unstable cleavage products would not only significantly reduce side-reactions but also provide viable pathways toward defined aromatic compounds derived from

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

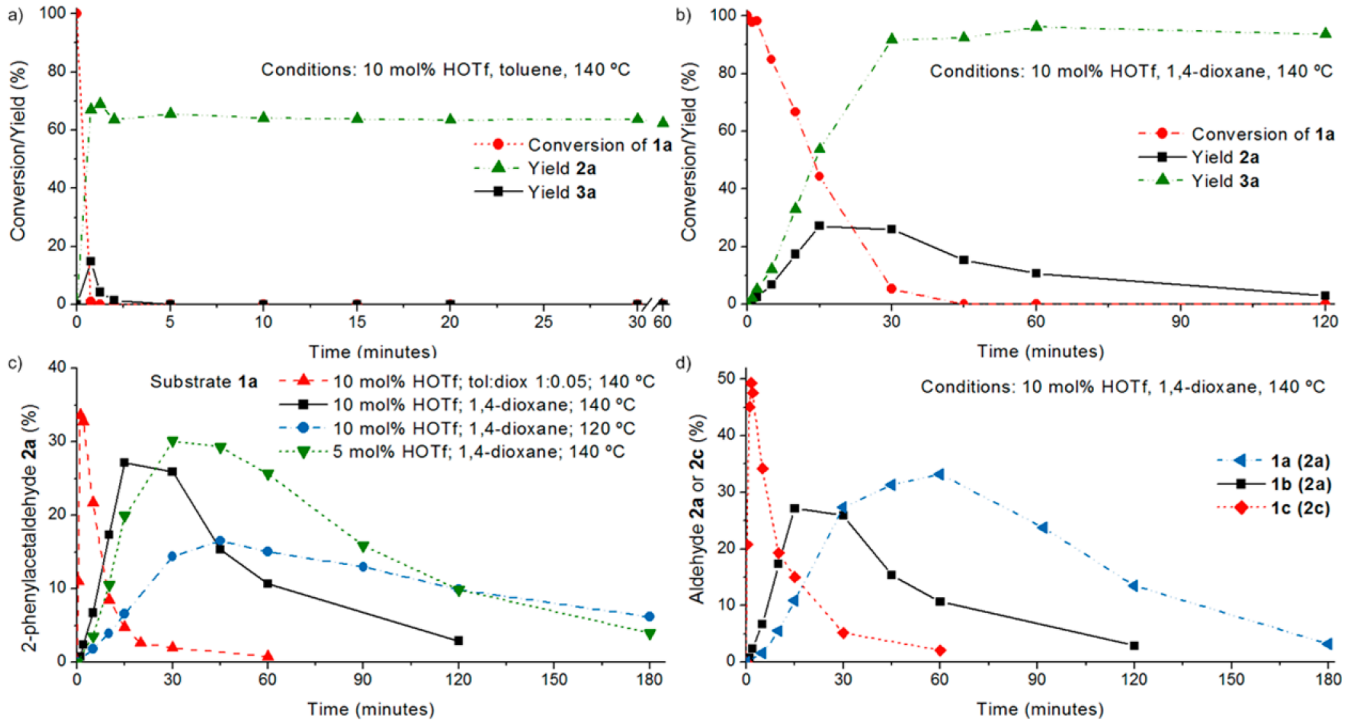
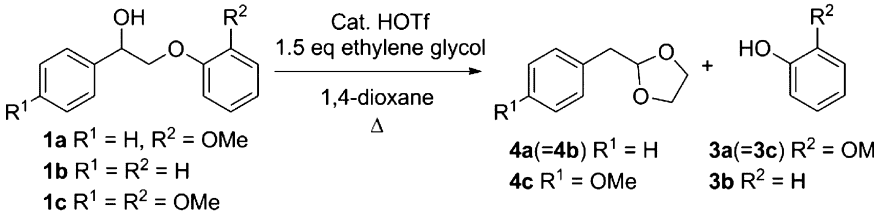


Figure 3. Reaction profiles for the cleavage of **1a**–**1c**, showing (a) all main products in toluene, (b) all main products in 1,4-dioxane, (c) the aldehyde product (**2a**) only at various reaction conditions, and (d) aldehyde products (**2a**–**c**) in reactions using substrates **1a**–**1c**.

Scheme 2. In Situ Acetal Formation with Ethylene Glycol upon Triflic Acid-Catalyzed Cleavage of Lignin *β*-O-4 Model Compounds 1a–c



1a R^1 = H, R^2 = OMe
1b R^1 = R^2 = H
1c R^1 = R^2 = OMe

4a(=**4b**) R^1 = H
4c R^1 = OMe

3a(=**3c**) R^2 = OM
3b R^2 = H

these C2-fragments. Methods, shown in Figure 2, were found suitable for this purpose.

During acid-catalyzed depolymerization of lignin as substrate, recondensation pathways[21] of analogous C2-aldehyde fragments could lead to the formation of higher molecular weight polymers.[2,14,22] However, with the methodologies shown in Figure 2 we were able to show a significant decrease in the formation of insoluble material typically associated with lignin acidolysis and obtain distinct sets of aromatic products in agreement with the model studies.

RESULTS AND DISCUSSION

Model Compound Studies. *Acid-Catalyzed Cleavage of C2-β-O-4 Model Compounds.* Model compounds **1a**–**c** that represent the *β*-O-4 lignin motif after loss of the *γ*-carbon were used to study Pathway B involving the C2-fragment. We first established that catalytic amounts of strong acid in nonprotic solvents, including those that can be derived from renewables (Scheme 1, Table S1), are very effective in cleavage of **1a**–**c**. In particular, triflic acid in toluene led to complete conversion of **1a** within seconds (Figures 3a and S1–S5) and the formation of guaiacol **3a** (>60%) as the only observable cleavage product. Interestingly, the rate of cleavage in toluene was orders of magnitude greater than in water with excess sulfuric acid, as reported earlier (6.5 min^{-1} vs 0.02 h^{-1}).[19a] The reaction was slower in 1,4- dioxane (k = 2.8 h^{-1}) but more selective, yielding up to 94% guaiacol (Figures 3b and S7). In this case, 2-phenylacetaldehyde **2a** was identified as a second, albeit minor, product (up to 30%). Good **1a** conversion was maintained under milder reaction conditions, but this did not improve **2a** selectivity (Figures 3c and S8–S9 and Table S2).

Similar observations were made for model compounds **1b** and **1c**, generally providing **1c** ≫ **1a** > **1b** as an order of reactivity (Figures 3d, S7, and S10–S11). Thus, the rate of cleavage (80, 2.8, and 1.1 h^{-1}) was greatly enhanced for substrates containing electron-donating methoxy substituents. This is important since the aromatic subunits in lignin contain similar moieties.[23] Monitoring the formation of **3a**–**b** and **2a**–**c** over time provided insight into the fate of these primary cleavage products (Figures 3a–d and S1–11). While **3a** and **3b** were stable (Figure 3a,b), aldehydes **2a** and **2c** were consumed rapidly upon formation (Figure 3c,d), due to the instability of **2a**–**c** under cleavage conditions.[24] Accordingly, gas chromatography revealed complex reaction mixtures and side products resulting from aldol condensation (Figures S12–S13). Similar behavior was later observed (vide infra) in the acid-catalyzed depolymerization of lignin, where these fragments lead to the formation of high molecular weight side products. In order to

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

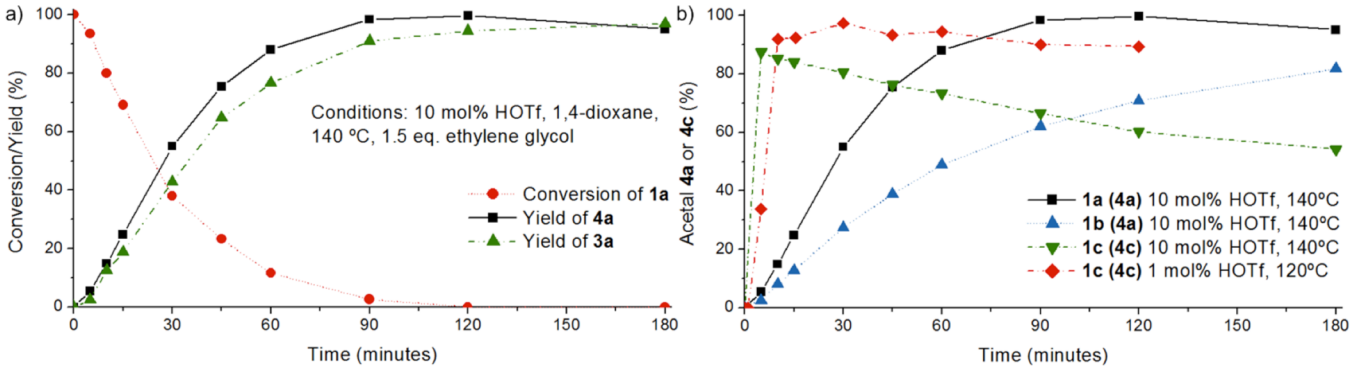


Figure 4. Reaction profiles showing clear effect of 1.5 equiv ethylene glycol in the stabilization of reactive intermediates in the cleavage of **1a** or **1a–c**. (a) Comparable **3a** and **4a** yields and (b) high yields of acetal products (**4a** and **4c**).

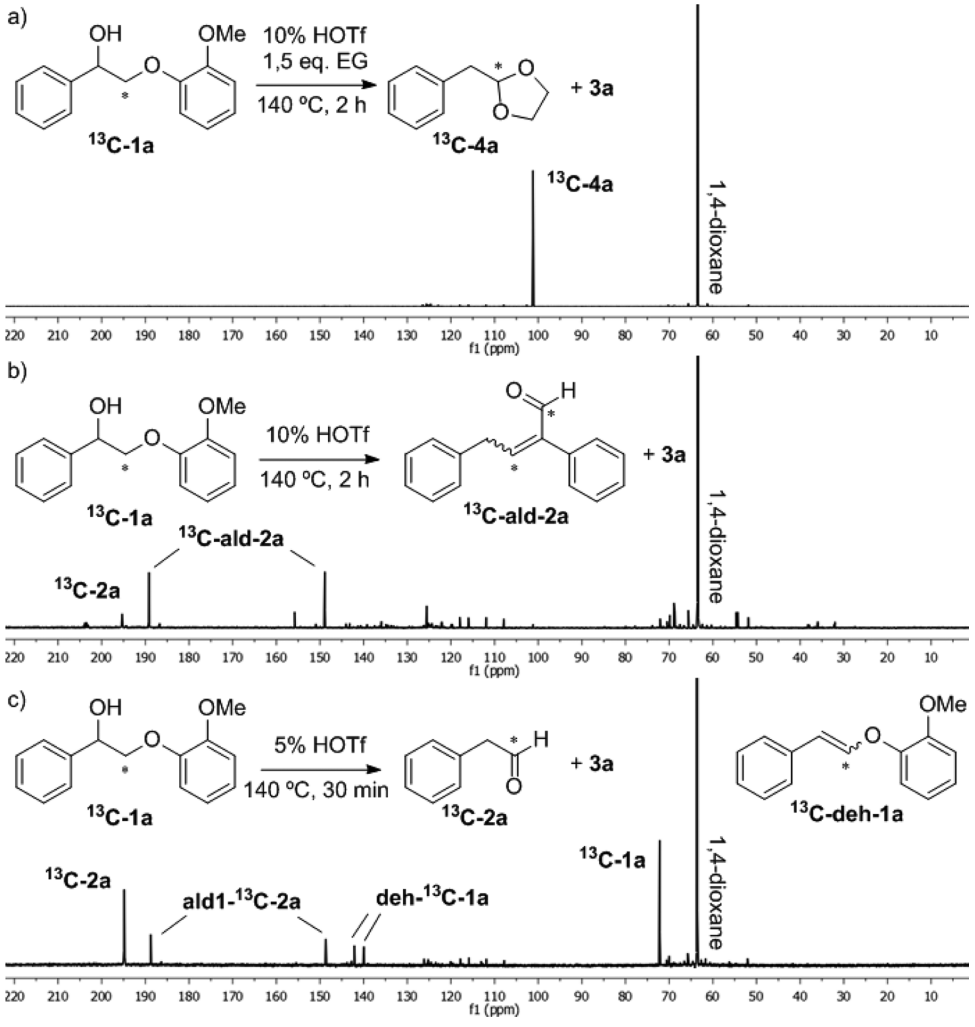


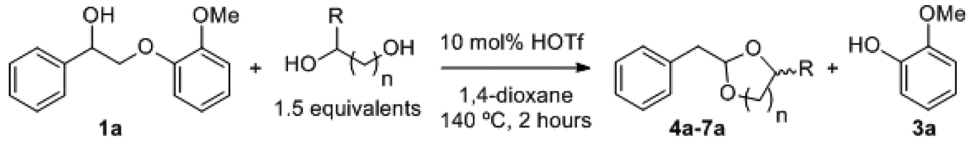
Figure 5. Comparison of ^{13}C NMR spectra of the crude reaction mixtures upon triflic acid-catalyzed cleavage of ^{13}C-labeled lignin β-O-4 model compound **^{13}C-1a** (* = ^{13}C): (a) in the presence of ethylene glycol (EG), (b) without ethylene glycol, and (c) at incomplete conversion.

prevent these undesired processes, several new strategies were developed for the immediate conversion of the unstable aldehydes using methods compatible with the cleavage conditions.

In Situ Conversion of the Aldehyde Intermediates to Acetals. Acetal formation with diols was selected to provide proof of principle for the aldehyde stabilization strategy (Table S3). This reaction itself is acid catalyzed, and the diols, used in stoichiometric amounts, can be derived from the sugar fraction of lignocellulosic biomass[25] or from glycerol, which is the major side product of biodiesel production.[26] Indeed, treatment of **1a–c** with 1.5 equiv of ethylene glycol and triflic acid resulted in excellent yields of the corresponding 1,3-dioxolanes **4a–c** (>90%, Scheme 2, Figure 4a,b). Clean product mixtures were obtained (Figure S21), and a good agreement between guaiacol (**3a**) and acetal (**4a–c**) yields (Figures S14–S19) was observed accordingly. The effect of ethylene glycol on the selectivity was clearly demonstrated using labeled substrate **^{13}C-1a**. Full **^{13}C-**

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

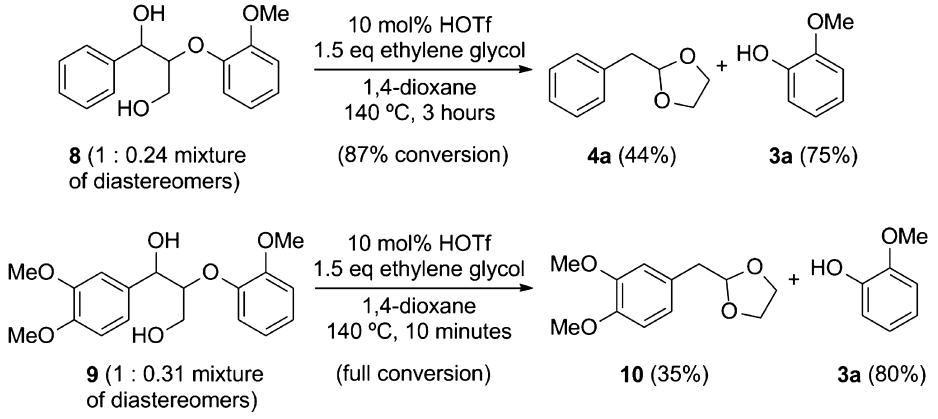
Scheme 3. High Yield, in Situ Acetal Formation with Different Diols upon Triflic Acid-Catalyzed Cleavage of Lignin β-O-4 Model Compound 1a



entry	diol	conversion of **1a**	acetal		acetal yield	yield **3a**
1	HO, OH	100%	Ph, O, O	**4a**	99%	94%
2	HO, OH	98%	Ph, O, O	**5a**	85%	86%
3	OH, HO	90%	Ph, O, O	**6a**	87%[a]	82%
4	OH, HO, OH	100%	Ph, O, O, OH	**7aa**	90%[b]	95%
			Ph, O, O, OH	**7ab**		

[a]1:1 mixture of diastereomers. [b]Near equimolar mixture of regioisomers **7aa** and **7ab** each being a mixture of diastereomers.

Scheme 4. In Situ Acetal Formation with Ethylene Glycol upon Triflic Acid-Catalyzed Cleavage of More Complex Lignin Model Compounds 8 and 9



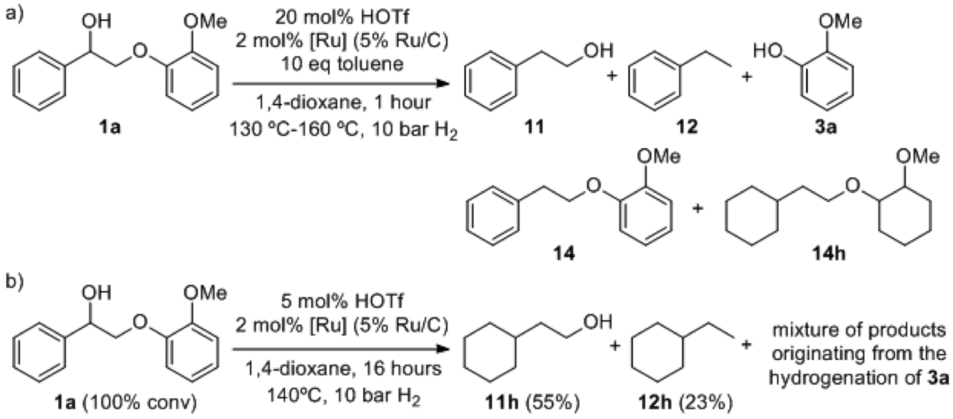
1a conversion and clean formation of ^{13}**C-4a** was seen after 2 h (Figure 5a). However, in the absence of ethylene glycol only using HOTf at 140 °C, aldol condensation products (^{13}**C-ald-2a**) of the formed aldehyde ^{13}**C-2a** were observed (Figure 5b) even at low conversion (Figure 5c).

Substrates **1a**–**c** showed a reactivity trend similar to that observed for the cleavage reactions depicted in Figure 4b, albeit with slightly lower reaction rates (e.g., from 2.8 to 1.6 h^{-1} for **1a**). Notably, only 1 mol % HOTf and 120 °C were sufficient to achieve full conversion of the more labile **1c** within minutes (Figure 4b).

The procedure was generally applicable with a range of diols. Addition of 1,3-propanediol and 1,2-butanediol provided the corresponding 1,3-dioxolane and 1,3-dioxane acetals (**5a**–**6a**) in excellent yields, **6a** being a mixture of diastereomers (Scheme 3). To our surprise, reactions with 1.5 equiv glycerol also resulted in clean mixtures of acetals without side reactions involving glycerol dehydration. A rate very similar to the reaction using ethylene glycol (1.4 h^{-1} to 1.6 h^{-1}) was observed (Figure S19). A near-equimolar mixture of the kinetically favored **7aa** and thermodynamically favored **7ab** was obtained, each being a mixture of two diastereomers.[27] The two distinct **7ab** diastereomers were isolated as single compounds using preparative HPLC, while **7aa** was isolated as a mixture. All four isomers were fully characterized by a combination of 1D and 2D-NMR methods (Supporting Information (SI) section 3.5). Interestingly, it has been shown that glycerol acetals are flavoring agents,[28] and **7aa** and **7ab** are components of hyacinth fragrances.[27] These products contain two different types of

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

Scheme 5. Catalytic in Situ Hydrogenation upon Triflic Acid-Catalyzed Cleavage of Lignin β-O-4 Model Compound 1a to Give Aromatic Products or Cyclic Aliphatic Products



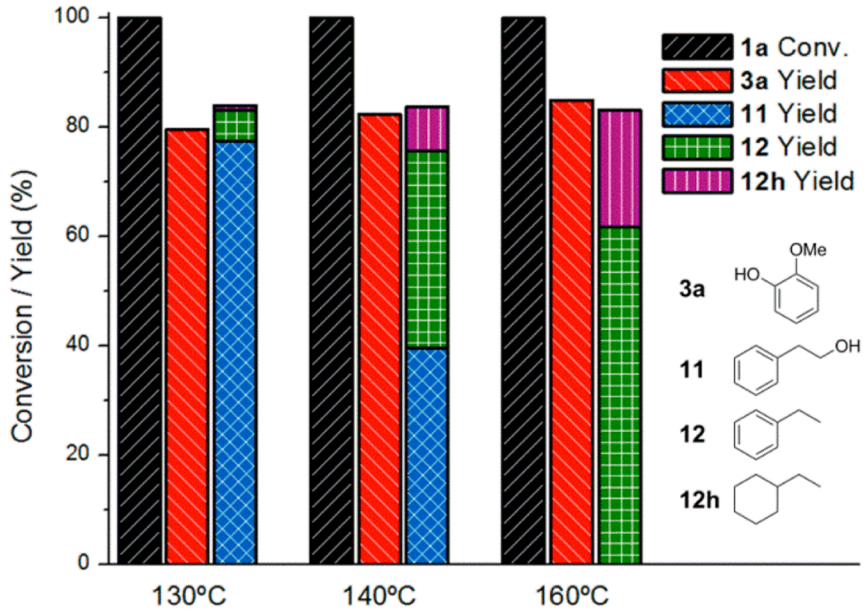


Figure 6. Tunable formation of products **11** and **12**(**h**) upon triflic acid-catalyzed cleavage of β-O-4 model compound **1a** at variable reaction temperatures (Table S4 and conditions shown in Scheme 5).

hydroxyl functionalities and may also find potential application as useful bioderived polymer building blocks.

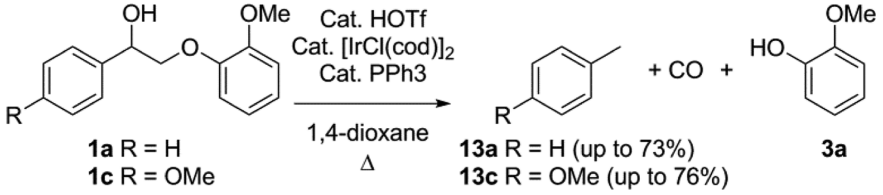
Cleavage of C3-β-O-4 lignin model compounds **8** and **9** (as diastereomeric mixtures as in lignin)[29] in the presence of ethylene glycol provided guaiacol (**3a**) and the corresponding 1,3-dioxolane acetals (Scheme 4). The good, 44% and 35%, yields of **4a** and **10**, respectively, correspond well to Pathway B occurring about 50% of the time giving a C2-fragment.[19a,b] Ketals related to the C3-Hibbert ketones formed via Pathway A were also observed (although were not isolate in pure form). The reactivity trend was similar to that observed for **1a**−**c**, showing full conversion of **9** within minutes and slower cleavage of **8** (Figure S20).

In Situ Catalytic Hydrogenation. Metal-catalyzed approaches were also adapted for aldehyde stabilization to provide desirable simpler aromatics. Key requirements were compatibility with the cleavage conditions and surpassing the rates of aldehyde recondensation. In situ hydrogenation with Ru (5 wt %) on carbon, in conjunction with catalytic amounts of HOTf, was successfully carried out leading to a range of interesting products depending on reaction conditions (Scheme 5). First, the Ru:HOTf ratio was varied to optimize for the highest yield of aromatic products **3a** and **11** (Scheme 5a, Table S4). This balance is delicate, as too much Ru/C led to significant hydrogenation of the early vinyl-ether intermediate[16,19] to form **14** and **14h** that were resistant toward further cleavage.[30] Up to 77% of 2-phenylethanol **11** was obtained at 130 °C (Figure 6). The formation of ethyl-benzene **12** (62%) was favored at 160 °C, with the corresponding ring hydrogenation product **12h** (21%) also detected. At prolonged reaction times, a mixture of fully hydrogenated products containing 55% 2-cyclohexylethanol **11h** and 23% ethyl-cyclohexane **12h** (Scheme 5b) was obtained.

In Situ Catalytic Decarbonylation. Catalytic decarbonylation was selected as a defunctionalization strategy unique to the aldehyde to obtain methyl-aromatics, previously not systematically targeted from lignin. Decarbonylation of aromatic aldehydes has previously been reported using iridium and phosphine ligands in refluxing 1,4-dioxane.[31] Compatibility with the strongly acidic media was first established through extensive screening, using β-O-4 model compound **1a**. Toluene **13a** was obtained in 73% yield at 120 °C using **1a** and 2 mol %

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456−7467

Scheme 6. Catalytic in Situ Decarbonylation upon Triflic Acid-Catalyzed Cleavage of β-O-4 Model Compounds 1a and 1c To Give Toluene 13a and 4-Methylanisole 13c



triflic acid (Scheme 6 and Figure 7). These milder reaction conditions were ideal, as the slow decarbonylation required

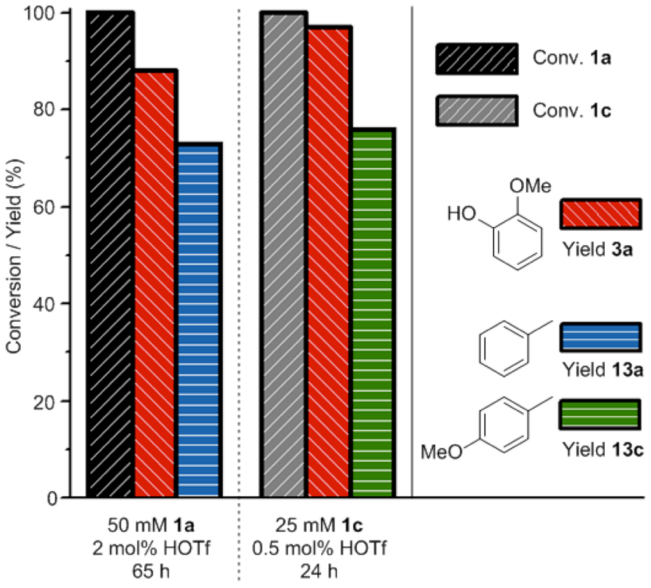


Figure 7. Catalytic decarbonylation of **2a** formed upon triflic acid-catalyzed cleavage of **1a** to obtain toluene **13a**. Reaction conditions: 5 mol % $[IrCl(cod)]_2$, 10 mol % PPh_3, and 120 °C in 1,4-dioxane (Table S5).

slow release of **2a**. A phosphine to iridium ratio of >1.5 was detrimental not only to the decarbonylation[31] but also inhibited the cleavage reaction itself (Table S5). Using more labile **1c** as substrate (Table S6), 4-methylanisole **13c** was obtained in 76% yield with triflic acid loading as low as 0.5 mol %.

Aromatics from Walnut Dioxosolv Lignin. The new catalytic methods relying on the in situ conversion of reactive intermediates during acidolysis developed for model compounds were successfully translated to lignin. Protocols suitable for assessing the result of catalytic treatment were developed, and analysis was carried out by a combination of various methods.

Isolation and Characterization of Walnut Dioxosolv Lignin. Dioxosolv lignin was isolated from walnut shells via established organosolv procedures.[32] A molecular weight average typical for organosolv lignins (M_n = 1290 g mol^{-1}, M_w = 1680 g mol^{-1}, and d = 1.3) was confirmed by GPC analysis (Figure S23). The relative ratios of the main linkages were determined by 2D-HSQC NMR techniques following reported procedures.[6l,11b] Relative quantification of the main linkages provided a β-O-4:β-5:β–β ratio of 0.45:0.36:0.19. The β-O-4 to monomer ratio was 1:3.14 (Figures 8 and S24). These values correspond to a relatively condensed lignin structure, which is likely the result of the extraction conditions. Based on these values, the theoretical maximum monomer yield from this lignin was estimated to be 10 wt % assuming that only the β-O-4 linkages are cleaved and monomeric products are only obtained when two β-O-4 linkages flank a monomer.[11b] Additionally, the 2D-HSQC NMR revealed a H (*p*-hydoxyphenyl):G (guaiacyl):S (syringyl) subunit ratio of 0.29:0.42:0.29, which corresponded well to the H:G:S ratios of product mixtures obtained after catalytic treatment (vide infra).

Methods for Lignin Depolymerization and Fractionation of Products. The three novel strategies for in situ conversion of reactive intermediates were applied to organosolv walnut lignin, and reaction conditions are summarized in Figure 9. A low acid loading (2 wt %) was adopted in all runs to accommodate the increased lability of the β-O-4 linkages in lignin compared to model compounds, due to the higher degree of methoxy substitution. In situ acetal formation (Method B) was performed at 140 °C for 4 h. Catalytic hydrogenation (Method D) and decarbonylation (Method E) were carried out at 120 °C for 24 h. Corresponding control reactions (Methods A and C) were carried out with only triflic acid.

The two main aspects of the product analysis focused on determining the amounts of insoluble material generated by recondensation reactions and the types and quantities of aromatic monomers formed. To this end, a suitable fractionation procedure was developed to separate products belonging to different molecular weight ranges (fractions 1–3, Figure 9). While fraction 1 represented the dark-brown insoluble material directly related to recondensation reactions, fraction 3 contained the desired low molecular weight products and fraction 2 comprised of higher M_w, dioxane soluble material (for details of GPC analyses see Figures S27 and S28).

Suppressing Recondensation Phenomena. The dry weight analysis of the different fractions (1–3), summarized in Figure 10, allowed us to compare Methods A–E and validated our approach for the stabilization of reactive intermediates during acidolysis. Ideally, a product mixture consists entirely of fractions 3, and the amount of fraction 1 is minimal. The control reactions (Methods A and C) using only acid contained significant amounts of insoluble material (fraction 1), as expected (44% and 64%, respectively). This amount was markedly reduced to 9% for acetal formation (Method B) and 4% under hydrogenation conditions (Method D). A decrease from 64% to 34% was seen under decarbonylation conditions (Method E). The expected significant increase in the weights of the corresponding low molecular weight fractions was observed accordingly especially for Methods B and D. In these cases, fraction 3 made up 27% and 37% of the product mixtures. Dioxane solubles (fraction 2) were the largest fraction of the samples obtained upon stabilization strategies (Methods B, D, and E), while in the corresponding control reactions (Methods A and C), clearly the solids (fraction 1), were the major

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

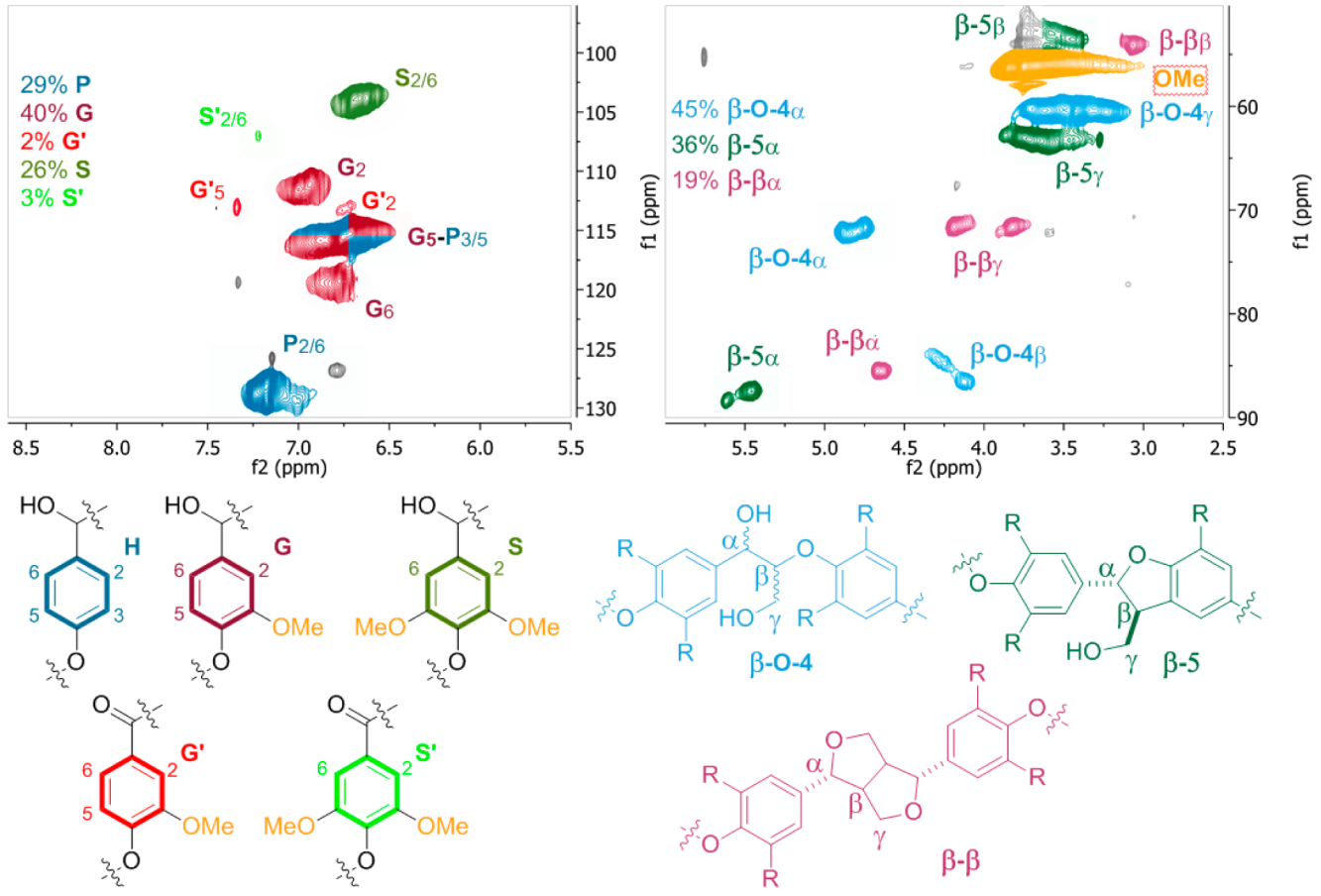


Figure 8. Assignment and quantification of linkages and monomeric units of walnut dioxosolv lignin by 2D-HSQC NMR (DMSO-d_6).

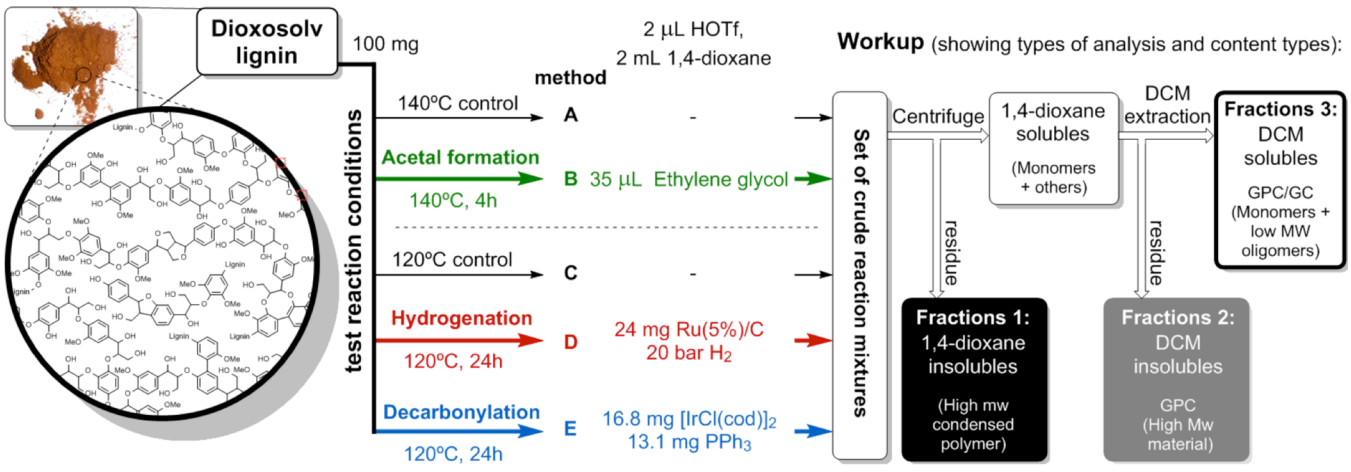


Figure 9. Reaction conditions for depolymerization of dioxosolv walnut lignin using Methods A–E (left). Scheme representing the workup procedure to obtain fractions 1–3 (right).

products (for more details regarding the fractionation procedures see SI, section 4.4.1).

Monomer Yields. In-depth analysis was performed for all fraction 3 samples, obtained in Methods A–E using GC-FID and GC-MS (Figures S26–S30). For details of the analysis see SI sections 4.4.2–4.4.5. Products from lignin depolymerization consisted of mainly aromatic monomers, dimers, and a few low M_w oligomers. The results of quantification are presented in Table 1 and Figure 11. Methods B and D clearly delivered more monomer yields than the corresponding control reactions (6.4 and 6.8 mg, respectively). In addition, the total low molecular weight products were 9.1 (Method B) and 16.2 mg (Method D). These results represent 60% and 80% of the theoretical maximum monomer yields for Methods B and D, respectively, calculated based on previously established methods[6l,11b] for the applied lignin source (vide supra, see also SI, section 4.2), adjusted according to a method used for the calculation of monomer yields (see SI, pages S36 and S37). Thus, the applied methodologies, especially acetal formation and hydrogenation, have the potential to deliver monomer yields close to

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

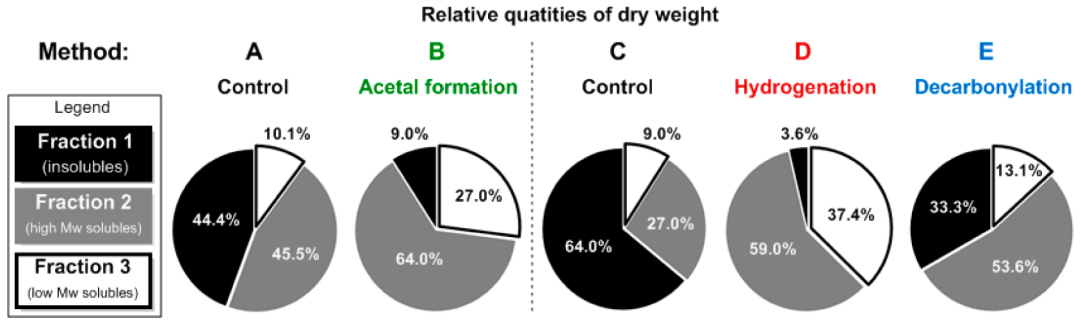


Figure 10. Dry weight analysis of the different fractions obtained from lignin depolymerization experiments (Tables S7 and S8). The values are derived from masses of crude fractions determined by weighing the solid residues upon solvent evaporation and drying.

Table 1. Distribution of Monomeric and Dimeric Products in Fraction 3 for Methods A–E Determined by GC-FID Analysis

	products in fraction 3 (in mg)[b]		
method[a]	total	monomers	dimer (+ higher)
A (control)	5.4	2.0	3.4
B (acetal formation)	9.1	6.4	2.7
C (control)	5.7	1.3	4.4
D (hydrogenation)	16.2	6.8	9.4
E (decarbonylation)	3	2.0	1.0

[a]For reaction conditions related to these methods see Figure 9 and SI, section 4.3. [b]Values obtained by integration of GC-FID traces, using *n*-octadecane as internal standard. The amounts refer to products derived from 100 mg starting lignin. Note that this quantification only includes products of lignin origin, quantifiable by GC-FID and GC-MS. For more information on details of quantification see SI, section 4.4.

theoretically expected values. The obtained yields are in agreement with other recently developed, mild β-O-4 cleavage methodologies.[9,33] Other methods are also known, especially those using special lignin sources[10,11a] or higher temperatures[5,34] that afford higher monomer yields. We expect that the strategies described in this paper will be generally applicable to a broader range of lignins with sufficient β-O-4 content. Especially CEL lignins[10a] with high β-O-4 content should lead to increased monomer yields.

Distinct Classes of Aromatic Monomers from Lignin. One of the most crucial questions was whether the different Methods A–E would deliver the types of monomers, determined by model studies. The products were identified to a large extent (>90%) by GC-MS (all details in Tables S10–S14). The corresponding product mixtures were analyzed according to several key descriptors, which are summarized in Figure 11. These analyses showed excellent agreement between the lignin and the model studies considering products formed via C2-pathways. It should also be noted that products derived from lignin also included compounds formed through C3-pathways, as expected.

This finding, together with the marked reduction of high molecular weight solids (fraction 1) and the GC-MS and ^{13}C NMR studies using model compounds, indicates a central role of these unstable C2-aldehyde fragments in recondensation. However, it should be noted, that the C2-aldehyde-intermediates might not be the only source of recondensation reactions. The in situ stabilization strategies (Methods B, D, E) may also stabilize other unstable reaction intermediates. More extensive mechanistic insight is needed, and studies are underway in our laboratories.

The acetal formation methodology (Method B) clearly showed excellent selectivity toward the expected products, as 79% of all identified monomeric products were C2-acetals (Figure 12), which corresponded to an overall yield of 5 wt % from dioxosolv lignin (Figure 11b). Ketals formed by ethylene glycol, of the expected C3-Hibbert ketones, were also observed. These reactions were successfully upscaled, and the corresponding acetals **A1** and **A2** were isolated as single compounds by column chromatography from beech ethanosolv lignin in 2.0 wt % (39 mg) and 2.6 wt % (53 mg) yields, respectively (See SI section 5), in accordance with the values determined by GC-FID for walnut lignin.

Catalytic hydrogenation (Method D) provided substantial amounts of phenolic C2-fragments (44%), the expected ethyl and ethanol-substituted aromatics[34b,35] being the main C2-products. While 4-ethylphenol was the major product for the phenolic subunits, 2-(4-guaiacyl)-ethanol is a major product for the guaiacol subunit (see Figure S32). Additionally, propyl-phenolics were found, originating from the analogous hydrogenation of the C3-cleavage intermediates formed through Pathway A.[7d–g,30,34b,36] Overreduction of the aromatic rings was not significant (8%).

Catalytic decarbonylation (Method E) led to lower overall quantities of monomeric aromatic products, however, the corresponding product mixture showed agreement with the used methodology (Figure S33). C1-phenolics (35%) arise from decarbonylation of the C2-aldehyde intermediate. The C0-phenolics (15%, phenol, guaiacol and syringol) are likely products of decarbonylation of the corresponding C1-vanillin-type aldehydes that are known products during acid-catalyzed lignin depolymerization. These results indicate that decarbonylation is a promising strategy to access C1 aromatics from lignin, and future research should focus on the development of more active decarbonylation catalysts.

The control reactions (Methods A and C) provided mainly C3-monomers (Hibbert ketones) typical for acid-catalyzed lignin depolymerization (Figures S11a, S29, and S31),[15,16] and as expected, monomer quantities were low due to the severe recondensation processes.

The in situ conversion of the C2-adehyde fragment using Methods B, D, and E is a remarkably efficient method for obtaining distinctly different aromatics from lignin.

■ CONCLUSION

For economically viable establishment of biorefineries, valorization of lignin is essential. To this end, new methods are

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

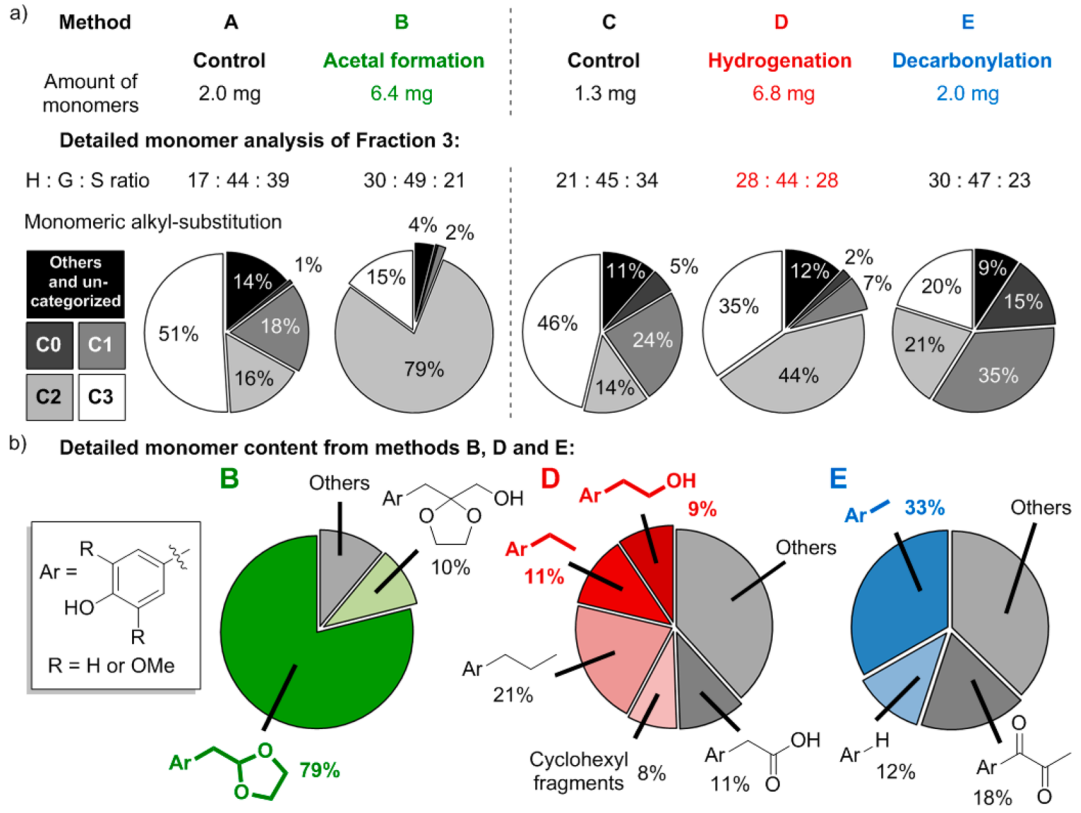


Figure 11. GC(FID/MS) analysis of fraction 3 obtained in the different Methods A–E showing: (a) distribution of alkyl chain lengths (C0–C3) within the product mixtures as well as H:G:S ratios and (b) major products in fraction 3, corresponding to the stabilization strategies (Methods B, D, and E, percentages are based on the total weight of lignin monomeric products identified by GC-MS).

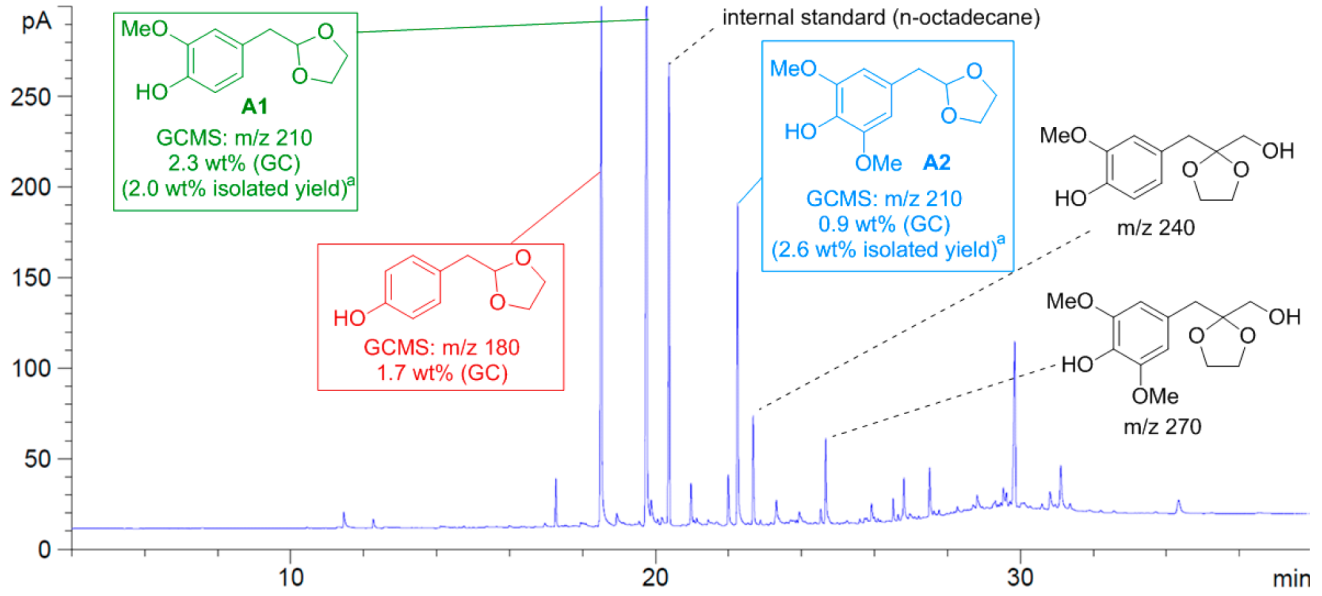


Figure 12. GC-FID trace of a typical crude product mixture from depolymerization of walnut dioxosolv lignin using Method B. Identification based on GC-MS data of major peaks is shown (full peak overview in Table S11). Isolated from an upscaled reaction using 2 g beech organosolv lignin (see SI, section 5).

desired that depolymerize lignin in a sufficiently controlled manner so that the isolation of single compounds can be achieved. Here we present a novel approach to catalytic lignin depolymerization. Our key innovation is the in situ conversion of the reactive C2-aldehyde fragments (**C2-aldehyde**), formed during acid-catalyzed depolymerization of lignin. This novel approach markedly suppresses the formation of high molecular weight side products and leads to three distinct classes of aromatic compounds upon acidolysis of lignin depending on the methodology used. This represents an important step toward extending the available pool of possible lignin-derived fine chemicals,[1c] especially since aldehydes can also be obtained

DOI: 10.1021/jacs.5b03693
J. Am. Chem. Soc. 2015, 137, 7456–7467

by other catalytic routes.[1a,2a,6k] Future research will focus on in-depth mechanistic understanding of lignin conversion pathways and the precise role of reaction intermediates in order to maximize the amount of monomeric products.

■ ASSOCIATED CONTENT

Supporting Information

Details on the materials and methods (section 1), synthesis of the model compounds (section 2), procedures and additional data on the cleavage of β-O-4 model compounds (section 3) as well as on the depolymerization of walnut dioxosolv lignin (section 4), and isolation of acetals from beech ethanosolv lignin (section 5). The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.5b03693.

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Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

The authors gratefully acknowledge financial support from the European Commission (SuBiCat Initial Training Network, Call FP7-PEOPLE-2013-ITN, grant no. 607044) as well as T. Yan, A. Narani, and B. Oldenburger (Rijkuniversiteit Groningen) for their contribution to the synthesis of model compounds and development of lignin isolation procedures.

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