

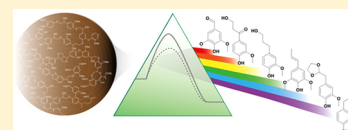
Bright Side of Lignin Depolymerization: Toward New Platform Chemicals

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S Supporting Information

ABSTRACT: Lignin, a major component of lignocellulose, is the largest source of aromatic building blocks on the planet and harbors great potential to serve as starting material for the production of biobased products. Despite the initial challenges associated with the robust and irregular structure of lignin, the valorization of this intriguing aromatic biopolymer has come a long way: recently, many creative strategies emerged that deliver defined products via catalytic or biocatalytic depolymerization in good yields. The purpose of this review is to provide insight into these novel approaches and the potential application of such emerging new structures for the synthesis of biobased polymers or pharmacologically active molecules. Existing strategies for functionalization or defunctionalization of lignin-based compounds are also summarized. Following the whole value chain from raw lignocellulose through depolymerization to application whenever possible, specific lignin-based compounds emerge that could be in the future considered as potential lignin-derived platform chemicals.



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1. INTRODUCTION

Living with limited resources on the planet represents a tremendous challenge due to our increasing global population.¹ The growing demand for fuels and chemicals and the society's dependence on nonrenewable petroleum should be addressed simultaneously through the development of sustainable technologies that would enable the efficient utilization of renewable resources.^{2–5} Such an attractive, carbon-neutral and nonedible starting material is lignocellulose, generated in considerable quantities from forestry and agricultural activity worldwide.^{5,6} Moreover, food waste has been put forward as an economically significant, lignocellulose-rich resource.⁷ In the past decade, significant advances have been achieved regarding the development of biorefineries suitable for the fractionation of lignocellulose to its main constituents: cellulose, hemicellulose, and lignin.^{8–10} However, in order to create economically feasible biorefineries and overcome the initial energy cost associated with processing and pretreatment, all three major constituents should be fully valorized.^{7–10} Novel chemo- or biocatalytic routes should enable the conversion of these biobased starting materials to chemicals and fuels. In this regard, the catalytic conversion of lignin was found extremely challenging,¹¹ mainly due to the robustness and complexity of its structure.^{12–14}

Despite these encountered challenges, the catalytic conversion of lignin has remained a scientifically intriguing research problem

that can bring clear rewards.¹⁵ Lignin is the largest renewable source of aromatic building blocks in nature and has significant potential to serve as starting material for the production of bulk or functionalized aromatic compounds to offer suitable alternatives to the universally used, petroleum-derived BTX (benzene, toluene, and xylene).^{11,16}

The quest for novel catalytic methods and lignin-derived platform chemicals^{17,18} initiated tremendous activity in fundamental research, especially in the past decade. Creative approaches in many fields such as homogeneous catalysis,^{19–22} heterogeneous catalysis,^{11,23,24} or alternative solvents²⁵ have emerged and were extensively reviewed. Furthermore, recent reviews have summarized recent progress regarding thermochemical,^{26–30} oxidative,^{31,32} photocatalytic,³³ or biochemical^{34,35} depolymerization methods that focused on conversion of lignin to various product classes.

In order to solve one of the greatest challenges, which is to deliver high product yields in an energy- and material efficient manner, integrated biorefinery approaches that bridge multiple disciplines are desired.^{36,37} It has been shown that the native structure of lignin should be as regular as possible, which opens possibilities for modification of lignin biosynthesis pathways.^{37,38} The selection of suitable processing conditions during lignocellulose fractionation has proven crucial, since fractionation methods may significantly alter the native lignin structure, frequently producing extremely refractory lignin streams.^{39,40} It became clear, that the development of efficient catalytic methods for lignin depolymerization will play a central role in lignin valorization. Several promising catalytic methods have been developed, especially in recent years, and in many cases, the new methods delivered surprising new product structures in significant amounts.^{37,40,41} Recent research has been devoted to the valorization of these structures, as well as other potential lignin-derived monomers, especially for the production of new lignin-based polymers.

The core of this review (section 2) summarizes the recent advances in chemical catalysis regarding the conversion of lignin to product mixtures that consist of a limited number of low molecular weight products in high yield, under 250 °C, and the lignin isolation methodologies used by the various research groups are compared. Where discussion requires, processes in the range of 250–300 °C are also included. In section 3, the possibilities for functionalization and defunctionalization of frequently encountered lignin-derived scaffolds are summarized. Section 4 provides an overview of the recently described applications of lignin-derived compounds for the production of biobased polymers and the properties of such polymers. In section 5, structures of known pharmaceutically active compounds that can be obtained from some of the monomers provided by the novel lignin depolymerization strategies are summarized along with existing synthetic routes.

Thus, this review gives an overview of existing value chains starting from the raw lignocellulose through catalytic lignin depolymerization to potential final application of lignin-based monomers and bridges heterogeneous and homogeneous catalytic or synthetic routes. Several structures may be, in the future, evaluated with respect to serving as “lignin-derived platform chemicals”.

1.1. General Considerations

Lignin depolymerization is an intriguing task that is challenged by the structural complexity and recalcitrance of this aromatic biopolymer, which is randomly held together by strong C–C and

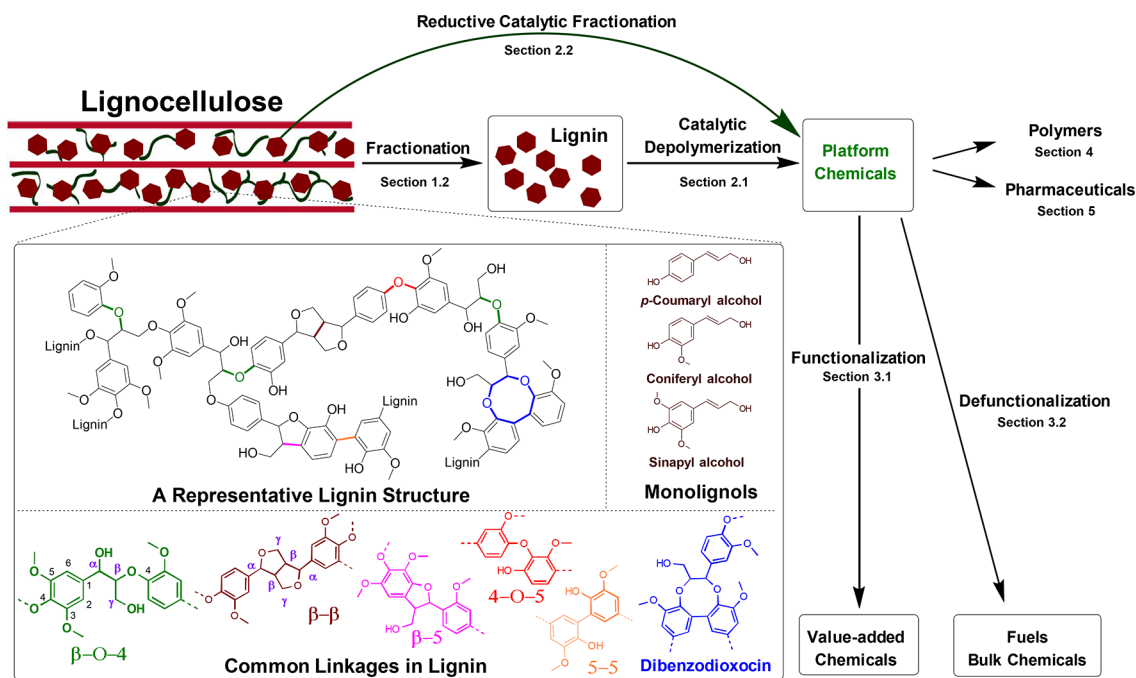


Figure 1. (Left) A representative lignin structure displaying typical lignin subunits and linkages encountered. (Right) General strategies for depolymerization of lignin and application of lignin-derived platform chemicals.

C–O bonds.²¹ Several types of linkages exist in lignin, and their type and ratio is dependent on the plant source.¹⁵ The most common linkages are shown in Figure 1. Systematic theoretical studies by Beckham determined the bond dissociation energies of the most representative lignin linkages.⁴² The most recurring type is the β -O-4 linkage that typically makes up about 50% of all linkages and therefore has been the focus of most depolymerization strategies. The cleavage of this linkage takes between 68.2 and 71.8 kcal/mol, depending on substitution pattern. Any sustainable methodology aiming for lignin depolymerization should deliver specific (preferably) aromatic compounds in high enough yield and selectivity to allow separation and subsequent valorization to well-defined products. Since the β -O-4 linkage is most abundant, the vast majority of catalytic methods focus on the scission of the C–O linkage in this moiety in order to affect depolymerization.

1.2. Fractionation

1.2.1. Considerations Regarding Lignocellulose Pre-treatment. Several methods are available for the isolation of lignin from lignocellulosic biomass. The existing strategies can be divided into two main categories related to the extent of structural modification induced in lignin by the fractionation conditions, an important aspect when considering catalytic valorization of any lignin feed.

One major source of lignin is provided by the pulp and paper industry that produces roughly 50 million tons of lignin annually, of which less than 2% is actually recovered for utilization as a chemical product.⁴³ However, the money equivalent of lignin used as fuel is estimated to be 0.18 US \$/kg while 1.08 US \$/kg in case it is converted to useful chemicals.⁴⁴ Thus, the importance of concentrating on the latter approach appears clear.

The second main lignin source is related to the production of cellulosic ethanol, which was estimated to make up 125 million liters for the year 2013 in the USA alone, and its volume is expected to grow. With every liter of produced ethanol 0.5–1.5

kg of lignin is cogenerated; however, it is still generally considered as waste and burned to produce energy.⁴⁵

Techno-economic analysis of lignocellulose-based biorefineries was recently described.^{46–54} In several cases, lignin was treated as waste or burnt for energy recovery;^{49,52} however, more favorable carbon yields were found when lignin was valorized by hydrotreating, (hydro)pyrolysis, or gasification.^{46–48}

Foust and Aden carried out a detailed techno-economic analysis of an ethanol biorefinery that operates based on cornstover (18% lignin content) with a 2000 dry tones/day capacity.⁵⁰ From one ton of cornstover, 340 L of ethanol was produced while the lignin byproduct was converted to 1.64 tons of steam and 326 kWh electricity of which 40% was used on the spot and 60% was sold for the grid. Besides sustaining the energy demand of the plant, 26.7\$ worth of steam⁵⁵ and 13\$ worth of electricity was generated next to the primary product bioethanol. However, it was concluded that if the energy demand of the process would be covered from other renewable resources such as wind or tidal energy, the lignin content could be utilized to produce chemicals, which hold more added value.

The summary report for biochemical ethanol production in 2013 and biochemical hydrocarbon production report in 2015 completed by the National Renewable Energy Laboratory with the Harris Group Inc., proposed improvements to already existing procedures in order to achieve the 2022 DOE target of 3\$/gallon gasoline equivalent (GGE).^{56,57} An important recommendation was to maximize the overall carbon efficiency by converting currently underutilized lignocellulose fractions, such as lignin. Four specific chemicals: 1,3-butadiene, 1,4-butanediol, cyclohexane, and adipic acid were suggested as potential valuable lignin-derived products with sufficient market volumes (greater than 1 MM tons/year world market). On the basis of a minimum fuel selling price (MFSP) of \$5.10/GGE, the targeted \$3/GGE can be achieved if 60–80% of available lignin is converted to coproducts adipic acid and 1,4-butanediol.

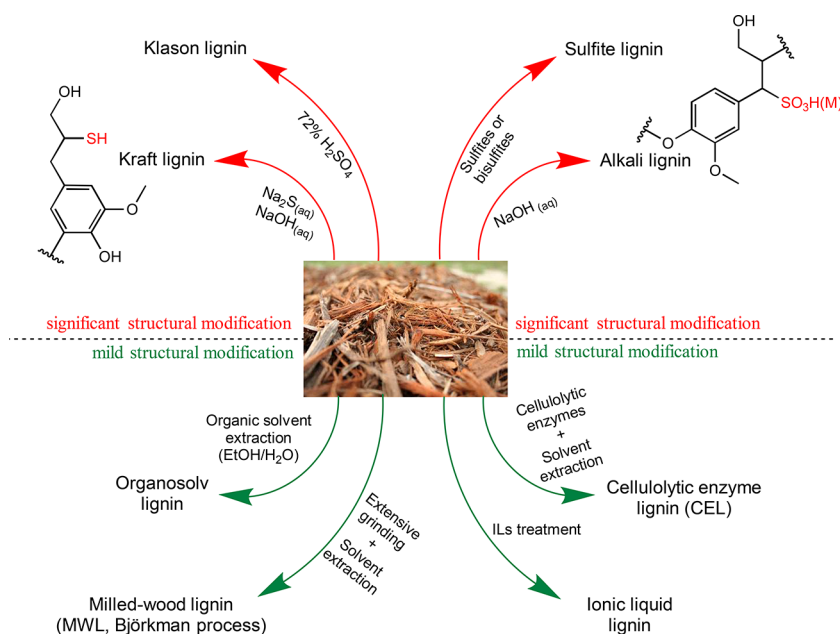


Figure 2. A summary of procedures for isolation of lignin from lignocellulose.

From the statements above, it is clear that in order to guarantee the economic feasibility of biorefinery processes, every lignocellulose component should be fully valorized,^{58,59} and therefore it is of paramount importance to find novel ways of lignin valorization.^{5,10,37,43} Before providing a detailed description of such new catalytic methods (section 2), we will give a short summary of the most important lignin isolation procedures used on the industrial and laboratory scale. This reviews the various lignin sources that can be used as starting materials in subsequent catalytic conversions.

1.2.2. Methods Resulting in Significant Structural Modification. Pulping methods such as the Kraft,^{60,61} the Sulfite,^{39,62} the Alkaline,⁶³ and the Klason^{64,65} process (Figure 2) generally focus on obtaining high quality cellulose from lignocellulose and result in structurally heavily modified lignins under relatively harsh processing conditions such as the extensive use of inorganic salts, base, or acid.^{66,67} For instance, Kraft lignin is modified by cleavage of most α -aryl ether and β -aryl ether bonds⁶¹ and in addition to recondensation reactions, the system is attacked by strongly nucleophilic hydrogen sulfide ions, leading to a sulfur-enriched structure (1.5–3% sulfur). The presence of sulfur poses an additional difficulty to catalyst development since it frequently leads to decreased activity of, especially, noble metal catalysts. Due to its abundance, there is increasing interest to develop novel catalytic methods for the efficient valorization methods of Kraft lignin to valuable chemicals^{12,68,69} and fuels.⁷⁰ In this review, we do not focus on Kraft lignin depolymerization, since these novel approaches usually result in more complex product mixtures.²⁹

Similarly to Kraft, sulfite lignin is also characterized by the incorporation of about 4–8% of sulfur, albeit in the form of sulfonate groups, providing water-soluble lignin. As a result, catalytic depolymerization of lignosulfonate to aromatics without it being negatively affected by sulfur is a challenging task. A promising solution is the catalytic removal of sulfur from the reaction system in the form of H₂S gas, as proposed by Song and co-workers with heterogeneous Ni catalysts.⁷¹ The Klason process that employs 72% sulfuric acid causes a significant damage to the native lignin structure, while the soda pulping

process presents structural modification to a lesser extent compared to the other technical lignins allowing for catalytic conversion, as reviewed recently.²⁴

1.2.3. Methods Resulting in Mild Structural Modification. *Björkman Process.* The Björkman process involves extensive grinding followed by extraction of lignin with an organic/aqueous solvent (usually dioxane/water 96/4 v/v for 24 h) to produce the so-called milled-wood lignin (MWL). This lignin has a more similar structure to native lignin due to the pH neutral and mild conditions used during extraction. However, the milling process can cause structural modification such as the presence of additional carbonyl and hydroxyl groups, especially in hardwood.⁷² The obtained lignin yields, typically 20–40%, depend on the raw material used.⁶²

Cellulolytic Enzyme Lignin and Enzymatic Mild Acidolysis Lignin (EMAL). The procedure to obtain cellulolytic enzyme lignin (CEL) involves the treatment of the finely ground wood with cellulolytic enzymes, which cause the partial hydrolysis of cellulose and hemicellulose. Afterward, the residue is extracted with a solvent (typically dioxane/water), the solution is concentrated, and lignin precipitated in water. This procedure typically requires a few days and leads to protein and carbohydrates impurities. An improvement is represented by enzymatic mild acidolysis lignin (EMAL), where the enzymatic treatment is combined with mild acidolysis of biomass.⁷³ This procedure is reported to offer gravimetric lignin yields 2–5 times greater than those of the corresponding MWL and CEL.⁷⁴ Interestingly, Guerra et al.⁷⁴ then investigated the differences in the lignins obtained by MWL, CEL, and EMAL treatment,⁷⁵ employing several raw materials and showed that EMAL is characterized by a highest molecular weight ($M_n \sim 30000$ – 63000 g/mol) followed by CEL ($M_n \sim 17000$ – 30000 g/mol) and MWL being the lowest value ($M_n \sim 6000$ – 16000 g/mol).

Ionic Liquid Treatment. It has to be mentioned that ionic liquids (IL) have also been proposed as solvents for lignocellulose fractionation due to their special and highly tunable solvent properties.^{25,76–82} Limitations exist related to the cost of IL as well as ease of product separation and solvent recyclability. Interestingly, George et al.⁸⁰ reported the synthesis

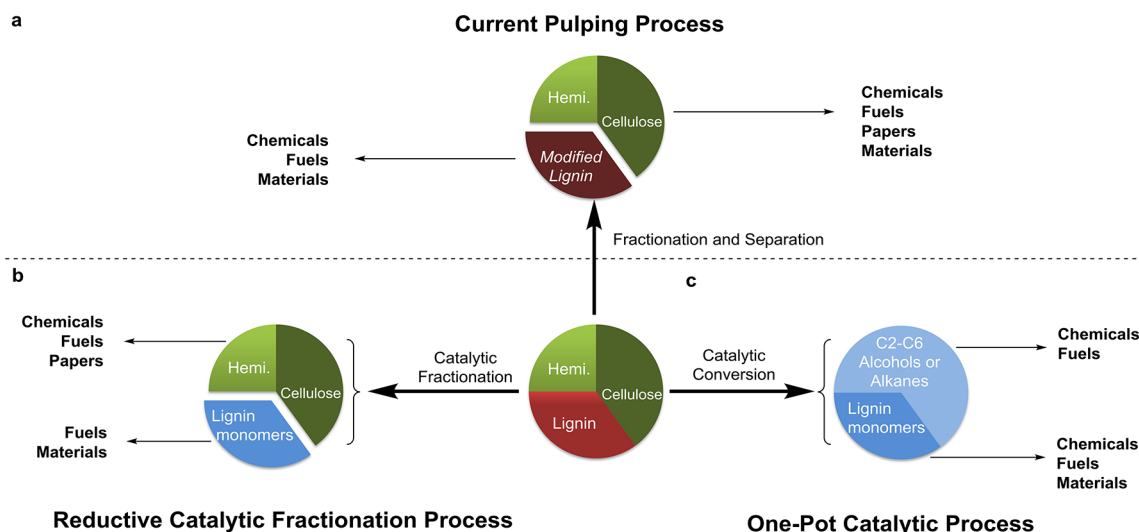


Figure 3. Types of starting materials used for the development of novel catalytic methods targeting high yield production of aromatics from lignin. (a) Isolation of lignin by lignocellulose fractionation prior to catalytic processing. (b) Reductive catalytic fractionation (RCF) using lignocellulose in the presence of a catalyst. (c) Complete conversion of all lignocellulose components by one-pot catalytic processing.

of several ethylammonium sulfate ILs resulting in efficient delignification without significant reduction of cellulose crystallinity. In addition, a production cost close to conventional organic solvents was shown. Furthermore, ILs can act as reaction media for lignin dissolution and depolymerization due to the incorporation of acidic or other catalytic properties.^{83–87}

Organosolv Process. Organosolv lignin originates from treatment of lignocellulose with organic solvents such as ethanol, acetic acid, methanol alone, or mixed with water at 140–220 °C.⁸⁸ This delignification method is known to be more environmentally friendly compared to Kraft or sulphite lignin, especially when performed without added acid. The most well-known example is the Alcell process where a mixture of EtOH/water (1:1) is employed as the cooking medium at 175–195 °C for 1 h, enabling the dissolution of lignin and producing furfural as a byproduct.⁸⁹ Several variations have been reported, mainly in order to improve the yield of lignin, involving different solvent mixtures (including glycerol,⁹⁰ THF,^{91–93} MeTHF,⁹⁴ and GVL⁹⁵) and several catalysts (oxalic acid,⁹⁴ HCl,⁹⁶ Lewis acids,⁹⁷ metal chlorides,⁹⁸ and ammonia⁹⁹), indicating varying efficiencies.^{39,100} Typically, cleavage of the β -O-4 linkages occurs to a lesser extent compared to technical lignins, leading to a more natively like structure, and the recovered materials are characterized by molecular weights (M_n) typically between 500 and 5000 g/mol^{101–103} and good solubility in polar organic solvents.¹⁸ However, organosolv processing does lead to partial degradation of the native structure and some decrease in the fraction of β -O-4 linkages, the extent of which depends on the plant source and specific reaction parameters used.¹⁰⁴

However, the presence of repolymerization reactions and the formation of stable C–C linkages during organosolv processing is still inevitable, especially when a small amount of acid¹⁰⁵ is introduced to the system. The recent review of Rinaldi et al.³⁷ discusses several aspects of the influence of pulping conditions on the structure of resulting lignins in great detail. For instance, the gradual structural changes observable by HSQC NMR spectroscopy in acetolysis lignin upon low-, mild- and high-severity conditions are described. It was concluded that mild processing conditions (110 °C, no H₂SO₄, 15 min) produce natively like lignin structure, while more severe conditions (160 °C,

0.6% H₂SO₄, 45 min) result in completely modified lignin structure, in which, besides the –OCH₃ and general aromatic signals, no beta-ethers are left. Another excellent way to provide a more quantitative description of the extent of structural modifications is to compare lignins originating from the same lignocellulose source but via a different treatment method by subjecting them to the same catalytic treatment conditions.³⁷ The yield of aromatic monomers thus obtained would correlate with the content of cleavable β -O-4 linkages (assuming that the catalytic methodology targets these linkages). The influence of processing conditions on the aromatic monomer yields obtained via acidolysis in conjunction with stabilization of reactive intermediates with ethylene glycol to produce C2 acetals (see also section 2) was also studied by Deuss, Barta, and co-workers.¹⁰¹ It was confirmed that the highest monomer yields were obtained from lignins that were obtained by mild organosolv methods.

The addition of formaldehyde during organosolv processing as was reported recently by Luterbacher and co-workers (see section 2)¹⁰⁵ is an excellent approach to avoid repolymerization.

Thus far, specific methods of general applicability have not been developed, and the groups working on the development of novel catalytic methods typically reported on specific organosolv procedures prior to catalytic treatment (Figure 2). Indeed, structural modification during pretreatment is one of the greatest challenges in catalytic lignin valorization since the β -O-4 linkages are required for efficient depolymerization with the catalytic methods currently available. Therefore, the formation of more robust C–C bonds causes low efficiency of depolymerization and decreases monomer yields.

1.3. Types of Starting Materials

Generally, the catalytic methods targeting lignin depolymerization can be divided into three categories as illustrated in Figure 3 according to the nature of the starting material used for catalytic processing. Most research has focused on the conversion of lignin streams that were first isolated from the lignocellulose matrix usually by “organosolv processing”. A large quantity of similar lignin wastes can also be generated by the wood pulping process¹⁰⁶ or cellulosic ethanol production, however, as described in section 1.2, where both will result in lignins with

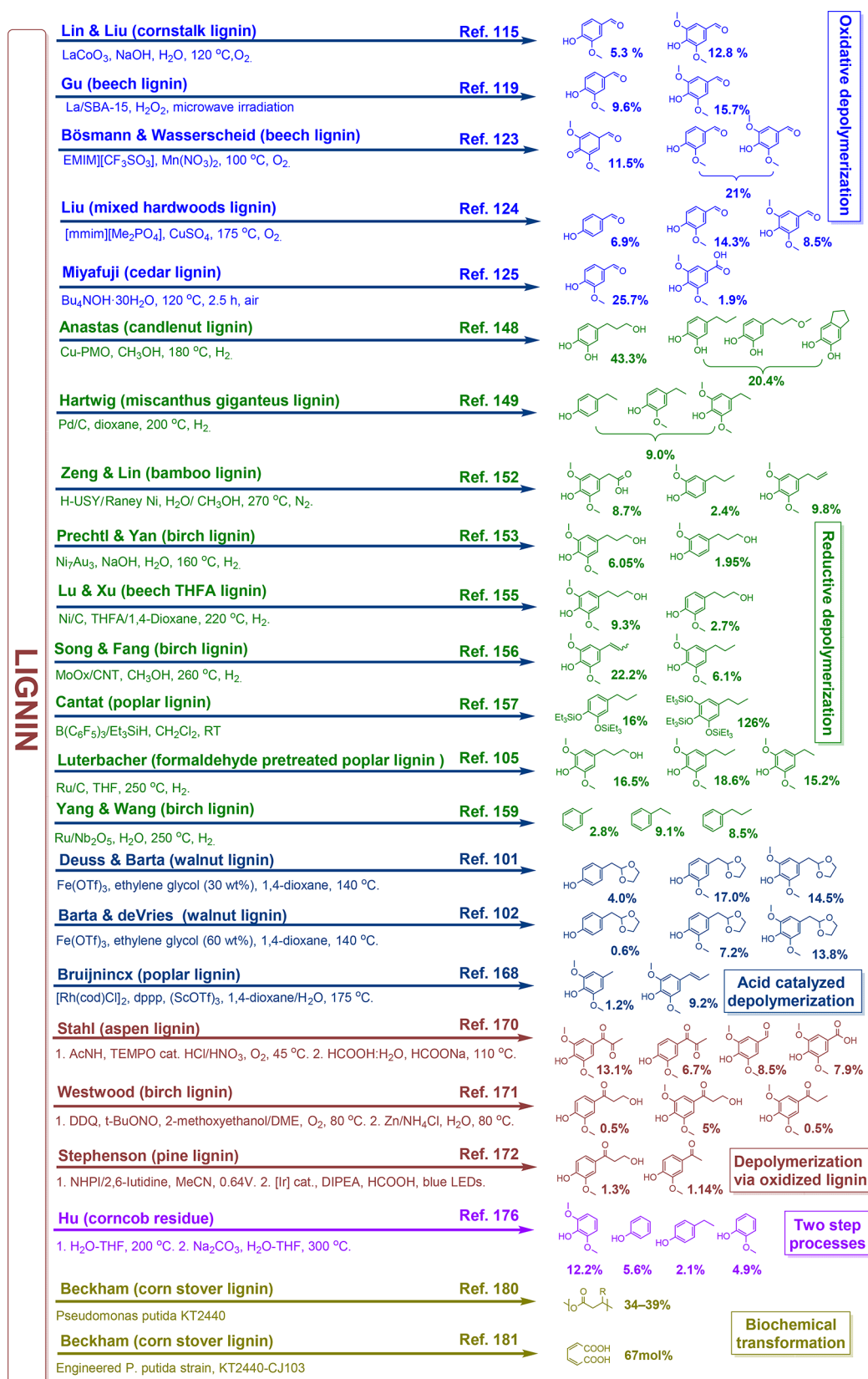


Figure 4. Strategies and yields of main products established for the depolymerization of lignins isolated from lignocellulose prior to catalytic treatment.

different degree of structural modification depending on the lignocellulose fractionation conditions.^{37,101,107} Since the structure of lignin directly effects the monomer yield obtained,^{101,105} novel methods enabling reductive catalytic

fractionation (RCF) have recently emerged as promising alternative technologies (see section 2.2). These methods involve the extraction and immediate catalytic conversion of lignin to monomers in a one-pot process applying lignocellulose

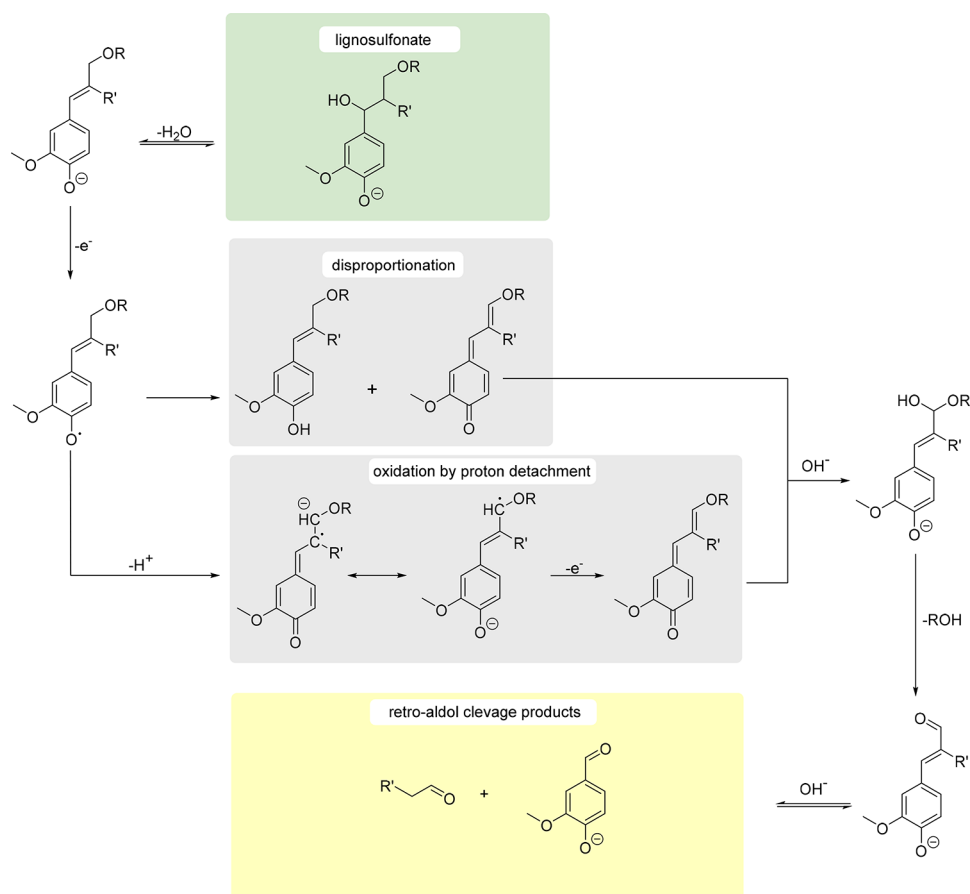


Figure 5. Proposed reaction mechanism for vanillin formation during alkaline oxidation of lignin. Reproduced with permission from ref 111. Copyright 2000, Springer Nature. Reproduced with permission from ref 112. Copyright 2004, Springer Nature.

directly in the presence of a catalyst usually under reductive conditions. The immediate catalytic processing of lignin, largely in its unmodified, native form, will result in higher yield of aromatic monomers due to the higher presence of cleavable C–O linkages and less C–C linkages. The products resulting upon reductive catalytic fractionation are a solid carbohydrate pulp plus the catalyst as solids, and a mixture of aromatic monomers, dimers and oligomers derived from catalytic lignin depolymerization in solution, as two easily separable fractions. Finally, it is also possible that lignocellulose itself is directly converted to (typically) mixtures of products both from the lignin as well as the cellulose fraction.

2. CATALYTIC STRATEGIES AIMING AT HIGH YIELD AND SELECTIVE PRODUCTION OF DEFINED AROMATIC MONOMERS FROM LIGNIN AND LIGNOCELLULOSE

2.1. Methods Using Lignins Isolated from Lignocellulose Prior to Catalytic Processing

In this section, we provide a detailed discussion of the novel catalytic methodologies that were developed using lignin isolated from lignocellulose using the organosolv, enzymatic processing or were obtained from biorefineries or as byproduct of paper production (Kraft lignin). An overview of these methods, which can be related to six main strategies, is shown in Figure 4.

2.1.1. Oxidative Depolymerization. In the past few years, novel strategies for oxidative depolymerization of lignin model compounds^{19,31} or lignin have been developed,³² including

electrochemistry,¹⁰⁸ photocatalysis,³³ and use of heterogeneous catalysts³² or ionic liquids.²⁵ Among these, several systems lead to high yield or selectivity of lignin-derived monomers. Oxidative strategies for lignin depolymerization, especially employing oxygen, hydrogen peroxide, or peroxyacids may become important and economically feasible delignification technologies, since oxidative methods are already widely employed in the papermaking industry for pulp bleaching.³¹ Oxidative methods have the potential to use generally mild conditions; however, it requires sufficient selectivity to avoid overoxidation of the substrate to gaseous products. In addition, especially contrary to reductive depolymerization methods, oxidation reactions may lead to addition of functionalities to the already complex lignin-derived aromatic compounds, thereby increasing the possibility of formation of isomers that leads to increase of complexity of the obtained product mixtures. Also, processes involving radicals during oxidation may lead to decreased product yields due to lignin repolymerization. Ideally, oxidation methods should enable efficient depolymerization under mild conditions, directly converting lignin to specific fine chemicals bearing alcohol, aldehyde, or carboxylic acid moieties.^{25,31,32}

The oxidative cleavage of lignin to produce vanillin is one of the oldest processes known in this field,^{14,29} yet the reaction mechanism, which has been studied extensively^{31,109} is still the subject of much debate. In 1977, Imsgard and co-workers¹¹⁰ proposed several reaction pathways regarding selected lignin model compounds in alkaline media, involving oxygen or hydrogen peroxide. Later, Tarabanko and co-workers¹¹¹ performed mechanistic studies involving lignosulfonate as well

as a range of model compounds such as lignosulfonates, eugenol, isoeugenol, guaiacylethanol, and guaiacylpropanol and postulated a reaction mechanism (Figure 5),^{112,113} which suggests that vanillin is formed through a retro-aldol condensation as last step and the process involves several unsaturated intermediates. It can be generally concluded that the vanillin yield crucially depends on pH as well as oxygen concentration.

Considering the high activity and stability of perovskite-type oxides in the catalytic oxidation of hydrocarbons, Liu, Lin, and co-workers found that LaMnO₃ and LaCoO₃ are highly active and robust non-noble metal catalysts for the catalytic wet aerobic oxidation (CWAO) of lignin to aromatic aldehydes.^{114,115} In these studies, LaMnO₃ and LaCoO₃, prepared by sol-gel method, enhanced the selectivity toward vanillin (M1G) (~5%) and syringaldehyde (M1S) (~10%) compared to most other oxidative methods and noncatalytic oxidation (see supplementary Table S1 for structures, codes and names of identified lignin monomers). Changes in lignin conversion or in aromatic aldehyde yield were not observed even after five successive catalytic runs. Although the precise role of this catalyst system in lignin oxidation has yet to be elucidated, XPS and TPR measurements confirmed the existence of surface bound Mn⁴⁺/Mn³⁺ (for LaMnO₃) and Co³⁺/Co²⁺ (for LaCoO₃) redox couples as well as chemisorbed oxygen, which were proposed to play a crucial role in achieving high activity and selectivity. Lignin conversions were in the range of 40–60%, while the yield of identified aromatic products were lower likely due to competing oxidation pathways that lead to gaseous products. The authors have also found that addition of 10–20% Cu dopant to the LaCoO₃ catalyst increased the surface chemisorbed oxygen species in this perovskite type catalyst.¹¹⁶ As a result the maximum yield of *p*-hydroxybenzaldehyde (M1P), vanillin (M1G), and syringaldehyde (M1S) increased to 2.8%, 5.3%, and 12.8%, respectively. The use of Cu as dopant in steam reforming, oxidative steam reforming, CO oxidation, and NO reduction was also reported.^{117,118}

Gu and co-workers¹¹⁹ have developed a new method using La/SBA-15 as heterogeneous catalyst and hydrogen peroxide as an environmentally friendly and low-cost oxidant, for the efficient oxidation of organosolv beech lignin yielding vanillin (M1G, 9.6%) and syringaldehyde (M1S, 15.7%) under microwave irradiation.

Pinto and co-workers¹²⁰ have studied the oxidative degradation of Eucalyptus globulus pulping liquors obtained upon different stages of industrial Kraft liqueur processing compared to isolated lignins in the presence of oxygen in an alkaline medium. Syringaldehyde (M1S) and vanillin (M1G) were found as main products, alongside with smaller amounts of the corresponding acids. The best M1S yield (10.3%) was obtained starting from Kraft lignin.

Wang and co-workers¹²¹ described the use of cerium oxide-supported palladium nanoparticles (Pd/CeO₂) in the oxidative conversion of 2-phenoxy-1-phenylethanol in the presence of O₂ to produce phenol, acetophenone, and methyl benzoate as major products. The Pd nanoparticles played a crucial role in the selective oxidation of the secondary alcohol moiety to the corresponding ketone. Subsequent C–O bond cleavage afforded phenol and acetophenone. Oxidative cleavage of the C_α–C_β bond also took place producing benzoic acid, which was, in the presence of methanol as solvent, further converted to methyl benzoate. The Pd/CeO₂ catalyst could also catalyze the oxidative conversion of organosolv lignin, albeit obtaining products different from model studies: under mild conditions (185 °C,

O₂ 1 bar), vanillin (M1G, 5.2%), guaiacol (M24G, 0.87%), and 4-hydroxybenzaldehyde (M1P, 2.4%) were obtained.

Ionic liquids (IL) have shown promise in oxidation of lignin model compounds, promoting the cleavage of strong aromatic ether bonds.¹²² Bosmann, Wasserscheid, and co-workers¹²³ have found that Mn(NO₃)₂ in 1-ethyl-3-methylimidazolium trifluoromethanesulfonate [EMIM][CF₃SO₃] results in the formation of a unique and relatively simple product mixture consisting of aromatic aldehydes, phenols, and unsaturated propyl-aromatics under mild conditions (100 °C). Interestingly, 2,6-dimethoxy-1,4-benzoquinone (M2S) was isolated as a pure compound in 11.5 wt % yield by a simple extraction/crystallization procedure.

An interesting catalyst system relying on the use of several dimethylphosphonium-based ionic liquids and CuSO₄ as metal catalyst was developed by Liu et al.¹²⁴ Key for obtaining a high total yield (30%) of aromatic aldehydes was the use of an IL/methyl isoutyl ketone (MIBK) biphasic system, whereby the continuous separation of the aromatic products to the extraction phase (MIBK) from the oxidation phase (IL) avoided their over oxidation. The experiments were performed in a batch reactor and the best results, e.g. 100% conversion, and nearly 30% total yield of aromatic aldehydes (M1S, M1G, M1P) were achieved with [MMim][Me₂PO₄] and [mPy][Me₂PO₄]. In addition, after easy product separation the IL phase demonstrated good reusability.

Recently, Miyafuji et al.¹²⁵ found that using Bu₄NOH·30H₂O (tetrabutylammonium hydroxide 30-hydrate) instead of the commonly used aqueous NaOH solution during aerobic oxidative degradation of lignin improved the yield of aromatic monomers. At 120 °C, total monomer yield of 6.5–22.5% was obtained with vanillin (M1G) and vanillic acid (M20G) as the main products.

2.1.2. Reductive Depolymerization. Reductive treatment of lignin dates back to early works on structural elucidation, when lignin was treated in the presence of CuCr catalysts^{126–128} under relatively harsh reaction conditions (250–260 °C, 220–240 bar), to obtain aliphatic compounds (mainly 4-propylcyclohexanol M3) which were isolated and characterized mainly based on boiling or melting points and elemental analyses.

Reductive approaches⁵⁵² require catalysts capable of selective scission of C–O bonds leading to depolymerization.¹²⁹ This approach is attractive since the stepwise reductive deoxygenation of the aromatic monomers obtained after depolymerization generally leads to a decrease of complexity in the product mixtures, increasing the selectivity to defined aromatic compounds.¹³⁰ A factor decreasing selectivity, on the other hand, is the presence of competing ring hydrogenation reactions, which is one of the major challenges related to this method. To this end, novel catalysts that do not lead to over-reduction of the obtained aromatic monomers have also been developed, for example a PdFe/C catalyst, which exhibits a high selectivity to benzene without ring saturation or ring opening.^{131–133} At this point it should be mentioned that total and selective hydrogenation/deoxygenation would provide clean mixtures of alkanes (mainly C9 cycloalkanes) as demonstrated by the two step method developed by Kou and co-workers,¹³⁴ as well as recent elegant work of Yang¹³⁵ and Lercher and Zhao.^{136–142}

Excellent recent reviews provide a comprehensive overview of reductive depolymerization of lignin and model compounds by both homogeneous and heterogeneous catalysts.^{11,21,24} Reductive approaches generally use hydrogen gas or hydrogen-donor solvents and mainly focus on the production of bio-oils and fuels.^{143–147} In this section, we focus on systems that use lignin

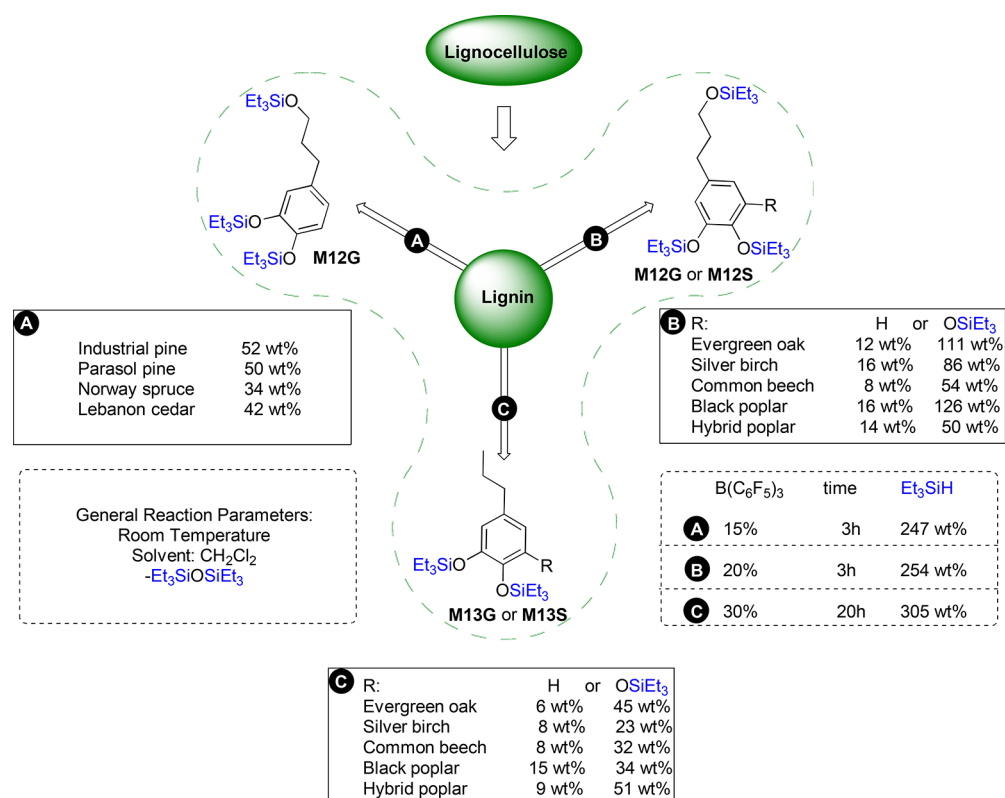


Figure 6. First example of transition metal free, room temperature reductive depolymerization of formacell lignin using B(C₆F₅)₃/Et₃SiH.

directly for the production of monomeric phenols in high yield and selectivity, typically below 250 °C.

One of the first reductive systems displaying high isolated yield for specific aromatic compounds was described by Anastas and co-workers¹⁴⁸ under mild reaction conditions at 140–180 °C. In this work, organosolv lignin extracted from candlenut shells was depolymerized to well-defined aromatic monomers over copper-doped porous metal oxide (CuPMO) in the presence of hydrogen gas (50 bar). The main product at 140 °C was 4-propanolcatechol (**M4**) that was isolated by column chromatography in 43.3% yield and the total monomer yield reached 63.7%.

Hartwig and co-workers¹⁴⁹ reported that complex β-O-4 model compounds can be selectively cleaved by commercially available Pd/C catalyst resulting in acetophenone or ethyl-substituted arenes and phenols. The process occurred through dehydrogenation of the secondary alcohol in the β-O-4 moieties, followed by hydrogenolysis of the alkyl C–O bond through the hydrogen generated in the first step. When applied to organosolv lignin, the addition of a small amount of hydrogen was necessary as the presence of olefins in natural lignin samples consumed the generated hydrogen. Under optimized conditions, acetonesolv lignins from *miscanthus giganteus* produced 12–15% combined yields of seven major products and 9% yield of alkyl-substituted phenols (4-ethylphenol **M6P**, 4-ethylguaiaicol **M6G**, and 4-ethylsyringol **M6S**) was obtained from pine lignin.

Samec and co-workers developed a robust catalyst system for cleavage of C–O bond in lignin β-O-4 linkages in model compounds that used Pd/C and formic acid as a reducing agent under very mild reaction conditions (80 °C in air).¹⁵⁰ Further degradation experiments with organosolv lignin revealed partial lignin depolymerization to lower molecular weight species based on GPC analysis. Interestingly, the group has found that the addition of catalytic amounts of a hydrogen source (e.g.,

HCOOH, NH₄HCO₂, 2-propanol, and NaBH₄) was sufficient to promote the redox neutral cleavage of the β-O-4 linkage.¹⁵¹

Similarly to the reactivity of Pd/C, a dehydrogenation/hydrogenation sequence can be also implemented using Raney Ni, as was demonstrated by Lin and co-workers¹⁵² in the depolymerization of cellulosytic enzyme lignin from bamboo without addition of any external hydrogen source. Compared to the use of Raney Ni alone, the combination of Raney Ni and zeolites lead to an increased yield of phenolic monomers, which mainly included 4-propylguaiaicol **M7G**, 4-hydroxy-3,5-dimethoxy-benzeneacetic acid **M8S**, and 4-allyl-2,6-dimethoxyphenol **M9S** (12.9% to 27.9%), and more than 60 wt % bio-oil yield was achieved under optimized conditions (270 °C, 1 atm N₂). The authors concluded that a synergistic effect exists as this catalyst combination lead to highly efficient depolymerization while minimizing the formation of undesired high molecular weight polymers.

Yan and co-workers¹⁵³ studied the influence of pH in the range of 1 to 14 on the reductive depolymerization of lignin using Ni₇Au₃ catalyst in water and found a positive correlation between the rate of hydrogenolysis and increasing pH values. In an experiment using organosolv lignin from birch sawdust and Ni₇Au₃ catalyst under 10 bar hydrogen at 160 °C, the total monomer yield increased from 7.6% to 10.9% after addition of NaOH. The main products included 4-propylguaiaicol (**M7G**), 4-propanolguaiaicol (**M10G**), and 4-propanolsyringol (**M10S**) and the addition of base accounted for more selective depolymerization. After characterization by TEM, UV–vis, and XPS, the catalyst itself was found structurally and chemically unchanged after the addition of NaOH. The authors concluded that the basic reaction medium leads to an increase of selectivity as the base hinders the coordination of the bulky aromatic ring to the catalyst, thereby inhibiting arene hydrogenation. More impor-

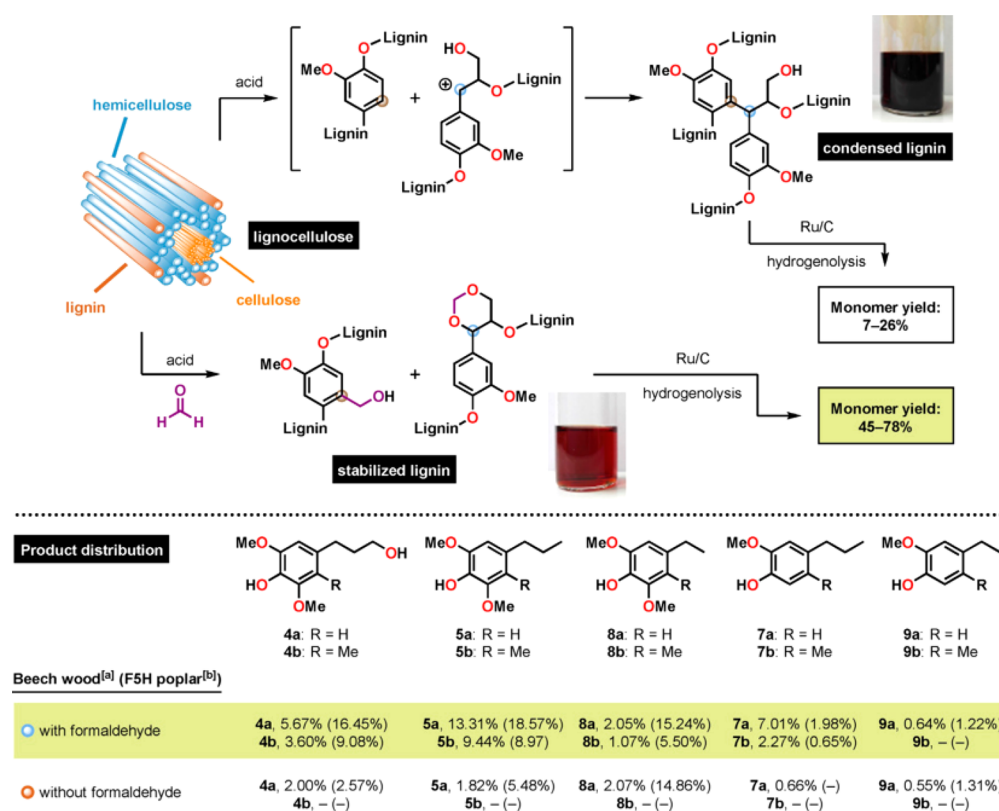


Figure 7. Highly efficient catalytic conversion of lignin through formaldehyde stabilization (top) and product distribution for beech wood and F5H poplar lignin with or without formaldehyde stabilization (bottom). Reprinted with permission from ref 158. Copyright 2017 Wiley-VCH.

tantly, the depolymerization of organosolv lignin into aromatic monomers is enhanced considerably using NaOH as an additive.

On the other hand, Singh and Ekhe¹⁵⁴ have investigated the effect of solid acids on depolymerization. The research group developed a one-pot process using Cu/Mo loaded ZSM-5 catalyst for the production of alkyl phenols using methanol as a hydrogen donor, and water was used as cosolvent. At 220 °C, Kraft lignin was almost fully converted (>95%) after 7 h, and only a little amount of char (<0.5%) was formed. The products were then analyzed on a GC-MS/FID, which showed 3-methoxy-2,5,6-trimethyl phenol (M11) as the predominant product with a high selectivity (70.3%) in the reaction catalyzed by Cu/Mo-ZSM-5 with a solvent ratio of 1:1 (methanol/H₂O).

Xu and co-workers¹⁵⁵ found that treating woody biomass (170–200 °C) in the combination of tetrahydrofurfuryl alcohol (THFA) and water in the absence of acid, leads to 92.8% yield of good-quality cellulose and high yield of lignin (77.4%), simultaneously. Because no acid was used, high-quality lignin was obtained with high retention of β-O-4 linkages that was well-suited for obtaining a high yield of aromatic monomers upon catalytic treatment. Hydrogenolysis using Ni/C at 220 °C resulted in a total monomer yield of 14.7% (mainly M10G and M10S).

Song and co-workers¹⁵⁶ reported a low-cost nanostructured MoO_x/CNT catalyst that is comparable to precious-metal-based catalysts in terms of activity, reusability, and biomass feedstock compatibility. High aromatic product yield (up to 47%) was obtained from enzymatic mild acidolysis lignins (EMALs). Interestingly, unsaturated monomeric phenols (M18G and M18S) were obtained in high yields.

Cantat and co-workers¹⁵⁷ presented the first example of reductive depolymerization of lignin under metal-free conditions

at room temperature to obtain well-defined aromatic products in high yield (Figure 6). In place of hydrogen gas, hydrosilanes were used as reductants and B(C₆F₅)₃ as a Lewis acid catalyst. This versatile approach could be successfully applied to different lignin species extracted by a formacell process, which included 15 gymnosperms and angiosperms woods. Several aromatic products (M12G, M12S, M13G, and M13S) were obtained in excellent selectivity, depending on wood type, and the isolated yield ranged from 7–24 wt % based on lignin or 0.5–2.4 wt % based on lignocellulose. In order to evaluate the efficiency of the depolymerization step, it is important to estimate the maximum yield of monoaromatics from lignins. Thus, the authors also included a more quantitative assessment of the theoretical yield based on equation 1 in order to determine the efficiency of depolymerization:

$$Y = \frac{(N - 2)P^2 + 2P}{N} \times 100 \quad (1)$$

where Y represents the theoretical yield of total monomers, N is the number of monomers occurring in the polymer chain, and P corresponds to the cleavable linkages (e.g., α-O-4 and β-O-4 linkages). On the basis of this calculation, depolymerization with the hydrosilane–B(C₆F₅)₃ systems showed an efficiency of 28 to 85% depending on the wood source and the targeted product.

As mentioned in section 1.2, lignocellulose pretreatment inevitably modifies the native structure of lignin, by formation of robust C–C linkages.¹⁵⁸ To minimize this structural modification Luterbacher and co-workers¹⁰⁵ devised an elegant strategy that involved addition of formaldehyde during biomass pretreatment, leading to a soluble lignin fraction that could be subsequently converted by reductive treatment to a mixture of guaiacyl and syringyl monomers at near theoretical yield. As

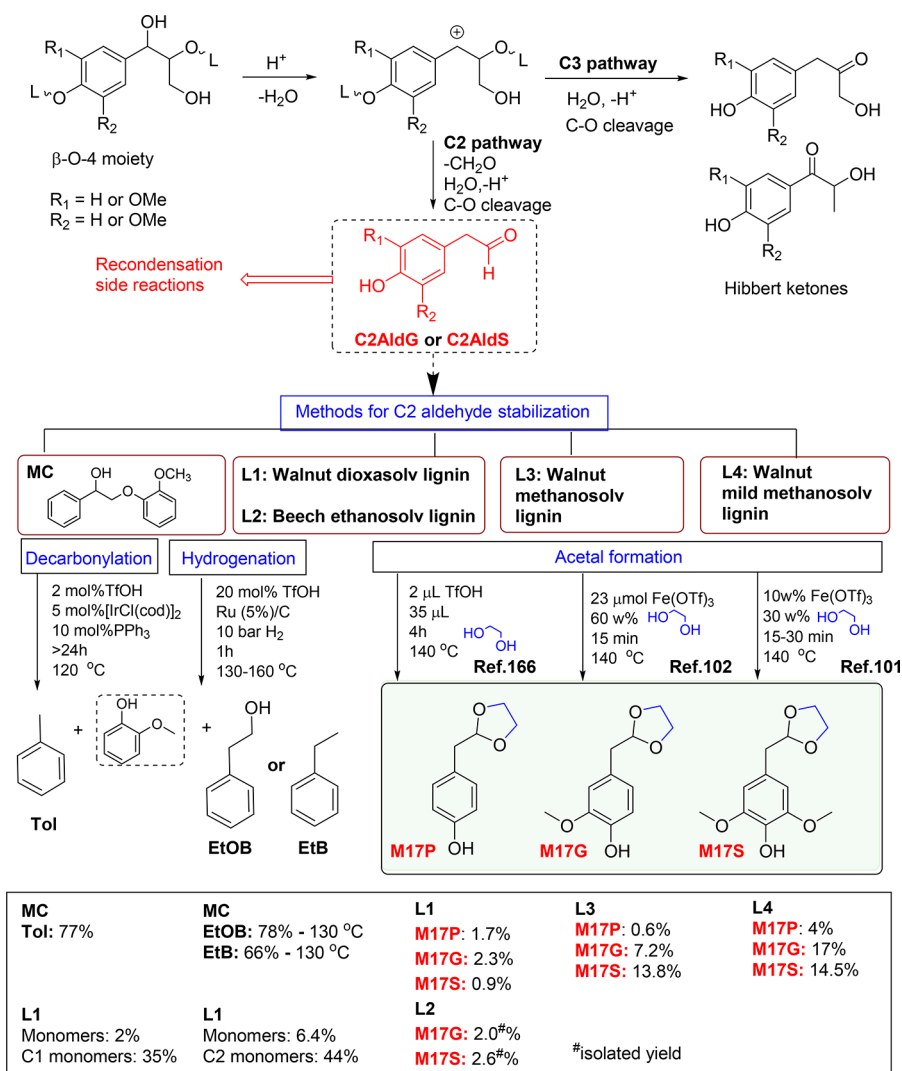


Figure 8. Acid catalyzed depolymerization of lignin in conjunction with stabilization of reactive C2-aldehydes. Comparison of the yields of aromatic C2-acetals obtained by the addition of ethylene glycol obtained from various lignin sources.

shown in Figure 7, the role of the formaldehyde was to stabilize the native lignin structure via the formation of a 1,3-dioxane moiety. The lignin obtained this way was substantially lighter in color compared to the lignin obtained in the absence of formaldehyde, qualitatively confirming the lack of recondensation processes. After hydrogenolysis with Ru/C at 200 °C for 6 h, a combined yield of 45% of monomeric species (mainly M7S, M7G, M10S, and methylated analogues) was achieved from the isolated beech lignin extracted with formaldehyde, whereas in the absence of formaldehyde, a much lower 7% monomer yield was obtained. With “formaldehyde stabilized” poplar lignin a monomer yield (mainly M6S, M7S, M10S, and methylated products) as high as 78% was achieved upon hydrogenolysis with Ru/C at 250 °C.

Very recently, Wang and co-workers¹⁵⁹ developed a catalytic method that enabled the complete removal of oxygen content and resulted in liquid aromatic hydrocarbons with a yield of 35.5 wt % from lignin. Remarkably, a near-quantitative carbon yield was observed when using birch lignin, and the selectivity to arenes (methylbenzene M14, ethylbenzene M15, and propylbenzene M16) was as high as 71 wt %. The arenes were obtained by direct hydrodeoxygenation of organosolv lignin over a porous Ru/Nb₂O₅ catalyst in water at 250 °C. A combined inelastic

neutron scattering (INS) and density functional theory (DFT) calculation analysis confirmed the existence of an active Nb₂O₅ species, and the catalytic activity was attributed to the combination of strong adsorption and selective activation of the phenols and a synergistic effect between the Ru and NbO_x species.

Besides using hydrogen gas or other reducing reagents, Wang and co-workers found that the aliphatic alcohol moieties (C_αH–OH) in lignin itself can act as the hydrogen donor.¹⁶⁰ Lignin β-O-4 linkages were initially dehydrogenated on ZnIn₂S₄ to form a “hydrogen pool”, and the adjacent C_β–O bond subsequently underwent hydrogenolysis by hydrogen derived from the “hydrogen pool”. With this strategy, 71–91% yield of phenols in the conversion of lignin β-O-4 models and a 10% yield of *p*-hydroxy acetophenone derivatives were obtained from organosolv lignin.

2.1.3. Acid-Catalyzed Depolymerization in Conjunction with Stabilization of Reactive Intermediates. The first acid-catalyzed lignin hydrolysis reaction was reported in 1924 by Hägglund and Björkman¹⁶¹ when they distilled lignin with 12% hydrochloric acid and attempted to obtain thiobarbituric acid, phloroglucinol, and barbituric acid. More recently, different types of acids including mineral and Lewis acids, zeolites, ionic liquids

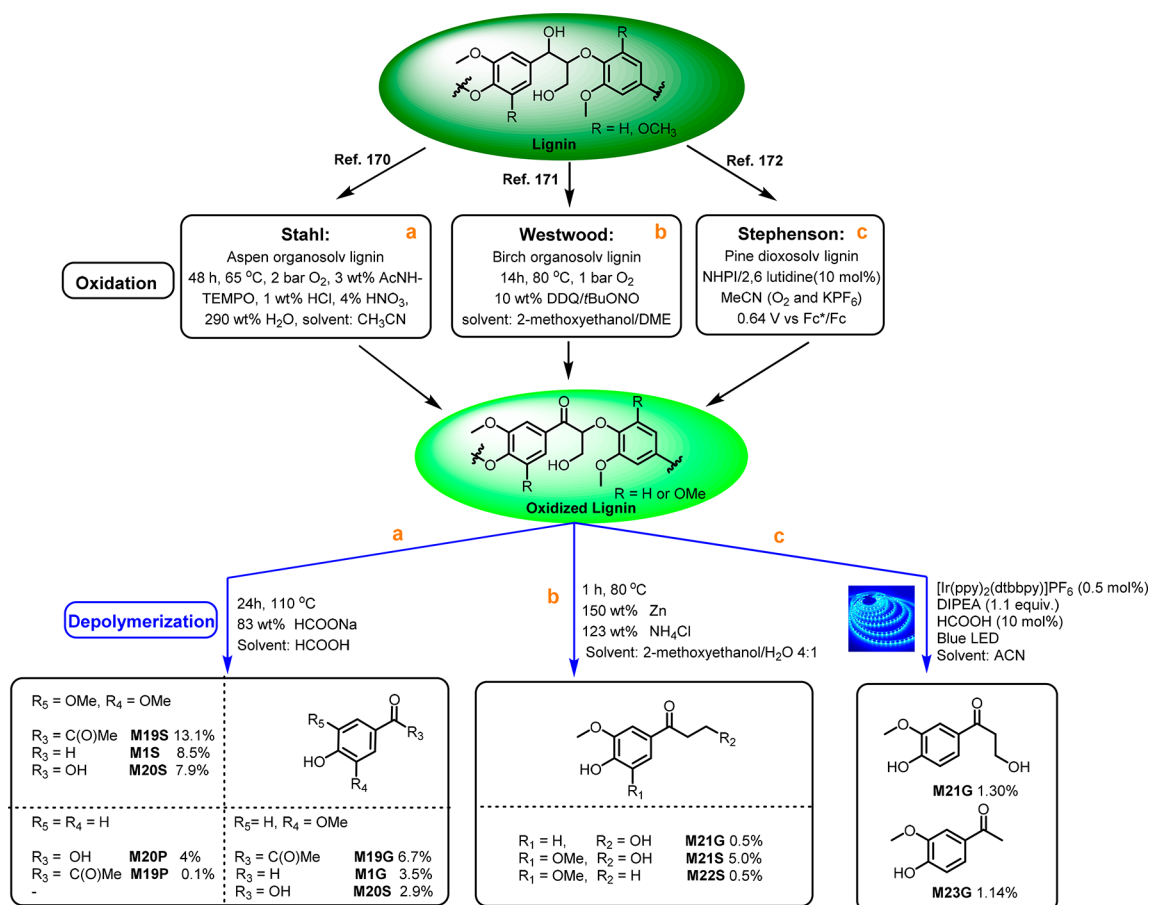


Figure 9. Selective oxidation and cleavage of isolated lignin into monomeric aromatic products.

with Bronsted acidic functionalities, as well as organic acids have been tested for depolymerization of lignin and these were summarized in recent reviews of Zhang,²⁴ Barta,²¹ Yokoyama,¹⁶² and Weckhuysen.¹¹

Pulping under acidic conditions is one of the most classical methods used for the fractionation of lignocellulose into its main components.²¹ In early days, acidolysis was relevant regarding the structural determination of lignin.^{163–165} During these studies it became apparent that treatment of lignin with acid resulted in low yield of aromatic chemicals, and recondensation of the formed fragments were observed under these reaction conditions. However, the precise reasons for these phenomena were not fully elucidated. Barta, de Vries, and co-workers have established that triflic acid, even in catalytic amounts, is very efficient in cleaving the β -O-4 linkage in lignin model compounds.¹⁶⁶ Labeling studies revealed that the formed C2-aldehyde products undergo recondensation reactions under depolymerization conditions and are one of the reasons for the formation of high molecular weight side products. To prevent this, a stabilization strategy was developed that entailed the in situ conversion of the reactive C2 aldehydes to more stable products, leading to well-defined classes of aromatic chemicals. By “trapping” the aldehyde by addition of ethylene glycol, the corresponding (more stable) C2-acetals were obtained. Alternatively, catalytic hydrogenation of the C2 aldehyde lead to the corresponding ethanol-aromatics (**EtOB**) or ethyl-aromatics (**EtB**), and decarbonylation resulted in methyl-aromatics, such as toluene. Applying these methods on actual dioxasolv lignin resulted in a decrease of undesired side products and the same

classes of aromatics as found in model compound studies. Especially the acetal formation method gave a 3-fold increase in monomer yields relative to the control experiments and acetals (**M17P**, **M17G**, **M17S**) as main products. Next, Barta and Westwood developed scalable synthetic routes to next generation model compounds combining the β -O-4 as well as the β -5 linkages and have all functionalities to serve as realistic models of the lignin structure. An in-depth research using such advanced lignin models confirmed that ethylene glycol also plays a role in “trapping” the formaldehyde released both from the β -O-4 as well as the β -5 linkage.¹⁶⁷ Importantly, it was possible to quantify the amount of released formaldehyde in model and lignin reactions via the corresponding 1,3-dioxolane formed. Later the reactivity of a broad range of metal triflates was evaluated,¹⁰² and it was found that Bi(OTf)₃, Fe(OTf)₃, and Hf(OTf)₄ performed the best for the depolymerization of methanosolv walnut lignin to three major aromatic products (**M17P**, **M17G**, and **M17S**). The best aromatic monomer yield of 19.3 wt % was obtained with Fe(OTf)₃. Aiming to further increase the yield of phenolic monomers, lignins obtained from a range of different biomass sources and pretreatment methods were investigated.¹⁰¹ After screening a library of 27 lignins obtained from 13 different pretreatment methods, it was found that a β -aryl ether rich organosolv lignin gave the best combined yield of up to 35.5 wt % of acetal products and the best yield of a single component (**M17G**, 16.5 wt %) was achieved starting from walnut lignin obtained by a specially developed, mild organosolv procedure (Figure 8).

In line with the previous strategy, Bruijninx and co-workers¹⁶⁸ described the tandem acidolysis/decarbonylation using water-tolerant Lewis acids to promote depolymerization and a homogeneous Rh complex to enable decarbonylation of the C2-aldehyde formed in the first step. The method was established using model compounds and subsequently applied to dioxasolv lignin, isolated from brewer's spent grain. Poplar dioxasolv lignin was successfully depolymerized using Yb(OTf)₃ to obtain an overall monomer yield of 12.4% at 175 °C in dioxane/H₂O and the major products were 4-(1-propenyl)-phenols (M18G and M18S).

2.1.4. Highly Efficient Depolymerization via Oxidized Lignin. Innovative two-step methodologies lead to efficient lignin depolymerization relying on cleavage of the most abundant β -O-4 unit by selective preoxidation of the secondary alcohol followed by a reductive C–O ether bond rupture. The rationale behind preoxidation is that it decreases the bond dissociation energy of the C–O bond and therefore makes the β -O-4 linkage more labile. An analogous Ru-catalyzed hydrogen neutral method on simplified lignin β -O-4 model compound resulted in efficient cleavage of the phenyl ether bond, resulting in the formation of acetone and guaiacol.¹⁶⁹

Following this strategy, Stahl and co-workers^{170,173} have achieved very efficient lignin depolymerization. The secondary alcohol in the β -O-4 linkage was first selectively oxidized to the corresponding ketone using catalytic amount of 4-acetamido-TEMPO/HNO₃/HCl under aerobic conditions (Figure 9, left). This oxidation step activated the linkage for the desired C–C or C–O bond scission in the second step that was accomplished by an excess of sodium formate in aqueous formic acid (85–90 wt %) at 110 °C. With this method, cellulosic lignin from aspen wood was successfully converted to low-molecular-mass aromatics (mainly M1S, M19S, M19G, and M20S) in more than 60 wt % yield.

Westwood and co-workers¹⁷¹ presented a new approach using selective oxidation of the secondary alcohol in a β -O-4 moiety (Figure 9, middle). This methodology used molecular oxygen as the oxidant and catalytic amounts of 2,3-dichloro-5,6-dicyano-1,4-benzoquinone (DDQ) and *tert*-butyl nitrite (tBuONO). Upon preoxidation, Zn/NH₄Cl was applied in the second step at 80 °C. In this case, birch lignin was converted to phenolic monomer (M21S) and the major product was also isolated in a 5 wt % yield. This two-step method for lignin depolymerization could also be conducted in one-pot.

The concept of utilizing solar energy via photocatalysis under mild conditions is one of the most intriguing strategies for lignin depolymerization.³³ In addition, electrochemical oxidation is an environmentally benign alternative to chemical oxidations due to the absence of chemical oxidants in the reaction media.¹⁷⁴ Combining these two emerging technologies, Stephenson and co-workers presented the first electrocatalysis/photoredox catalysis sequence for the depolymerization of lignin in a two-step, one-pot process at ambient temperature, which is conceptually related to the works of Stahl and Westwood (Figure 9, right).¹⁷² The work first explored different hydrogen transfer mediators for the selective oxidation of the benzylic position in β -O-4 lignin dimers under electrocatalytic conditions. Then, a NHPI/2,6-lutidine-catalytic system was found to be more efficient for the oxidation of 1-(3,4-dimethoxyphenyl)-ethanol. The scope of this methodology was examined on a variety of different lignin models and isolated pinewood lignin. The two-step protocol could also be conducted on a large scale. For example, when using 0.5 g lignin β -O-4 model compound, a

67% yield of ketone and a 67% yield of guaiacol was obtained. When lignin isolated from pine wood with dioxane was subjected to optimized (one-pot) reaction conditions, two monomers with the yield of 1.30% (M21G) and 1.14 wt % (M23G) were obtained, respectively.

This two-step methodology is suitable for dissociating interlinking lignin units; however, researchers following this strategy mainly focused on the scission of β -O-4 linkages. In order to improve the efficiency of lignin conversion, the transformation of other ether linkages should also be taken into consideration. With this in mind, Wang and co-workers¹⁷⁵ recently reported a two-step oxidation–hydrogenation strategy which was also able to cleave the α -O-4 linkages. In the first step, an organocatalytic system O₂/NaNO₂/DDQ/NHPI was used to oxidize the (C _{α} H–OH) moieties in lignin. In the second step, the obtained preoxidized β -O-4 as well as the α -O-4 moiety was further hydrogenated over a NiMo sulfide catalyst, leading to the cleavage of C _{β} –OPh and C _{α} –OPh bonds to aromatics. This system worked well for β -O-4 lignin models; however, an organosolv lignin isolated from birch powder gave lower monomer yield (<5%). This sharp contrast was attributed to new connections among isolated lignin molecules caused by hydrogen bonds. Finally the authors found that a 32% monomer yield, including mainly M7G/M7S and M18G/M18S, could be obtained from birch powder.

2.1.5. Depolymerization of Lignin via an Alternative Two-Step Processes. Corn cob residue is a high volume process waste typically left behind after the conversion of the hemicellulose component in corn cob to xylose. With this raw material Hu and co-workers developed the selective conversion of the lignin component in corn cob residue to phenolic monomers via a two-step process without addition of hydrogen.^{92,176} In the first step, a H₂O-THF (3:7, v/v) solvent mixture was used for the selective degradation of lignin to oligomers at 200 °C for 1 h, the extent of delignification being as high as 89.8%. In the second step, the THF soluble, oligomeric fraction was depolymerized to phenolic monomers, with the total monomer yield of 24.3 wt % at 300 °C after 8 h. It was postulated that in this two-step process H₂O was responsible for the cleavage of numerous intermolecular and intramolecular hydrogen bonds of cellulose in corn cob residue under the hydrothermal reaction conditions used, while THF dissolved the fragments derived from lignin. Next, it was found that the addition of Na₂CO₃ to this already established solvent system further improved product yields. Selective dissolution of lignin was achieved with 94.6% conversion in the first step, and further treatment at 300 °C lead to a 26.9 wt % yield of phenolic monomers with 4-ethylphenol (M6P, 10.5 wt %), guaiacol (M24G, 6.6 wt %), and 4-ethylguaiacol (M6G, 4.0 wt %) as the predominant product.

2.1.6. Biochemical Transformation of Lignin. In nature, lignin is depolymerized by means of fungi and bacteria that generally use powerful oxidative enzymes.^{177–179} The research toward finding or engineering an organism that is able to depolymerize lignin to specific chemicals is a very exciting prospect. By using the natural aromatic-catabolizing organism *Pseudomonas putida* KT2440, Beckham and co-workers¹⁸⁰ demonstrated that certain aromatic metabolic pathways (Figure 10) can be used to convert both lignin model compounds and lignin-enriched streams derived from pilot-scale biomass pretreatment into medium chain-length polyhydroxyalkanoates (M2S) with high yield (34–39%). They further demonstrated that mcl-PHAs can be depolymerized to alkenoic acids, which are

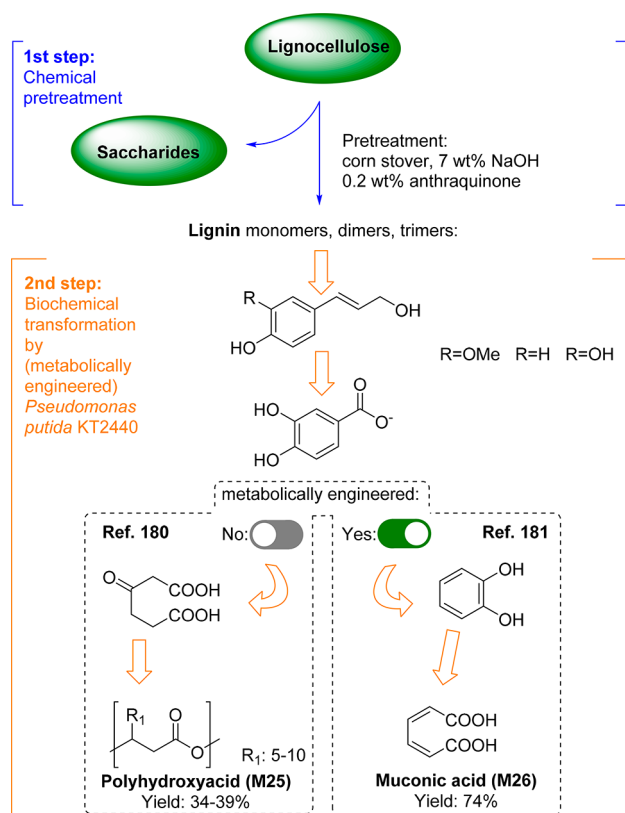


Figure 10. Biochemical transformation of lignin to polyhydroxyalkanoates and muconic acid.

precursors for diverse chemical applications. Subsequently, alkenoic acids were converted to alkanes by a bimetallic catalyst.

Beckham and his group have then introduced modification of the mentioned aromatic-catabolizing organism to demonstrate an integrated scheme for the conversion of lignin via biologically derived muconic acid (**M26**) to adipic acid that is one of the most widely produced dicarboxylic acid.¹⁸¹ First, *Pseudomonas putida* KT2440 was metabolically engineered to funnel lignin-derived aromatics through an atom-efficient biochemical transformation to *cis,cis*-muconate (**Figure 10**). Subsequently, *cis,cis*-muconic acid was recovered in high purity (>97%) and yield (74%) by activated carbon treatment and crystallization and hydrogenated over Pd/C to adipic acid with exceptional conversion (>97%) and selectivity (>97%).

2.1.7. Summary of Processes Related to Lignin Extraction and Depolymerization. It is important to mention that the presented novel methods and corresponding yield values are difficult to compare since the organosolv or enzymatic lignins that were used as starting materials have been isolated from different plant sources through different isolation methods. The isolation methods in some cases compare well to the organosolv processing that would take place in a biorefinery for the production of high purity cellulose; in other cases the fractionation has been already adjusted to gain high quality lignin with preferably large fraction of β -O-4 bonds. These isolation methods have been frequently developed in the corresponding laboratories, together with the catalytic processing. Therefore, here we also give an overview of the methods as well as isolation processes and lignin yields (**Figure 11**).

2.2. Catalytic Fractionation of Lignocellulose: Aromatic Monomers from Native Lignin

Reductive catalytic fractionation (RCF) of lignocellulose or “lignin first” processes employ heterogeneous catalysis directly during lignocellulose fractionation, converting native lignin to low molecular weight products.^{37,40,41} The advantage of converting the lignin released from lignocellulose *in situ*, is that generally higher yields and selectivity for aromatic monomers can be obtained due to the higher fraction of cleavable β -O-4 linkages in the yet unmodified substrate. The lignin-derived aromatic monomers are dissolved in the reaction solvent, allowing for easy separation from the solids that contain cellulose and the heterogeneous catalyst. In **Figure 12** and **Table 1**, selected systems are summarized that use this methodology and result in high product yield and selectivity. Variations exist related to lignocellulose sources, the type of solvent as well as catalyst used, and occasionally additives are used to improve the release of lignin from the lignocellulose matrix.

2.2.1. Structure of Monomers Related to the Starting Materials.

Woody biomass as well as herbaceous plants has been used for the production of aromatic compounds using the reductive catalytic fractionation process. The type and structure of these aromatic monomers is highly dependent on the original structure of native lignins contained in these resources. As shown in **Figure 13**, depolymerization of hardwood lignins generally results in high aromatic monomer yields because these feedstocks typically display high syringyl-to-guaiacyl (S/G) monolignol ratios. The higher portion of syringyl units in which both the 3 and 5 position of the aromatic ring are “blocked” from C–C bond formation result in less robust C–C linkages and higher proportions of easily cleavable β -O-4 linkages.³⁷ In contrast, softwoods or herbaceous plants that have much lower S/G ratios contain higher proportion of more robust C–C linkages, leading to more challenging depolymerization. However, while hardwoods result in higher monomer yields, they typically deliver mixtures of guaiacyl/syringyl related products. On the other hand, softwoods containing exclusively G-type units may result in fewer, all G-type components.

Sels and co-workers¹⁸⁸ (**Table 1**, entry 8) have compared the product yield obtained during the reductive catalytic fractionation of birch (hardwood), miscanthus (grass), and pine/spruce (softwood) lignocelluloses under identical reaction conditions (5% Ru/C, 3 h, 30 bar H₂, 250 °C) and obtained monomer yields (mainly **M7G** and **M7S**) of 50%, 27%, and 21%, respectively. In contrast to woody biomass, herbaceous plants contain ferulate linkages which result in methyl coumarate (**M27P**) and methyl ferulate (**M27G**) monomers when methanol is used as solvent;^{195,199} saturated products methyl 3-(4-hydroxyphenyl)propionate (**M28P**) and methyl 3-(4-hydroxy-3-methoxyphenyl)propionate (**M28G**) will be generated by following hydrogenation reaction at higher hydrogenation pressure¹⁹⁵ or longer reaction time.¹⁹⁹

Among several different hardwoods, birch has been identified as suitable starting material as it normally affords higher monomer yields (32%–55%).^{134,186–191,198,200–203,205} This could be attributed to its high β -O-4 linkages content as demonstrated by Samec and co-workers (**Table 1**, entry 13).¹⁹³ In their study, the effect of the lignin structure on the yield and distribution of products was investigated by treating wood chips of different origin under the same condition (Pd/C, 210 °C, Ar, ethanol/H₂O as solvent). A direct correlation between the β -O-4 content of the native lignin and monomer yield was observed (**Figure 14**). This also means that hardwood species that are rich

LIGNOCELLULOSE		Lignin Yield	Monomers Yield ^c
Lin & Liu (cornstalk)	Ref. 115		
Steam explosion, enzymatic hydrolysis, extraction with 1.5% NaOH solution		LaCo ₃ , NaOH, H ₂ O, 120 °C, O ₂	14.54%
Gu (commercial beech lignin)	Ref. 119		
		La/SBA-15, H ₂ O ₂ , microwave irradiation	32.13%
Bösmann & Wasserscheid (commercial beech lignin)	Ref. 123		
		EMIM][CF ₃ SO ₃], Mn(NO ₃) ₂ , 100 °C, O ₂	32.5%
Liu (commercial mixed hardwoods lignin)	Ref. 124		
		[mmim][Me ₂ PO ₄], CuSO ₄ , 175 °C, O ₂	29.7%
Miyafuji (Japanese cedar)	Ref. 125		
		Bu ₄ NOH·30H ₂ O, 120 °C, 2.5h, air	27.6%
Anastas (candlenut)	Ref. 148	11.9% ^a	63.7%
Methanol extraction, reflux, 12 h, Purification with DCM			
		Cu-PMO, CH ₃ OH, 180 °C, H ₂	
Hartwig (miscanthus giganteus)	Ref. 149	15% ^a	15%
extraction with 95% acetone/5% 0.2 M HCl (v/v), reflux, 4h			
		Pd/C, dioxane, 200 °C, H ₂	
Zeng & Lin (commercial CEL bamboo lignin)	Ref. 152		
		H-USY/Raney Ni, H ₂ O/ CH ₃ OH, 270 °C, N ₂	27.9%
Lu & Xu (beech sawdust)	Ref. 153	10.4% ^a	14.7%
Extraction with THFA/H ₂ O, 170 °C, 200 min, N ₂			
		Ni/C, THFA/1,4-dioxane, 220 °C, H ₂	
Song & Fang (birch lignin)	Ref. 155		
Enzymatic mild acidolysis			
		MoOx/CNT, CH ₃ OH, 260 °C, H ₂	47.1%
Luterbacher (poplar)	Ref. 156	73.29% ^b	77.66%
extraction with dioxane, HCl, formaldehyde, 80 °C, 5 h			
		Ru/C, THF, 250 °C, H ₂	
Cantat (poplar)	Ref. 157	17% ^a	142%
formic acid/acetic acid/water 30/50/20% v/v, 107 °C, 3h			
		B(C ₆ F ₅) ₃ /Et ₃ SiH, CH ₂ Cl ₂ , RT	
Wang & Yang (birch)	Ref. 105	12.3% ^a	35.5%
Extraction with MeOH, HCl, reflux, 12 h			
		Ru/Nb ₂ O ₅ , H ₂ O, 250 °C, H ₂ , 20 h	
Prechtl & Yan (birch)	Ref. 159	10% ^a	10.9%
Extraction with dioxane/H ₂ O, HCl, 90-95 °C, 6h.			
		Ni ₇ Au ₃ , NaOH, H ₂ O, 160 °C, H ₂	
Deuss & Barta (walnut)	Ref. 101	6% ^a	35.5%
Extraction with MeOH/water 95/5, 0.2 M HCl, 90 °C, 6h			
		Fe(OTf) ₃ , ethylene glycol (30 wt%), 1,4-dioxane, 140 °C.	
Barta & deVries (walnut)	Ref. 102	11% ^a	19.3%
Extraction with MeOH, 170 °C, 24h			
		Fe(OTf) ₃ , ethylene glycol (60 wt%), 1,4-dioxane, 140 °C.	
Bruijninx (poplar)	Ref. 168	9% ^a	12.4 %
Extraction with 1,4-dioxane, 2N HCl, gentle reflux, N ₂ , 1h			
		[Rh(cod)Cl] ₂ , dppp, Yb(OTf) ₃ , 1,4-dioxane/H ₂ O, 175°C.	
Stahl (aspen)	Ref. 170		61.2 %
CEL method, oxidation with 4-acetamido-TEMPO, O ₂ , HNO ₃ (AcCN), HCl(AcCN), 65 °C, 48 h			
		1. AcNH, TEMPO cat. HCl/HNO ₃ , O ₂ , 45 °C. 2. HCOOH:H ₂ O, HCOONa, 110°C.	
Westwood (birch)	Ref. 171	9.75% ^a	6 %
Extraction with 1,4-dioxane, 2N HCl, gentle reflux, N ₂ , 1h			
		1. DDQ, t-BuONO, 2-methoxyethanol/DME, O ₂ , 80°C. 2. Zn/NH ₄ Cl, H ₂ O, 80°C.	
Stephenson (pine)	Ref. 172	1.75% ^a	2.44 %
Extraction with EtOH/benzene, 12 h, 130 °C, reflux dioxane/aq. HCl, 4 h			
		1. NHPI/2,6-lutidine, MeCN, 0.64V. 2. [Ir] cat., DIPEA, HCOOH, blue LEDs.	
Hu (corn cob residue)	Ref. 176	89.8% ^b	26.9 %
Extraction with THF/water, 1 h, 200 °C,			
		1. H ₂ O-THF, 200°C. 2. Na ₂ CO ₃ , H ₂ O-THF, 300°C.	
Beckham (corn stover)	Ref. 180	56% ^b	34-39%
Alkaline pretreatment with NaOH _(aq) , antraquinone, 100 °C			
		Enzymatic treatment Pseudomonas putida KT2440	
Beckham (corn stover)	Ref. 181	56% ^b	67%
Alkaline pretreatment with NaOH _(aq) , antraquinone, 100 °C			
		Enzymatic treatment Engineered P. putida strain, KT2440-CJ103	

a. Yield based on weight of lignocellulose
b. Yield based on weight of lignin
c. Monomers yield refers to the highest reached in every paper

Yield is not reported or using commercial lignin

Figure 11. Summary of processes including the isolation and depolymerization of lignin.

in β -O-4 bonds could result in higher monomer yield and more efficient delignification in comparison with softwood species.

Song and co-workers¹⁸⁶ (Table 1, entry 6) reported the use of a Ni/C catalyst in the presence of alcohol as the hydrogen donor. The established method depolymerized birch woodmeal and resulted in a mixture of 4-propylphenols (mainly M7G and M7S) in very high selectivity (89%) and total monomer yield of 54% at 200 °C. Abu-Omar¹⁹¹ (Table 1, entry 11) attempted to explore this catalyst in the treatment of different lignocellulose sources. Compared to poplar and eucalyptus, birch resulted in the highest

monomer yields (mainly M7G and M7S, 32%) at 200 °C. However, when birch woodmeal was tested with the same catalyst by using the reaction conditions reported by Song and co-workers, only 20% monomer yield (versus 54%) was obtained. The authors pointed out that the difference may be attributed to the variation of biomass composition since it is known that the structure of lignin could be different across regions, growing periods, and even age of the lignocellulose.²⁰⁶

The advantage of using softwoods is that they normally deliver higher selectivity of guaiacol type monomers [e.g., 4-

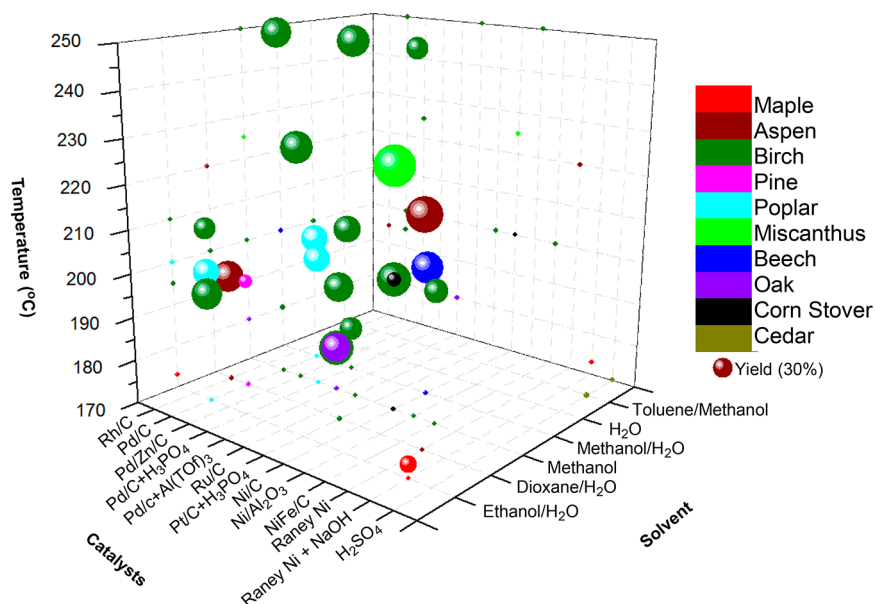


Figure 12. Summary of reductive catalytic fractionation processes developed to obtain aromatic monomers at high yield and selectivity. (The ball size represents the total monomer yield).

propylguaiaicol (**M7G**) and 4-propanolguaiaicol (**M10G**), although in a lower yield compared to hardwood, due to the lower β -O-4 content as evidenced by Torr and co-workers¹⁸⁵ (Table 1, entry 5) who have found that the treatment of *Pinus radiata* (a species of pine native to the Central Coast of California and Mexico) with Pd/C at 195 °C for 24 h in dioxane/water (1:1) under hydrogen, results in high yield (~20%) of 4-propanolguaiaicol (**M10G**). Due to the high product selectivity in these systems, the further isolation of pure products is much easier compared to using hardwoods. For example, Abu-Omar and co-workers could obtain 4-propylguaiaicol (**M7G**) in 100% selectivity from softwood (WT-lodgepole pine) in the presence of their Pd/Zn/C catalytic system.¹⁸⁹

2.2.2. Role of the Catalyst Used. Catalysts play a central role in the reductive catalytic fractionation process since the hydrogenolysis of C–O bonds is metal dependent.^{11,21,24,32} Thus, a high degree of delignification and product yield can be accomplished by appropriate choice of the metal catalysts. In Figure 15, the most typical supported metal catalysts used for reductive catalytic fractionation processes are shown and these typically contain Ru, Pd, Rh, and Ni on activated C or occasionally Al₂O₃ supports. On the basis of these results it can be concluded that Ni,^{196,203} Pd,^{197,198} and Rh¹⁸⁴ based catalyst normally lead to 4-propanolguaiaicol (**M10G**) and 4-propanolsyringol as main products. On the other hand, when using Ru, mainly 4-propylguaiaicol (**M7G**) and 4-propylsyringol (**M7S**) can be obtained.¹⁸⁸ Interestingly, when Fe²⁰² or W²⁰⁷ was added to the Ni catalysts, the –OH content in the monomer mixtures decreased dramatically and shifted the main products to 4-propylguaiaicol (**M7G**) and 4-propylsyringol (**M7S**).

In order to further address the role of catalyst composition, Sels and co-workers compared Ru/C and Pd/C catalysts under identical reaction conditions (250 °C, 30 bar, 3 h in methanol)¹⁹⁰ (Table 1, entry 10). With the use of identical starting material, the liquid product yields were very similar for both catalysts, as expected; however, with Ru/C preferentially 4-propylphenolics (**M7G** and **M7S**) were obtained among which 75% accounted for 4-propylguaiaicol (**M7G**) and 4-propylsyringol (**M7S**), while the use of Pd/C favored the formation of 4-propanol-derivatives with

a combined 91% selectivity toward 4-propanolguaiaicol (**M10G**) and 4-propanolsyringol (**M7S**).

Abu-Omar and co-workers²⁰⁸ designed an easy method to prepare and fully recyclable Zn/Pd/C catalyst, which was far more effective than Pd/C alone for the hydrogenolysis of the β -O-4 lignin model compounds and the subsequent reductive deoxygenation of the obtained aromatic fragments. Dimer as well as polymer (all β -O-4 synthetic lignin polymer that has a Mn of 3390 and DPn of 12.1) model compounds²⁰⁹ were used to confirm the rapid hydrogenolysis of the aromatic ether bonds as well as selective removal of the hydroxyl groups on the alkyl chains. The same catalyst was successfully applied in the conversion of lignocellulose as well¹⁸⁹ (Table 1, entry 9). Three different types of poplar lignocelluloses were depolymerized using the Zn/Pd/C catalyst in methanol, which resulted in 40–54% conversion of the native lignin and 4-propylguaiaicol (**M7G**) and 4-propylsyringol (**M7S**) as main products. Surprisingly, when pine lignocellulose was used as feedstock, 100% selectivity of 4-propylguaiaicol (**M7G**) was achieved. A detailed mechanistic study to explain the synergistic effect between Pd/C and Zn^{II} system was conducted, using both lignin model compounds and lignocellulosic biomass.²¹⁰ As shown in Figure 16, reaction of lignin model compound with Pd/C in the absence of Zn^{II} removes the benzylic OH group at C_ω leaving the OH group at C_γ intact to selectively produce 4-propylguaiaicol (**M7G**) and guaiaicol (**M24G**). While using the Zn/Pd/C catalyst, a six-membered intermediate involving Zn^{II} was formed (confirmed by NMR spectroscopy), which resulted in the removal of the primary OH at C_γ of the β -O-4 ether linkage. After further hydrogenation reaction, 4-propylguaiaicol (**M7G**) was obtained as the main product.

2.2.3. Influence of Additives. Regarding the use of reductive catalytic fractionation (RCF) in a biorefinery, the extent and rate of delignification as well as the activity of the catalyst toward depolymerization are key factors determining the yield and chemical structure of the obtained products. Both these processes can be strongly affected by the choice of an appropriate catalyst. Without any additives, delignification is relatively inefficient, generally requiring long reaction times or relatively

Table 1. Reductive Catalytic Fractionation of Lignocellulose^{a,b,c,d}

Entry	Feedstock	Catalyst	Reaction conditions			Sugar retention	Yield of main products	Monomer Yield ^a	Year ^{ref.}	
			Solvent	T (°C)	P (bar)					T (h)
1	Maple	Raney Ni + NaOH	Dioxane/ H ₂ O (1:1)	173	H ₂ (210)	6	N. R. ^b	 15.4 wt% 2.2 wt% 6.2 wt% 3.6 wt%	27.3 wt%	1948 ¹⁸²
2	Aspen	Raney Ni	Dioxane/ H ₂ O (1:1)	220	H ₂ (35)	5	N. R.	 5.6wt% 6.6wt% 28.5wt% 12.7wt% 5.7wt%	59.1 wt%	1963 ¹⁸³
3	Aspen	Rh/C	Dioxane/ H ₂ O (1:1)	195	H ₂ (34)	5	N. R.	 12.9 wt% 7.4 wt% 25.6 wt% 4.2 wt%	50.1 wt%	1978 ¹⁸⁴
4	Birch	H ₃ PO ₄ + Pt/C	Dioxane/ H ₂ O (1:1)	200	H ₂ (40)	4	N. R.	 21.1 wt% 6.1 wt% 14.5 wt% 4.8 wt%	46.5 wt%	2008 ¹⁸⁴
5	Pine	Pd/C	Dioxane/ H ₂ O (1:1)	195	H ₂ (34.5)	24	N. R.	 1.6 wt% 20.8 wt%	22.4 wt%	2011 ¹⁸⁵
6	Birch	Ni/C	Methanol	200	Ar (1)	6	N. R.	 36.2 wt% 11.9 wt% 0.5 wt% 5.4 wt%	54 wt%	2013 ¹⁸⁶
7	Birch	Pd/C	Ethanol/ H ₂ O (1:1)	195	Ar (4)	1	N. R.	 49 %	49 % (C- Yield)	2014 ¹⁸⁷
8	Birch	Ru/C	Methanol	250	H ₂ (30)	6	81 % (C-Yield)	 30.5 % 10.4 % 2.3 % 2.3 % 6.0 %	51.5% (C- Yield)	2015 ¹⁸⁸
9	Poplar	Zn/Pd/C	Methanol	225	H ₂ (34.5)	12	79 wt%	 29.7 wt% 24.3 wt%	54 wt%	2015 ¹⁸⁹

Table 1. continued

Entry	Feedstock	Catalyst	Reaction conditions			Sugar retention	Yield of main products	Monomer Yield ^a	Year ^{ref.}	
			Solvent	T (°C)	P (bar)					T (h)
10	Birch	Pd/C	Methanol	250	H ₂ (30)	3	89 % (C-Yield)	 1.4 % 0.4 % 35.2 % 9.7 % Others 2.6 %	49.3 % (C-Yield)	2015 ¹⁹⁰
11	Birch	Ni/C	Methanol	200	N ₂ (2)	6	N. P.	 18 wt% 10 wt% 3 wt% 1 wt%	32 wt%	2015 ¹⁹¹
12	Cedar	H ₂ SO ₄	Toluene/ Methanol	170	Air	0.1	N. P.	 ~5.4 % ~4.6 %	10 wt%	2015 ¹⁹²
13	Birch	Pd/C	Ethanol/ H ₂ O (1:1)	210	Ar	15	84.4 wt%	 20 wt% 4 wt% 11 wt% 1 wt%	36 % (C-Yield)	2016 ¹⁹³
14	Poplar	H ₃ PO ₄ + Pd/C	Methanol	200	H ₂ (20)	3	72 wt%	 4 % 1 % 21 % 14 % Others 2 %	42 % (C-Yield)	2016 ¹⁹⁴
15	Miscanthus	Ni/C	Methanol	225	H ₂ (60)	12	86 wt%	 19 wt% 21 wt% 16 wt% 12 wt%	68 wt%	2016 ¹⁹⁵
16	Beech	Ni/C	Methanol/ H ₂ O (3:2)	200	H ₂ (60)	5	N. P.	 7.9 wt% 0.7 wt% 28.9 wt% 9.8 wt% Others 4.1 wt%	51.4 wt%	2016 ¹⁹⁶
17	Poplar	Pd/C	Methanol/ H ₂ O (7:3)	200	H ₂ (20)	3	~66.7 wt%	 4.4 wt% 0.6 wt% 21.5 wt% 14.0 wt% Others 2.9 wt%	43.5 wt%	2016 ¹⁹⁷
18	Poplar	Pd/C	Ethanol/ H ₂ O (1:1)	200	H ₂ (20)	3	~73.2 wt%	 5.0 wt% 0.5 wt% 21.5 wt% 14.2 wt% Others 2.2 wt%	43.3 wt%	2016 ¹⁹⁷

Table 1. continued

Entry	Feedstock	Catalyst	Reaction conditions				Sugar retention	Yield of main products	Monomer Yield ^a	Year ^{ref.}
			Solvent	T (°C)	P (bar)	T (h)				
19	Birch	Pd/C	H ₂ O	200	H ₂ (30)	3	55 wt%		43.8 wt%	2016 ¹⁹⁸
20	Corn Stover	Ni/C	Methanol	200	H ₂ (30)	3	76 wt%		24.5 wt%	2016 ¹⁹⁹
21	Birch	Pd/C + Al(OTf) ₃	Methanol	180	H ₂ (30)	2	76.5 wt%		55 wt%	2017 ²⁰⁰
22	Oak	Pd/C + Al(OTf) ₃	Methanol	180	H ₂ (30)	2	76.6 wt%		46 wt%	2017 ²⁰¹
23	Birch	NiFe/C	Methanol	200	H ₂ (20)	6	N. R.		39.5 wt%	2017 ²⁰²
24 ^c	Birch	Ni/Al ₂ O ₃	Methanol	250	H ₂ (30)	3	84.9 wt%		36 wt%	2017 ²⁰³
25 ^d	Birch	Pd/C + H ₃ PO ₄	Methanol/ H ₂ O (7:3)	180	H ₂ (30)	3	~56 wt%		37 wt%	2017 ²⁰⁴

^aYield calculated based on lignin content in each wood. ^bN. R. means not reported. ^cNi/Al₂O₃ pellets in basket. ^dReaction operated in a flow-through system.

high temperatures and operating pressures (large energy input); however, a near-complete delignification is desired for achieving high monomer yields. Lignocellulose fractionation processes usually require the addition of acid or alkaline additives in order to enhance lignin and/or hemicellulose removal at lower temperature and pressure.¹¹ Therefore, such additives were also applied in the catalytic lignocellulose fractionation (Figure 17). The effect of these additives on the catalyst and the depolymerization step was studied.

Sels and co-workers studied the influence of H₃PO₄ and NaOH additives on the Pd/C catalyzed reductive processing of poplar lignocellulose in methanol¹⁹⁴ (Table 1, entry 14). The

addition of small quantities of H₃PO₄ resulted in the modification of the carbohydrate fraction: instead of a carbohydrate-rich pulp and stable lignin oil, three product streams were obtained consisting of lignin oil, cellulose pulp, and hemicellulose alcoholysis products. The addition of H₃PO₄ strongly promoted delignification and resulted in lignin product oil with narrow molecular weight distribution and a monomer yield close to the theoretical maximum. These results are similar to those reported by Yan and co-workers¹³⁴ (Table 1, entry 4). The yield of lignin-derived monomers and dimers both increased when 1 wt % H₃PO₄ was added to the Pt/C catalyst. The addition of NaOH under similar catalytic conditions also enhanced

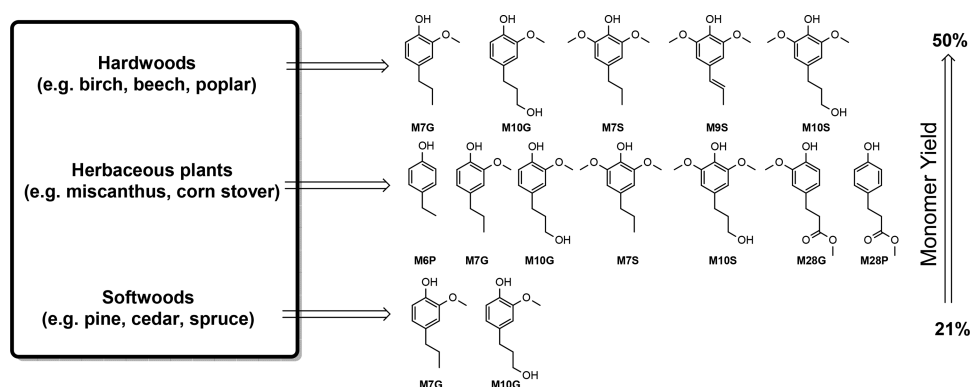


Figure 13. Structures of phenolic monomers derived from native lignin of different resources. On the basis of results of ref 188. Reaction conditions: 2 g of substrate, 0.3 g of 5% Ru/C, 40 mL of methanol, 250 °C, 3 h, 30 bar H₂.

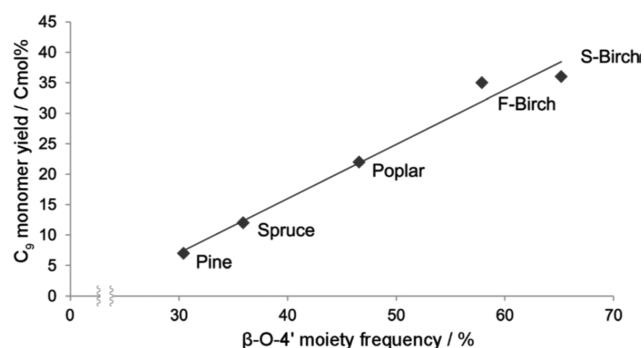


Figure 14. Correlation between the yield of phenolic monomers and the frequency of the β -O-4 moiety in native lignin for different lignocellulose substrates. Reprinted with permission from ref 193. Copyright 2016 Wiley-VCH.

delignification but led to lower monomer yield. This has been attributed to base-catalyzed repolymerization under these reactions, especially when softwood comprising mainly guaiacol units was used, whereby the free 3 position in the G-type monomers can participate easier in condensation reactions. Another disadvantage of using NaOH was the loss of cellulose, through partial cellulose amorphization and/or swelling, making the cellulose structure more accessible for catalytic processing. Pepper and Hibbert also reported the addition of NaOH when using Raney Ni as catalysts¹⁸² (Table 1, entry 1), and a high yield of phenolic monomers (mainly M6G, M6S and 4-(2-hydroxyethyl)-2-methoxyphenol M29G, 27.3%) at 175 °C were obtained; however, the influence of base on delignification and carbohydrate retention was not discussed.

Hensen and co-workers found that water-tolerant metal triflates are very active Lewis acid catalysts for the cleavage of

the chemical bonds between lignin and carbohydrates, leading to very efficient delignification and removal of a significant fraction of hemicellulose sugars from lignocellulose, leaving behind a cellulose-rich solid residue. The combination of Lewis and Brønsted acids with metal-catalyzed lignin depolymerization resulted in high aromatic monomer yields.^{200,201,205} In the presence of Pd/C as the hydrogenation and Al(III) triflate as acid catalyst, an excellent 46 wt % aromatic monomer yield was obtained (30 bar H₂, 180 °C). In order to understand possible synergistic effects between the metal triflates and Pd/C, the reactivity of several dimer model compounds was studied and it was concluded that both the metal triflate as well as the Pd/C played a role in the depolymerization step. Compared to Pd/C alone, the addition of metal triflates facilitated the cleavage of C–O bonds in (β -O-4) ether linkages. Further it was found that Pd/C is able to cleave a wide range of ether linkages such as α -O-4, 4-O-5, and β - β . Lower Pd/Al ratios resulted in 4-*n*-methoxypropylsyringol (M30S)/4-*n*-methoxypropylguaiacol (M30G) as dominant reaction products, while higher ratios led to formation of 4-propanolguaiacol (M10G)/4-propanolsyringol (M10S) and 4-propylguaiacol (M7G)/4-propylsyringol (M7S) products (Figure 18). The system was successfully upscaled to 100 g lignocellulose without any change in monomer yield. However, the authors considered the relatively high price of metal triflates for future industrial application. Therefore, strong Brønsted acids (H₂SO₄ and HCl) were successfully used in search for a cheaper acid cocatalysts²⁰¹ (Table 1, entry 22), both resulting in high yields of lignin monomers (40% and 44%) from oak sawdust. Weaker acid (H₃PO₄) was also able to cleave phenyl glycoside bonds and β -O-4 ether bonds but not the ester type lignin-carbohydrate linkages so the products contained lower amount of lignin monomers (26%).

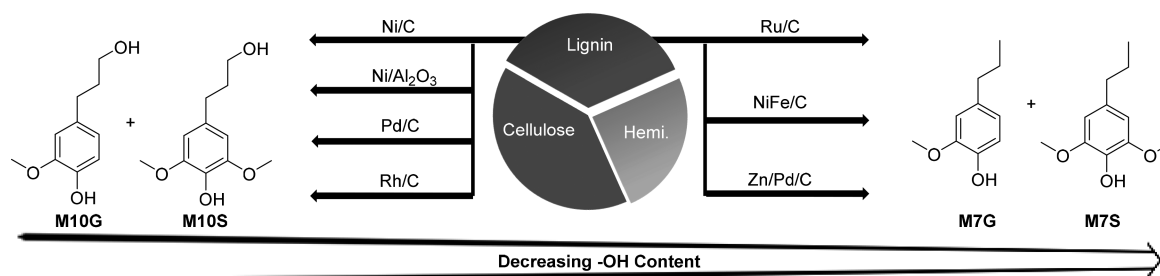


Figure 15. Structures of main products depending on type of catalyst after reductive catalytic fractionation under H₂ pressure.

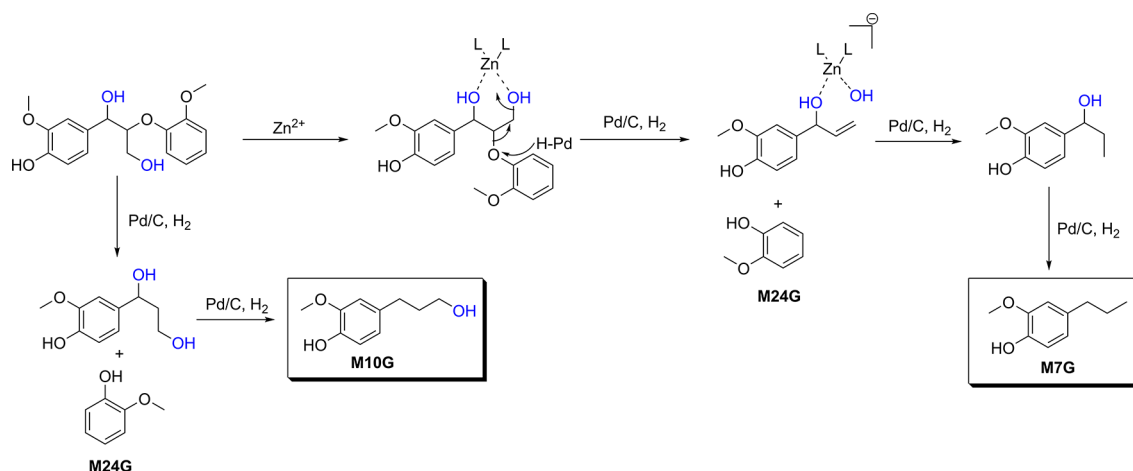


Figure 16. Proposed mechanism of cleavage and hydrodeoxygenation of β -O-4 ether linkage by Pd/C catalyst and Pd/C and Zn^{II} catalysts. Adapted with permission from ref 210. Copyright 2016 Royal Society of Chemistry.

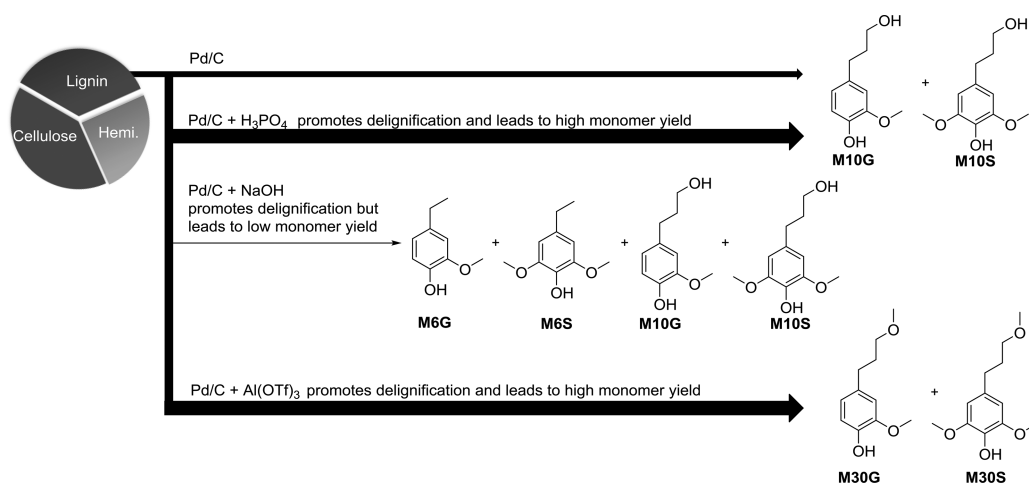


Figure 17. Reductive catalytic fractionation using Pd/C only or Pd/C in combination with different additives.

Román-Leshkov¹⁹⁹ (Table 1, entry 20) confirmed the promoting effect of homogeneous and heterogeneous acid cocatalysts in the reductive catalytic fractionation of corn stover using carbon-supported Ru and Ni catalysts at 200 and 250 °C in methanol. In one experiment, the application of acidified carbon support increased monomer yields to 32%, that is comparable to other systems in which phosphoric acid (38%) was used in combination with a Ni/C catalyst at 200 °C.

Watanabe and co-workers¹⁹² (Table 1, entry 12) treated two types of wood species, namely eucalyptus globulus and cedar, with a catalytic amount (<1%) of sulfuric acid in a mixture of hydrophobic solvent (e.g., toluene) and alcohol (e.g., methanol) to result in homovanillyl aldehyde dimethyl acetal (**M31G**) and homosyringaldehyde dimethyl acetal (**M31S**) at 140 °C. Owing to the presence of methanol, the aromatic C2 enol ether intermediate obtained upon acid catalysis underwent acetal formation in situ. This method also generated oligolignols besides the corresponding dimethyl acetal derivatives.

2.2.4. Influence of Solvents. Solvents also play a crucial role in delignification as well as depolymerization, influencing the yield of phenolic monomers and dimers, and the amount of carbohydrates retained.^{39,211} In this part, the impact of the solvent on both cellulose and hemicellulose retention and delignification efficiency will be addressed.

Sels and co-workers¹⁹⁸ (Table 1, entry 19) studied the solvent effects using bio-derived solvents with varying properties in the Pd/C catalyzed reductive processing of birch wood. The extent of delignification was found most favorable in water and decreased with increasing apolar character of the solvents (Figure 19). With ethylene glycol as well as methanol, high delignification was seen. This effect was lower in cyclic ethers, tetrahydrofuran, and 1,4-dioxane and totally disfavored in nonpolar solvents such as *n*-hexane. The phenolic mono-, di-, and oligomer yields roughly followed a similar trend. The phenolic monomer distribution was very similar in all solvents, mainly containing 4-propanolsyringol (**M10S**) and 4-propanolguaiacol (**M10G**). In contrast, the composition of the dimer fraction obtained in the various solvents was substantially different: in water and methanol mainly β -1- and β -5-linked dimers with a $-\text{CH}_2\text{OH}$ -substituted ethylene bridge were obtained, while in ethylene glycol unsubstituted analogues were found in much greater extent.

Several earlier studies for the valorization of *protolignin* described the application of ethanol/water,¹⁸⁷ isopropanol/water,^{212,213} and dioxane/water^{134,183–185} solvent mixtures. Similarly, Sels and co-workers¹⁹⁷ then studied the effect of different MeOH/water and EtOH/water mixtures on the reductive catalytic fractionation of poplar wood (Table 1, entries 17 and 18). It was demonstrated that the addition of water to an

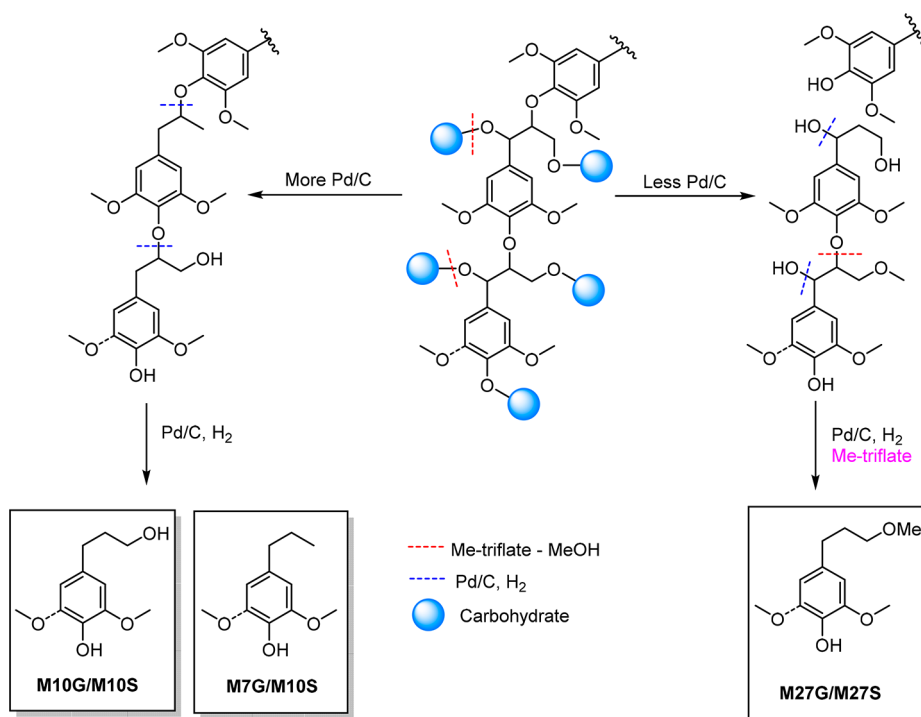


Figure 18. Reductive depolymerization of wood lignin into phenolic monomers over a tandem Pd/C and Al(III)-triflate catalyst system, at different Pd/Al ratios. Adapted with permission from ref 200. Copyright 2017 Royal Society of Chemistry.

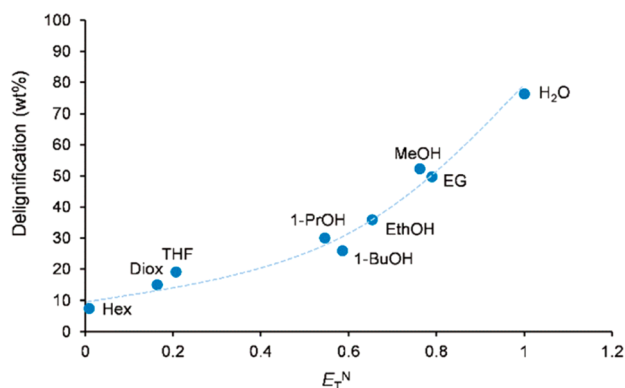


Figure 19. Birch delignification vs solvent polarity as described by the Reichardt parameter (E_T^N). Reproduced with permission from ref 198. Copyright 2015 Royal Society of Chemistry.

alcohol solvent significantly enhanced the extraction of lignin, and the results were similar to methanol/water and ethanol/water solvent systems. By adding low amounts of water (≤ 50 vol %), the delignification strongly increased from 52 wt % to 80 wt %. Addition of more water however decreased the degree of delignification, down to 65 wt % for pure water. Thus a positive synergetic effect of mixing methanol and water with respect to the conversion of lignin was observed. The monomer yields showed similar trends with increasing water loading and reached a maximal value of 44 wt % at 30 vol % water content. Similar experiments were performed with ethanol/water mixtures as ethanol is less harmful and more readily available from biomass fermentation. The maximal degree of delignification for ethanol/water (82 wt %) was almost equal to that of methanol/water (80 wt %). Additionally, the composition and structure of the pulp was characterized showing that low water concentrations (≤ 30 vol %) preserved most of the carbohydrates as solid pulp;

however, with water-rich (≥ 70 vol %) solvents, the majority of the hemicellulose fraction was removed, while the cellulose fraction was largely left unaltered.

The positive effect of adding water was also confirmed by Chen et al.¹⁹⁶ They developed the catalytic fractionation of beech sawdust using a Ni/C catalyst in a methanol–water cosolvent (Table 1, entry 16). The total monomer yield increased from 39.3 wt % to 51.4 wt % when 40 vol % water was added to pure methanol.

The ideal reductive catalytic fractionation process would proceed in pure water; however, redeposition of the dissolved lignin on the wood fiber surface presents a major problem, a phenomena only seldom discussed.²¹⁴ In this regard, the addition of an organic solvent plays an important role as it retards the redeposition of lignin onto the other biomass components after separation.²¹⁵ This is also likely the reason why higher product yields are obtained when an organic cosolvent is used.

2.2.5. Use of Hydrogen Donors Instead of Hydrogen Gas. Alcohols and acids that can be derived from renewable sources can serve as hydrogen source. A seminal method combining transfer hydrogenation and hydrogenolysis was developed by Rinaldi and co-workers using a commercial Raney Ni catalyst. In earlier studies, H-transfer reactions in 2-propanol for hydrogenolysis of lignin model compounds, organosolv lignin²¹⁶ and upgrading of bio-oil^{217,218} were investigated in the presence of Raney Ni and solid acids. Then poplar lignocellulose was treated in the presence of Raney Ni in 2-propanol/water solution, and a lignin-derived oil and a solid carbohydrate residue was obtained. The lignin bio-oil, originating from native lignin mainly contained phenolic monomers and was efficiently hydrodeoxygenated under low-severity conditions. Interestingly, separation of Raney Ni could be achieved by simple magnetic forces. The pulp obtained by this method contained very low amount of lignin, and the authors proposed that it may

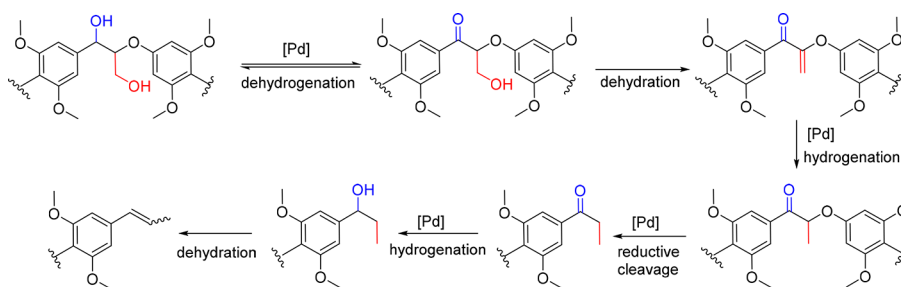


Figure 20. Proposed mechanism of aryl propene formation during Pd-catalyzed hydrogenolysis, established by model compound studies. Adapted with permission from ref 187. Copyright 2014 Wiley VCH.

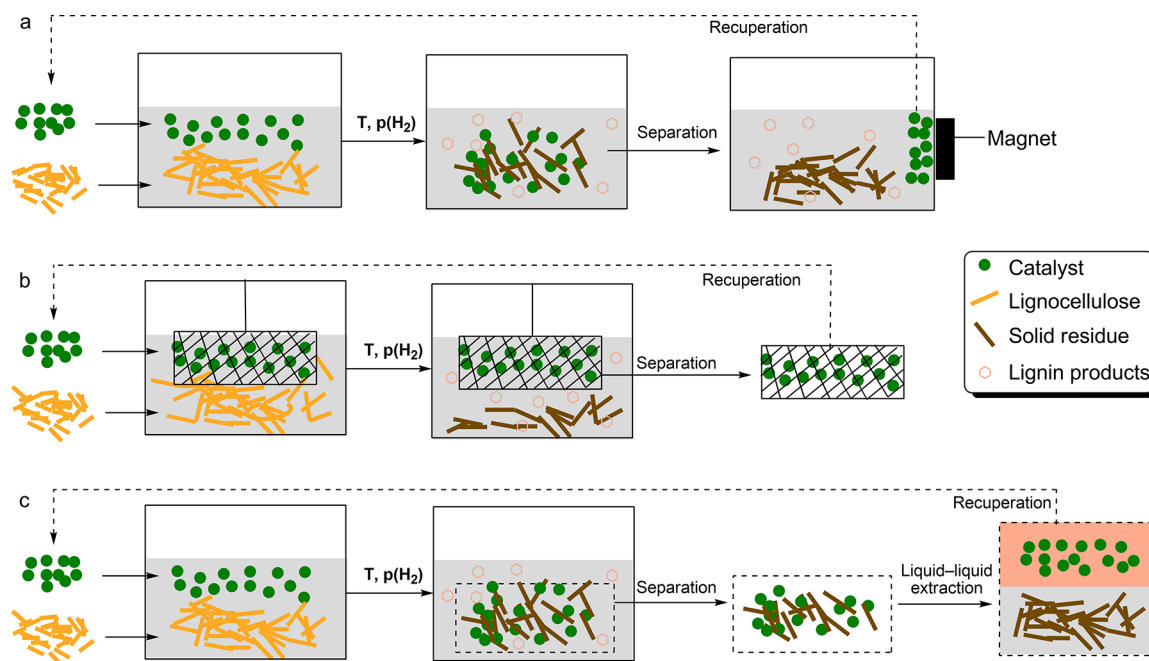


Figure 21. Solutions developed for the separation of catalysts from solid residue after reductive catalytic fractionation process. (a) Separation of a magnetic catalyst by application of magnetic field, (b) Using a microporous catalyst cage, and (c) Liquid-liquid extraction.

be suitable for further upgrading to the production of biofuels, chemicals, or papers.²¹⁹

Song and co-workers¹⁸⁶ (Table 1, entry 6) developed an elegant method using Ni/C catalyst in the presence of alcohols as hydrogen donors. Under optimized conditions (200 °C, 6 h, 1 MPa Ar), the native birch-wood lignin was converted into 4-propylguaiacol (**M7G**) and 4-propylsyringol (**M7S**) with the best selectivity of 97% for both and the total monomers yields reached 54%. It was proposed that lignin is first fragmented into smaller lignin species through alcoholysis reactions, and then smaller fragments are converted into monomeric phenols over the Ni/C catalyst.

Formic acid can be easily obtained from hydrogenation of carbon dioxide²²⁰ and is also generated as a byproduct from biomass degradation processes.²²¹ Recently it has attracted much interest in the area of green chemistry because of its potential as a hydrogen carrier and as means of utilizing carbon dioxide. Samec and co-workers developed the palladium-catalyzed transfer hydrogenolysis of primary, secondary, and tertiary benzylic alcohols by formic acid.²²² On the basis of this, a tandem organosolv and Pd-catalyzed transfer hydrogenolysis system was devised (Table 1, entry 7).¹⁸⁷ Surprisingly, 23% yield of 4-(1-propenyl)guaiacol (**M18G**) was generated from pine lignocellulose, and 49% yield of 4-(1-propenyl)syringol (**M18S**) was

obtained from birch wood. The generation of aryl propene from lignin in wood could be explained by the mechanism proposed by the authors (shown in Figure 20). First, the ketone intermediate was formed by Pd-catalyzed dehydrogenation of the benzylic alcohol. The corresponding α,β -unsaturated ketone was then generated by dehydration reaction. Pd with chemisorbed hydrogen then catalyzed the following hydrogenation and reductive cleavage reaction. Finally, the corresponding aryl propene was generated by first hydrogenation of ketone and then dehydration of the hydroxyl group.

Besides using hydrogen donors, it is also possible to perform the reductive catalytic fractionation of lignocellulose under hydrogen-free conditions as proposed by Samec and co-workers.¹⁹³ In this system, part of the lignocellulose (hemicellulose) could be utilized as an internal source of hydrogen for the reductive lignin transformations. In this efficient RCF process, the total monomers yield was as high as 40% (**M7S**, 23% and **M18S**, 14%) in only 2 h at 210 °C, using Pd/C.

2.2.6. Recycling of Catalysts. Recuperation of the heterogeneous catalyst⁵⁵³ after reductive catalytic fractionation is a very important aspect, considering the overall economics of the process. It is highly desired to achieve efficient catalyst recycling and at the same time sufficiently high quality catalyst-free pulp, that is suitable for further applications. Several studies

have reported good catalyst reusability by different separation processes which included using ferromagnetic catalysts (Figure 21a) like Ni/C¹⁸⁶ and Raney Ni,²¹² using a microporous catalyst cage,^{195,203} (Figure 21b) or catalyst recovery by liquid–liquid extraction^{188,200} (Figure 21c).

Song and co-workers¹⁸⁶ (Table 1, entry 6) demonstrated that nickel-based catalysts are highly active and selective in the conversion of native lignin, and the best selectivity of 97% toward monomeric phenols was achieved at 50% conversion from birch wood lignin. The magnetic Ni/C catalyst could be easily separated by a magnetic bar and reused. Conversion of lignin remained as high as 50% for 4 consecutive reactions, indicating good stability and reusability of the Ni/C catalyst. The Raney Ni could be separated with the same method as well, and the isolated yield of lignin bio-oil remained at $23 \pm 2\%$ throughout eight recycling experiments.²¹²

A different creative solution was developed in the group of Abu-Omar¹⁹⁵ that relies on the physical separation of the catalyst from the substrate by means of a microporous catalyst cage (Figure 21b). After reaction, over a Ni/C catalyst (Table 1, entry 15), nickel-free cellulose residue was obtained and the catalyst was reused in three consecutive reactions. However, the ability of the Ni catalyst to function as a hydrogenation catalyst decreased with each reuse, and this lead to the shift in monomer selectivity. Sels and co-workers²⁰³ developed a related method using a reactor basket, filled with catalyst pellets (Ni–Al₂O₃, 1.2 × 3 mm). The commercial Ni–Al₂O₃ catalyst pellets in the basket could be easily separated after reaction, resulting in monomer-enriched lignin oil, a catalyst-free carbohydrate pulp, and the catalyst could be quantitatively recuperated. Compared with Ni–Al₂O₃ powder, the Ni–Al₂O₃ catalyst in the basket gave slightly lower monomer yield but similar selectivity. A systematic decrease in the phenolic monomer yield of ~2% was observed, which showed catalyst deactivation after each recycling step; however, a H₂-treatment after 5 runs almost completely recovered the performance of the spent catalyst. Tandem regeneration/recycling experiments, in which the Ni–Al₂O₃ pellets were treated with H₂ before each run, showed excellent performance without significant changes in both monomer yields and selectivity.

Liquid–liquid extraction of the catalyst from the solid residue was first reported by Sels and co-workers¹⁸⁸ (Table 1, entry 8). In their study, the Ru/C catalyst could be recovered from the decane phase, while the more polar carbohydrate pulp was located at the bottom of the methanol phase. The recycled catalyst showed a phenolic monomer yield of 48% which is similar to the fresh catalyst (50%). Good selectivity toward 4-propanolsyringol (M10S) and 4-propanolguaiacol (M10G) as well as a higher C5 sugar retention of 83% was observed using the recycled catalyst. However, the drawback of the liquid–liquid extraction was that only a part of the catalysts could be recovered (about 30% recovery).¹⁹⁸

Considering the better solubility of metal triflates in water compared to common organic solvents, Hensen and co-workers²⁰⁰ recovered Al(III)-triflate from the liquid products by using a solvent mixture of ethyl acetate and water (Table 1, entry 21). However, Al(III)-triflate could not be fully recovered by this workup procedure, and the total monomer yield in the next catalytic step decreased to 37 wt % from 52 wt %.

2.2.7. Utilization of the Solid Residue. The advantages of reductive catalytic fractionation processes are mild reaction conditions and high selectivity for lignin-derived monomers. Another advantage is that the carbohydrate solid residue retains

its value for the further upgrading to produce platform chemicals (Figure 22) as long as separation from the catalyst is sufficient.

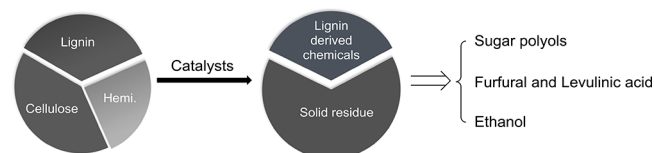


Figure 22. Possible applications of the solid residue after reductive catalytic fractionation.

Sels and co-workers¹⁸⁸ successfully converted the carbohydrate solid residue to sugar polyols in water by tungstosilicic acid with a maximal total yield of 74%. Abu-Omar and co-workers¹⁹⁵ targeted the platform chemicals furfural (55%) and levulinic acid (76%) by using iron-trichloride at 200 °C.

Furthermore, when Ni/Al₂O₃ pellets were used as catalyst²⁰³ in a microporous cage, the carbohydrate solid residue was easily separated with the catalysts and then subjected to a saccharification and fermentation experiment resulting in a total yield of 73% bioethanol, showing great promise for the total utilization of lignocellulose. Román-Leshkov¹⁹⁹ subjected the obtained sugars to enzymatic digestion, reaching conversions above 90% in 96 h. All of the residual solids showed comparable digestibility, producing glucan and xylan with more than 80% yield. Samec et al.¹⁹³ treated the pulp with a commercially available enzyme mixture at 50 °C for 72 h, thereby the pulp could be converted to glucose. The shorter treatment time of the first catalytic fractionation step generally resulted in higher glucose yields. The authors also found that hardwood pulps normally resulted in higher glucose yield than softwood pulps. This was attributed to either the difference in pulp structure (higher lignin content in softwood pulp) or the absence of softwood-specific hemicellulose activity in the enzyme cocktail used.

Recently, this group reported that the pulp generated in a flow setup consisting of a percolation reactor filled with woody biomass and a fixed catalytic bed reactor filled with Pd/C was enzymatically hydrolyzed to glucose in 87 wt % yield without prior purification.²⁰⁴

2.3. One-Pot Catalytic Processes

One-pot catalytic processes are able to completely convert all components of lignocellulose to a range of chemicals, simultaneously. Ford and his research group introduced the use of copper-doped hydrotalcite-based porous metal oxides (PMO) for the broader use in catalytic conversion of various lignocellulose-derived materials.²²³ First, the selective cleavage of the aromatic ether bond in a simple lignin model compound dihydrobenzofuran (DHBf) was achieved in supercritical methanol.²²⁴ The Cu-doped PMO served multiple purposes, catalyzing substrate hydrogenolysis and hydrogenation as well as the methanol reforming and water gas shift reaction, allowing for hydrogen to be in situ derived from the solvent itself. Later, under similar reaction conditions (300 °C, ~200 bar) poplar wood organosolv lignin was also successfully converted to very clean mixtures of substituted cyclohexanols.¹³⁰ Importantly, for the first time, no insoluble char was observed during the reaction. With this catalytic system, lignocellulose was fully and rapidly converted to a mixture of cellulose-derived (C2–C6) and lignin-derived (C9+) aliphatic alcohols without formation of char.²²⁵

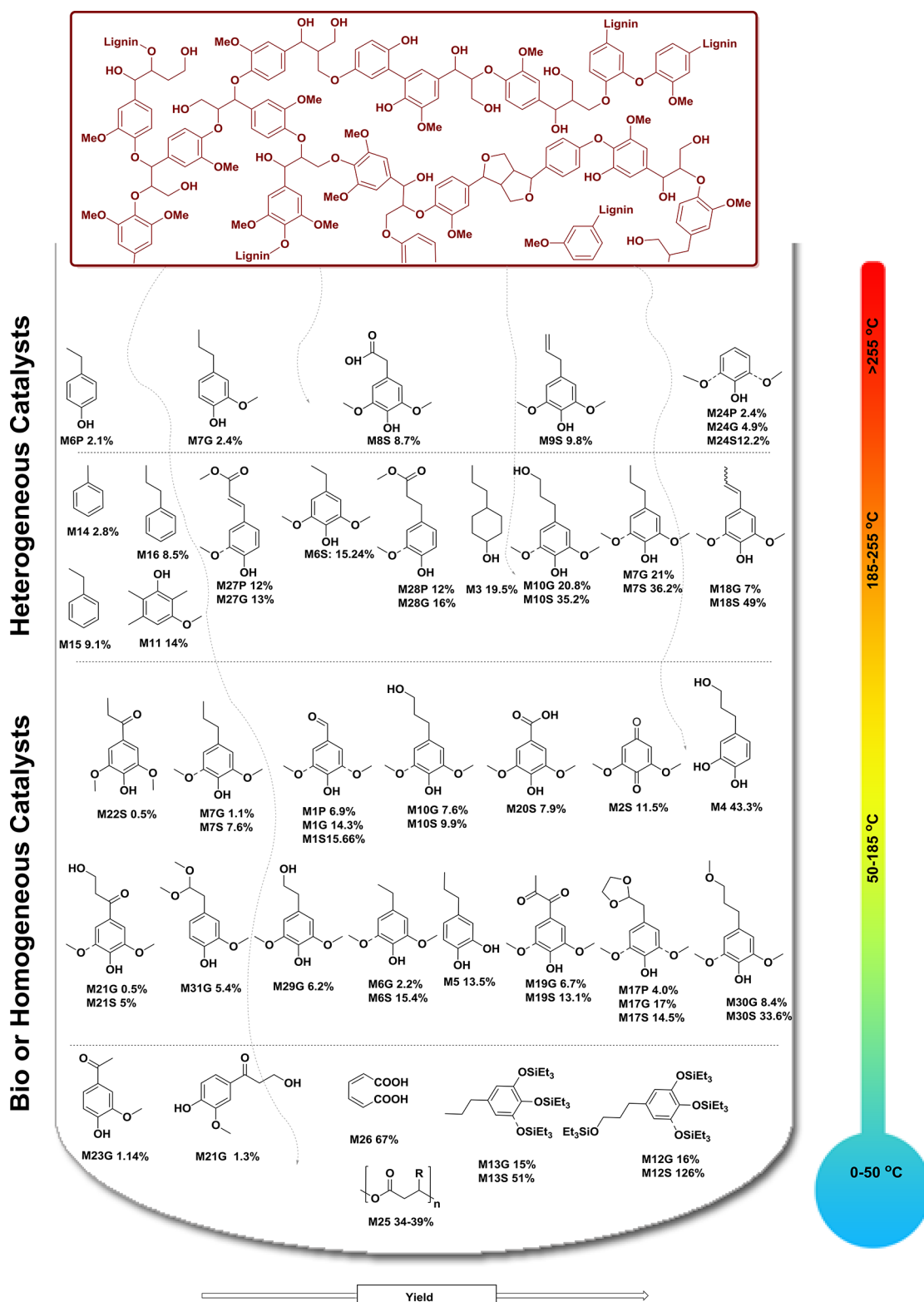


Figure 23. A summary of lignin-based monomers obtained via the different catalytic processes in section 2.

Zhang and co-workers²⁰⁷ converted woody biomass directly into two groups of chemicals over a carbon-supported Ni–W₂C catalyst. The carbohydrate fraction was converted to ethylene glycol and other diols with a total yield of up to 75.6% while lignin underwent selective catalytic processing into mono-phenols (4-propanolphenols and 4-propylphenols) with a yield up to 46.5% (based on lignin) at 235 °C under 60 bar hydrogen.

Catalyzed by layered LiTaMoO₆ in the presence of Ru/C in an aqueous phosphoric acid medium, different biomass resources (e.g., pine sawdust, corn stalk, corncob, wheat straw, and rice straw) were converted to gasoline alkanes, monophenols, and related hydrocarbons.²²⁶

A wide variety of raw lignocellulose could be used for the production of liquid alkanes by a one-pot catalytic process

reported by Wang and co-workers. With the multifunctional Pt/NbOPO₄ catalyst, excellent mass and carbon yields were achieved in cyclohexane as solvent.²²⁷ The same group also developed a selective procedure to obtain arenes via direct hydrodeoxygenation of organosolv lignin over a porous Ru/Nb₂O₅ catalyst. Remarkably, this catalytic system enabled the complete removal of the oxygen content from the lignin-derived aromatic monomers obtained from lignin.¹⁵⁹ The conversion of birch lignin was nearly quantitative, and the products consisted of C7–C9 hydrocarbons with a total mass yield of 35.5 wt % and arenes with an exceptional selectivity of 71 wt %. All these processes operated under relatively high temperature (>190 °C) and resulted in complex product mixtures.

2.4. Summary of Catalytic Processes

The catalytic methods targeting selective lignin depolymerization resulted in various defined building blocks, mainly aromatic chemicals, which are summarized on Figure 23 (the structure, full name, and code for each compound is also listed in Figure S1). Naturally, the degree of defunctionalization correlates with the reaction temperature, and the method of catalytic degradation have great influence on the structure of the obtained monomers. These monomers are mainly phenolic compounds with sufficient functionality to be further upgraded to value added chemicals.

It has to be mentioned that techno-economic calculations are available for a few products shown on Figure 23. For example, according to Global Market Insights, with the emerging expansion of the plastic industry, the muconic acid (M26) market is projected to grow from 36 million \$ in 2016 to 60 million \$ in 2024.²²⁸ Also, adipic acid that can be obtained from lignin is currently manufactured on a very large scale (2700000 tonnes annually) with relatively low price (1600\$/t) from petroleum.^{229,54} However, the conventional adipic acid production involving nitric acid oxidation presents serious drawbacks related to NO_x emissions.²²⁹

The selling price of petroleum-derived BTX components and phenol is currently low and difficult to compete with (benzene, 1.49\$/kg; toluene, 1.38\$/kg; xylene, 1.36\$/kg; phenol, 1.54\$/kg). However, if a cost competitive method would emerge for their production from lignin, there is huge potential (8000000 t annually for BTX and 8000000 t for phenol) without the danger of oversaturating the market.³⁷ 4-Alkylphenols may serve as replacements for petroleum-derived phenols in applications such as nonionic surfactants, lubricant additives, phenolic resins, polymer additives, and agrochemicals.^{143,230} In order to produce these from structures shown in Figure 23 (e.g., M6G, M6S, M7G, and M7S), methods for selective demethoxylation are needed. Phenol could also be produced from 4-alkylphenols through new C–C bond cleavage reactions.²³¹ Catechol is an important chemical that can be used directly or as a precursor for the production of pesticides, or other fine chemicals such as perfumes and pharmaceuticals; however, the conventional phenol to catechol pathways²³² generally suffer from low selectivities.²³³ An emerging pathway from lignin through guaiacol would provide a much more sustainable alternative. To this end, selective C–C bond cleavage and demethylation methods are required. Recent developments with regard to defunctionalization of lignin-derived aromatics to these simpler aromatics are discussed in section 3.

Another historically inexpensive petroleum-derived bulk chemical is styrene (1.9\$/kg).⁵¹ The demand for styrene shows a steady increase from 2.0 million metric tons (Mt) in 1970 to 3.2 million Mt in 1980 and 5.8 million Mt in 2004 in the

United States alone.²³⁴ A number of aromatic building blocks on Figure 23 could be potentially selectively defunctionalized to styrene; however, this will be the subject of future research.

The aromatic monomer 4-propylguaiacol (M7G) is frequently obtained by the lignin depolymerization strategies described in section 2. The price of such a typical monomer was recently found 1900\$/t.⁵³

Because lignin depolymerization is an emerging research area, selling prices for most obtained monomers are not yet available.

In the next section, we will explore the various possibilities for the further conversion of typical lignin-derived aromatic monomers to concrete products.

2.5. Conclusions

The large number of recent research papers summarized in section 2 suggests that lignin depolymerization has moved to the next level. A number of strategies exist that deliver interesting, emerging aromatic structures. It was generally recognized that recondensation phenomena either through lignocellulose processing or catalytic treatment seriously effect product yields, and a number of groups have focused on suppressing these side reactions. For example, near theoretical yields could be achieved by introducing formaldehyde during lignin isolation from lignocellulose,¹⁰⁵ or the stabilization of reactive intermediates during acidolysis of organosolv lignin^{101,166,167} was described. Catalytic fractionation methods, especially under reductive conditions have significantly improved the product yields, notably obtaining only a limited number of defined products instead of complex mixtures.⁴⁰

It is very difficult to provide a precise comparison of the novel catalytic methods developed for the depolymerization of organosolv lignin since the quality, molecular weight, solubility, and β -O-4 content of these starting materials differ strongly depending on the method of processing and isolation used by each research group. Therefore, standardization regarding method of isolation and reporting yields will be required to provide a better comparison of efficiency of the novel catalytic methods. A severe challenge at the moment is the lack of standard lignin samples of reproducible quality that would be suitable to benchmark novel methodologies. In addition, development of novel analytical methods and standardization of existing and emerging analytical techniques for understanding of the structure of lignocellulose and the resulting, frequently complex, product mixtures is desired.

Thus far, most catalytic methods have focused on tackling the fundamental challenge of selective bond cleavage in organosolv lignin or lignocellulose, focusing on the β -O-4 moiety. However, a significant knowledge gap exists regarding the cleavage of other types of linkages in lignin. In the future, more effort has to be devoted to the development of robust and recyclable catalysts which are tolerant to impurities. Novel catalytic systems should enable the full valorization of all lignocellulose components.

Upscaling of depolymerization methodologies as well as efficient methods for isolation and purification of the products, also in larger scale and efficient catalyst recycling should be investigated. Techno-economic analysis needs to be performed for these processes as well as possible products that may be derived from the emerging building blocks.

3. FUNCTIONALIZATION AND DEFUNCTIONALIZATION STRATEGIES

The lignin-derived monomers obtained in section 2 are less complex than lignin itself, however, keep some of the inherent

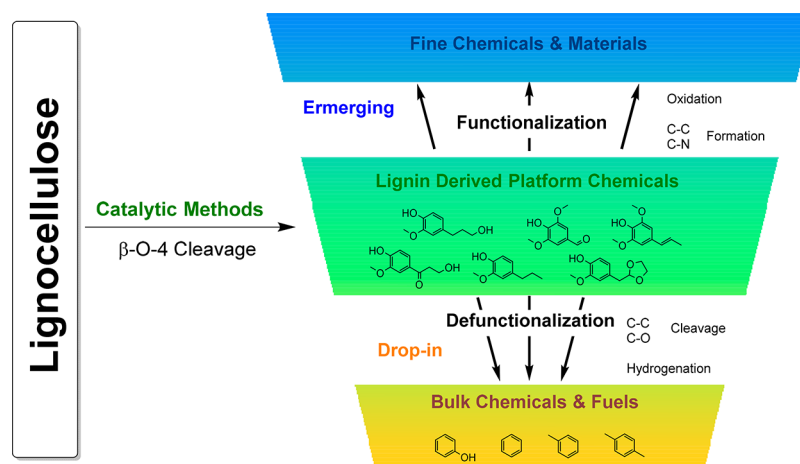


Figure 24. Summary of strategies for the conversion of lignin-derived monomers to emerging structures and bulk chemicals.

structural features of the renewable starting material. These structures will inspire new research directions in chemical catalysis that will focus on (a) selective functionalization to emerging building blocks and fine chemicals (b) selective defunctionalization to bulk chemicals (Figure 24).

Selective functionalization strategies should target atom economic and waste-free pathways for the direct conversion of aliphatic and aromatic alcohols to amines or the formation of new C–C bonds to obtain value-added products such as various polymer building blocks or pharmaceutical intermediates in few reaction steps, which will significantly contribute to achieving overall sustainability and meet green chemistry goals.²³⁵ Novel and efficient defunctionalization methods hold the promise of producing simpler drop in molecules (e.g., BTX, phenol, catechol, and cyclohexane), which have large market potential. The advantage of producing compounds equivalent to those obtained from petrochemicals is that these structures are fully compatible with existing infrastructure.^{236,237}

3.1. Functionalization Strategies

In this section, the possibilities for functionalization of aromatic monomers are detailed as such reactions have not yet comprehensively reviewed. Focus is devoted to catalytic methods able to transform moieties that constitute –OH as well as –OMe groups on the one hand and side chain functionalization of moieties on the other hand (Figure 25) related to compounds originating from catalytic depolymerization of lignin or lignocellulose (section 2).

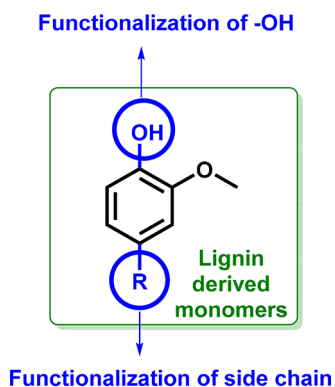


Figure 25. General strategies for functionalization of aromatic monomers obtained upon lignin depolymerization.

3.1.1. Functionalization of Guaiacyl-Type Substrates.

To detail the types of reactions able to functionalize phenol moiety in the presence of methoxy functionality, we have focused on guaiacol as model substrate. The guaiacol unit is the most abundant moiety in lignin-based monomers. However, compared to functionalization of phenol alone, methods for direct functionalization of phenol in the guaiacyl moiety are limited.

Direct Functionalization of the Phenol Moiety in Guaiacyl Type Substrates. Metal-free synthesis of aryl amines has been reported for the direct amination of phenols using aminating reagents in the presence of the stoichiometric amount of the base (Figure 26, route 1).²³⁸ Later, cross-coupling of guaiacol with aryl boronic acids was achieved with nickel-based homogeneous catalysts. In this reaction, initially, guaiacol was reacted with 2,4,6-trichloro-1,3,5-triazine (TCT) to give the aryl C–O electrophile for the cross coupling with arylboronic acid (Figure 26, route 2).²³⁹ Recently, Li explored the palladium-catalyzed direct cross-coupling of guaiacol with cyclohexylamine using sodium formate adding catalytic amount of acid (Figure 26, route 3). A tentative mechanism was proposed for this transformation.²⁴⁰ Efficient O-arylation of the phenol moiety in guaiacol with aryl bromoarenes was reported using iron/copper-catalyst in DMF as a solvent at 135 °C (Figure 26, route 4).²⁴¹

Functionalization of the Phenol Moiety in Guaiacyl Type Substrates via Derivatization. A strategy by which the free phenol group could undergo further catalytic transformation in a guaiacyl unit is through activation of the Ar–OH bond in the form of pseudohalogenides. Such strategy mitigates possible difficulties encountered due to the acidic hydroxyl group (pK_a = 10) that frequently interferes with organometallic complexes and reduces the high dissociation energy of the Ar–OH bond in phenol. Even after derivatization, applying such pseudohalogenides in catalytic transformations may result in decreased reactivity compared to simple halogenides, due to the increased steric hindrance and electron density induced by the methoxy group.

Following this strategy, derivatives such as triflates, carboxylates, carbamate, and tosylates were prepared and subjected to various catalytic functionalizations, mainly relying on cross-coupling reactions that involve the formation of C–C and C–N bonds containing a guaiacol moiety. For instance, Buchwald reported Pd-catalyzed amination of aryl sulfonates under mild conditions using CS₂CO₃ as a base (Figure 27, route 1).²⁴² Later, a microwave-assisted, palladium-catalyzed coupling of aryl

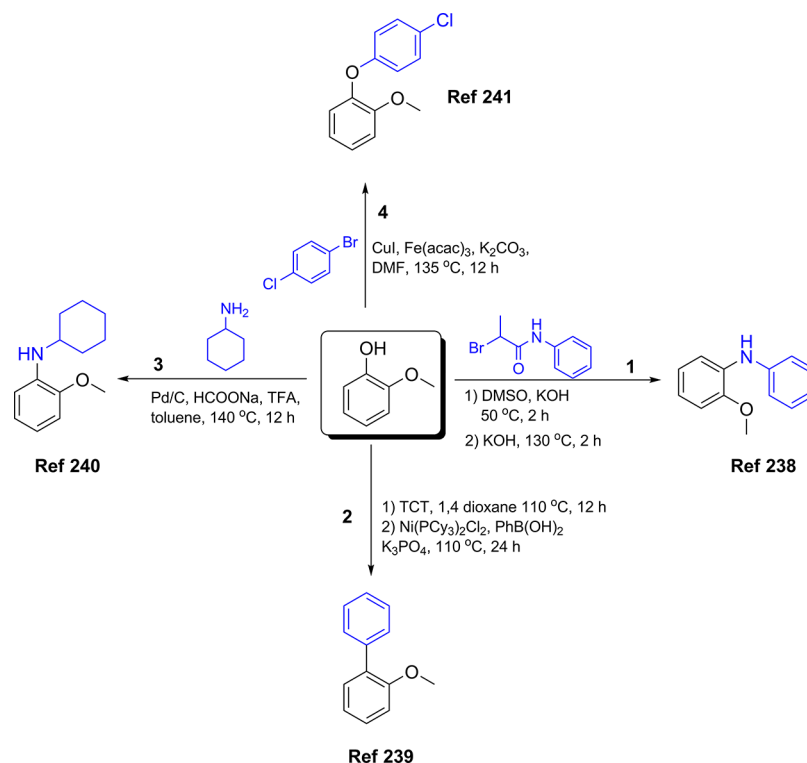


Figure 26. Direct functionalization of the phenol moiety in guaiacol.

nonaflates and anilines were described using soluble and weak amine base (Figure 27, route 2).²⁴³ In both cases, X-phos ligand showed good activity for the amination of guaiacol derivatives. Garg showed that aryl carbamates are attractive coupling partners for amination reactions using inexpensive and earth-abundant nickel catalyst (Figure 27, route 3, condition c).²⁴⁴ Later, the same group developed the air-stable nickel precursor and NHC ligand system for the amination of aryl carbamates and sulfamates in the presence of Ph-B(Pin) as a reducing agent (Figure 27, route 3, condition d).²⁴⁵ The Pd-PEPSSI catalyst was used for the cross-coupling of aryl tosylates with morpholine. In this work, an imidazol-2-ylidene ligand containing two dimethylamino groups enhanced both the electronic and steric properties of the carbene (Figure 27, route 3, condition e).²⁴⁶ Interestingly, Pd-catalyzed cross-coupling reactions of amides and aryl mesylates yielded *N*-aryl amides (Figure 27, route 4).²⁴⁷ The iron-catalyzed coupling of aryl sulfamates and carbamates with alkyl Grignard reagents was also reported, enabling carbon–carbon bond construction (Figure 27, route 5).²⁴⁸ Extending possibilities for C–C formation reactions, the Suzuki-Miyaura coupling reactions of aryl sulfamates and carbamates with boronic acid was developed and reported independently by Garg and Snieckus with K_3PO_4 (Figure 27, route 6).^{249,250} Interestingly, aromatic compounds comprising the small ring strained cyclopropyl moiety were constructed by palladium-catalyzed cross-coupling of mesylated guaiacol derivatives with potassium cyclopropyltrifluoroborate (Figure 27, route 7).²⁵¹ Notably, Ackermann et al. developed the palladium-catalyzed C–H activation coupling of benzoxazole with imidazole-sulfonates (Figure 27, route 8).²⁵²

Furthermore, 2-methoxybenzotrile could be prepared by palladium-catalyzed cyanation of hindered aryl triflates and aryl tosylates in the presence of $Zn(CN)_2$ ²⁵³ and $K_4[Fe(CN)_6]$ ^{254,255} as a cyanating agent, respectively. Nickel-catalyzed cyanation of

phenol derivatives was described by Itami and Yamaguchi using metal-free and easy-to-handle cyanating agents, aminoacetonitriles, for this transformation. Interestingly, dicyclohexyl-substituted phosphine ligands showed good reactivity to achieve this conversion effectively.²⁵⁶

3.1.2. Functionalization of the Side Chain. Alcohol 4-propanolguaiacol (**M10G**) is omnipresent in many lignin depolymerization methods. While catalytic methods involving **M10G** were not reported to the best of our knowledge, selected mild stoichiometric methods are known. Oxidative acetoxylation of **M10G** was carried out using hypervalent iodine reagents [phenyliodine(III) diacetate (PIDA)] via oxidative activation of arene that converted into isolable orthoquinol acetates (Figure 28, route 1).²⁵⁷ Alcohol **M10G** treated with 4-nitro benzaldehyde in the presence of $AlCl_3$ yielding 1,3,4,5-tetrahydrobenzo[c]oxepines (Figure 28, route 2).²⁵⁸ Silica gel supported BF_3 catalyst were used for the selective acetylation of aliphatic alcohol in the presence of phenolic hydroxyl group by treatment with EtOAc (Figure 28, route 3).²⁵⁹

Furthermore, vanillin (**M1G**) can be obtained from lignin through various oxidative catalytic methods. Rhodium catalyst were used for the reductive amination of aldehyde with ammonia to form the corresponding primary amine under mild conditions (Figure 28, route 4).²⁶⁰ The same amine could be obtained in the presence of palladium(0)-aminopropyl-mesocellular foam (Pd0-AmP-MCF) in toluene using $HCOONH_4$ (Figure 28, route 5).²⁶¹ Oxidation of the aldehyde group to the corresponding acids proceeds smoothly in the presence of Pd/C catalyst in aqueous methanol and sodium borohydride and potassium hydroxide at room temperature under air (Figure 28, route 6).²⁶² Another method to obtain the acid is thorough Ag_2O/CuO -catalyzed oxidation by molecular oxygen (Figure 28, route 7).²⁶³ 4-(1-Propenyl)guaiacol (**M18G**) is another encountered aromatic monomer from lignin depolymerization. It can be

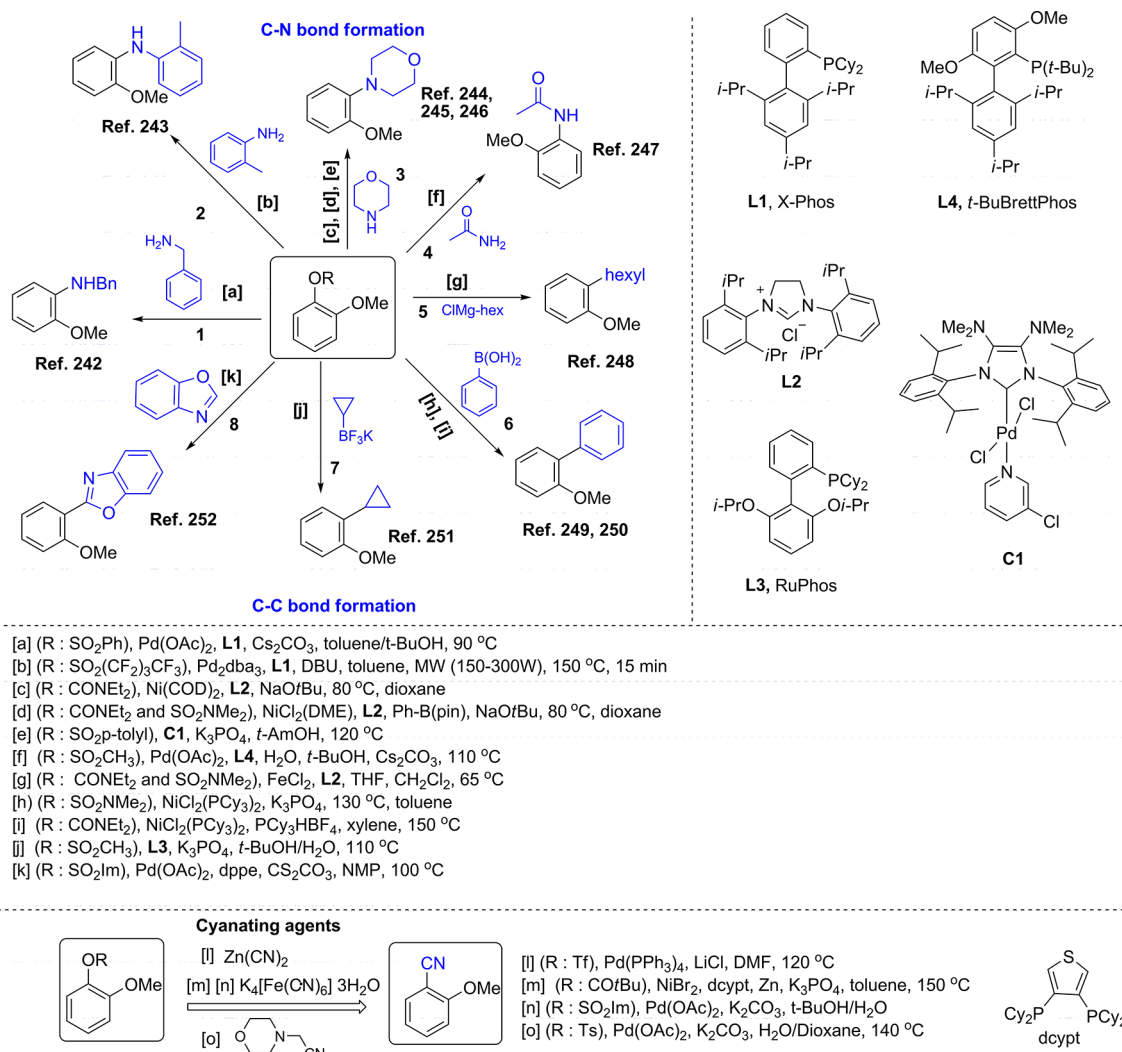


Figure 27. Functionalization of the phenol moiety in guaiacol through protective groups, applying homogeneous catalysts.

oxidized to vanillin (**M1G**) by H₂O₂ using the catalyst combination *n*-Bu₄NVO₃/pyrazine-2-carboxylic acid (Figure 28, route 8).²⁶⁴ 4-(1-Propenyl)guaiacol (**M18G**) can undergo oxidative cleavage by use of a special Co-porphyrin catalyst CoTPyP/TN and molecular oxygen as the oxidant to yield vanillin (**M1G**) (Figure 28, route 9).²⁶⁵ 4-(1-Propenyl)guaiacol (**M18G**) was also shown to undergo an interesting para-hydroxyl group-directed remote benzylic C(sp³)-H bond oxidation, by ligand and additive-free Cu(OAc)₂-catalyzed method and EG as solvent (Figure 28, route 10).²⁶⁶ The double bond in this substrate is a promising moiety for the versatile functionalization of this aromatic building block by olefin metathesis. For instance, a cross-metathesis method in order to obtain the corresponding stilbene product was developed for the 4-(1-propenyl)guaiacol (**M18G**) which can be obtained from lignin after depolymerization. Notably, the reaction proceeds under solvent-free conditions and at low catalyst loading (0.01 mol %) within a couple of minutes (Figure 28, route 11).²⁶⁷ In addition, acrylate cross-metathesis was developed for the synthesis of α,β -unsaturated esters (Figure 28, route 12).²⁶⁸ Palladium catalysts surrounded on molecular sieves effectively catalyzed the selective hydrogenation of the alkene in 4-(1-propenyl)guaiacol (**M18G**) (Figure 28, route 13).²⁶⁹ An effective continuous-flow approach was used for the hydrogenation of 4-(1-propenyl)guaiacol

(**M18G**) utilizing Wilkinson's catalyst (Figure 28, route 14).²⁷⁰ Furthermore, an efficient method for the selective cleavage of C-C bond in this substrate was developed. Such reactions are important for the controlled chain shortening of lignin-derived monomers that are frequently bearing C3 chains, originating from the native structure of lignin. Ethenolysis reactions of 4-(1-propenyl)guaiacol (**M18G**) to styrene compounds was achieved with ruthenium NHC complex using 1,7-octadiene as a solvent under room temperature (Figure 28, route 15).²⁷¹

3.2. Defunctionalization Strategies

With its intrinsic aromatic structure, lignin is by far the largest volume and most suitable renewable resource to substitute petroaromatics. Although several lignin-derived products are already useful starting materials (e.g., vanillin **M1G**), the large scale implementation of other lignin-derived phenolic monomers, for instance as fuels or chemicals, requires further (bio)chemical upgrading. Microbial transformation with or without combination with a chemo-catalytic reaction step is one promising route. In this way, lignin fragments could be converted into adipic acid,^{181,272} polyhydroxyalkanoates,^{206,273} alkenoic acids,²⁰⁶ and C9-C14 hydrocarbons.²⁷³

Catalytic hydrodeoxygenation (HDO) to alkanes and aromatics for direct use as liquid fuel or as feedstock for established petrochemical processes received increasing atten-

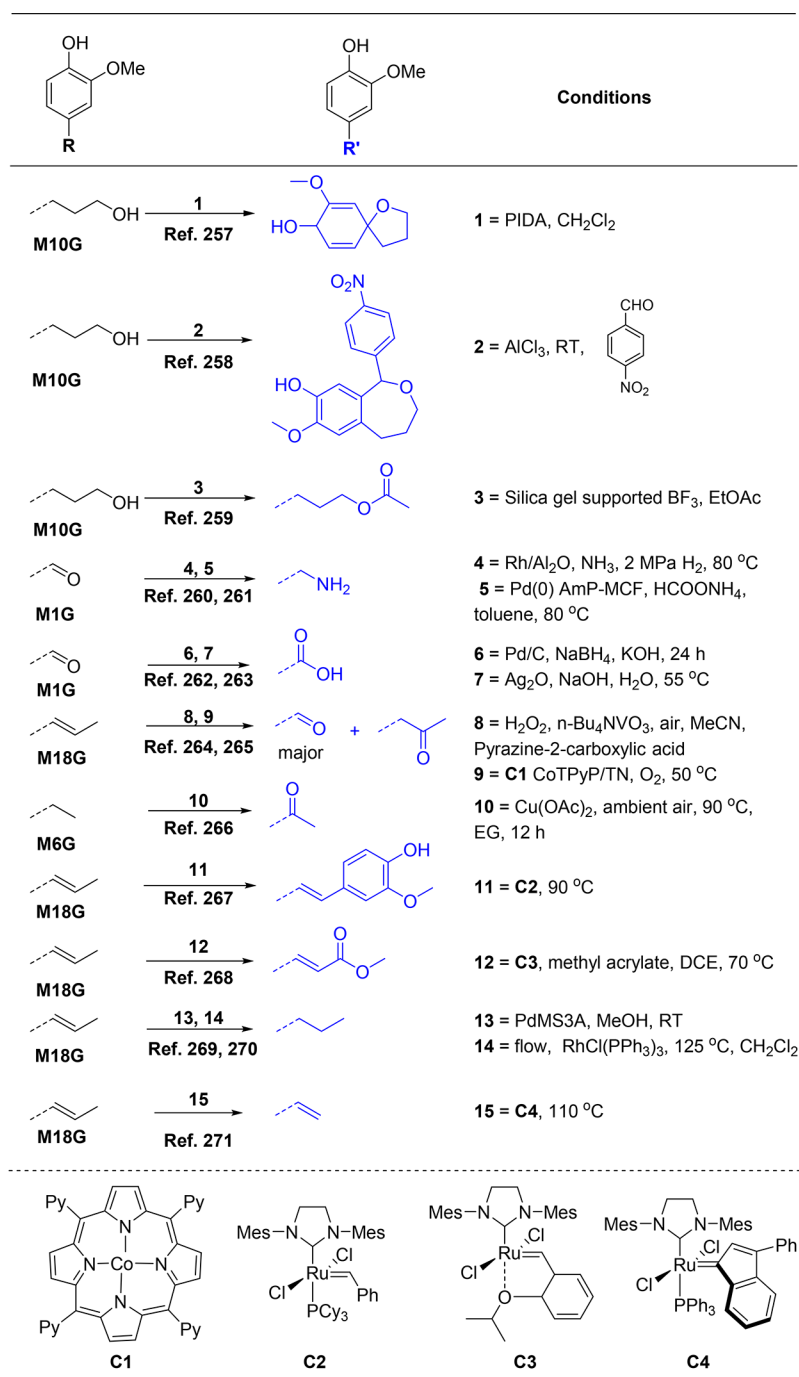


Figure 28. Catalytic strategies for the functionalization of the side chain of lignin-derived monomers.

tion (see Table 2). In Figure 29, the desired defunctionalization strategies applied on possible lignin-derived aromatics are summarized. These strategies have been primarily investigated with guaiacol and phenol as model compounds related to upgrading of biomass-derived pyrolysis oils, and studies have been summarized in several excellent reviews.^{30,274–278} Herein, we will give a short discussion about the catalytic systems developed after 2010.

Selective hydrogenation of aromatic rings is one of the most important chemical processes as the generated aliphatic derivatives are crucial starting materials in synthesis of polymers, resins, dyes, and fine chemicals.²⁸¹ This reaction is normally operated under hydrogenation conditions with supported metal

catalysts at high temperatures.²⁹⁶ A suitable catalyst for the selective hydrogenation of the aromatic ring is Pd/C. Schutyser and co-workers²⁷⁹ have shown that the selectivity for 2-methoxy-4-propylcyclohexanol could reach 90% when using lignin-derived 4-propylguaiacol (M7G) as substrate. Compared to Pd/C, a Ru/C catalyst gave slightly lower selectivity at 250 °C as the formation of cyclohexanol (19%) and cyclohexane (12%) as by products.²⁸⁰ It was also found that a ZrO₂ supported Rh catalyst is also selective for the aromatic ring hydrogenation in guaiacol as model compound.²⁸⁰ Beller and co-workers developed an intriguing method based on well-dispersed Ru nanoparticles supported on a nitrogen-doped carbon material. The method exhibited good-to-excellent activity in the selective

Table 2. Hydrogenation and Hydrodeoxygenation of Lignin-Derived Monomers

catalyst	reactor	T (°C)	P (bar)	solvent	substrate	conv. (%)	product (sele. %) ^a	ref
Pd/C	batch	300	40	hexadecane	4-propylguaiaicol	~99	2-methoxy-4-propylcyclohexanol (90)	279
Rh/ZrO ₂	batch	250	40	decane	guaiaicol	100	2-methoxycyclohexanol (89)	280
Ru/C	batch	250	40	decane	guaiaicol	100	2-Methoxycyclohexanol (60)	280
Ru@NDCs	batch	60	10	isopropanol	4-propylguaiaicol	N. R. ^c	2-methoxy-4-propylcyclohexanol (86) ^b	281
Ru@NDCs	batch	60	10	isopropanol	vanillin	N. R.	4-hydroxy-3-methoxycyclohexanecarboxaldehyde (81) ^b	281
Pt/C	batch	200	20	H ₂ O	guaiaicol	~80	cyclohexanol (~68)	282
Ru/C	batch	200	20	H ₂ O	guaiaicol	~75	cyclohexanol (~70)	282
RuZrLa	batch	200	40	H ₂ O	guaiaicol	100	cyclohexanol (91.6)	283
RuZrLa	batch	200	40	H ₂ O	4-propylguaiaicol	100	propylcyclohexanol (89.5)	283
RuZrLa	batch	200	40	H ₂ O	4-propylsyringol	100	propylcyclohexanol (86.9)	283
RuZrLa	batch	200	40	H ₂ O	syringol	100	propylcyclohexanol (90.8)	283
Ru/C + MgO	batch	160	15	H ₂ O	guaiaicol	98	cyclohexanol (79)	284
Ru-MnO _x /C	batch	160	15	H ₂ O	guaiaicol	>99	cyclohexanol (72)	285
Ru-MnO _x /C	batch	160	15	H ₂ O	syringol	>99	cyclohexanol (70)	285
Co/TiO ₂	batch	200	10	dodecane	eugenol	100	propylcyclohexanol (99.9)	286
Co/TiO ₂	batch	200	10	dodecane	guaiaicol	100	cyclohexanol (98)	286
Co/TiO ₂	batch	200	10	dodecane	syringol	100	cyclohexanol (99.9)	286
NiCo/Al ₂ O ₃	batch	200	50	H ₂ O	guaiaicol	96.0	cyclohexanol (70.9)	287
Ni/CeO ₂	batch	300	40	hexadecane	guaiaicol	100	cyclohexanol (81)	288
Ni/CeO ₂	batch	300	40	hexadecane	4-propylguaiaicol	100	propylcyclohexanol (82)	288
Ni/SiO ₂ -Al ₂ O ₃	batch	250	10	hexadecane	4-propylguaiaicol	100	propylcyclohexanol (85)	279
RANEY@ Ni	batch	80	atm ^d	isopropanol	guaiaicol	100	cyclohexanol (95)	218
RANEY@ Ni	batch	80	atm	isopropanol	syringol	95	cyclohexanol (92)	218
RANEY@ Ni	batch	80	atm	isopropanol	4-propylguaiaicol	100	propylcyclohexanol (80)	218
RANEY@ Ni	batch	120	atm	isopropanol	4-allylsyringol	100	propylcyclohexanol (78)	218
RANEY@ Ni	glass H-cell	75	atm	H ₂ O	guaiaicol	~99	cyclohexanol (79)	289
Ru/ACC	glass H-cell	80	atm	isopropanol	guaiaicol	~53	cyclohexanol (~72)	290
Ni/SiO ₂ (64.2%)	batch	320	170	no solvent	guaiaicol	96.7	cyclohexanone (~55)	291,292
NiCu/CeO ₂ -ZrO ₂	batch	320	170	no solvent	guaiaicol	94.2	cyclohexanone (~60)	291,292
Raney Ni and nafion/SiO ₂	batch	300	40	H ₂ O	guaiaicol	100	cyclohexane (86)	137
Raney Ni and nafion/SiO ₂	batch	300	40	H ₂ O	syringol	100	cyclohexane (57)	137
Raney Ni and nafion/SiO ₂	batch	300	40	H ₂ O	4-propylguaiaicol	95	propylcyclohexane (91)	137
Pd/C and H ₃ PO ₄	batch	250	50	H ₂ O	4-propylguaiaicol	99	propylcyclohexane (65)	136,142
Pd/C and H ₃ PO ₄	batch	250	50	H ₂ O	eugenol	100	propylcyclohexane (71)	136,142
Pd/C and H ₃ PO ₄	batch	250	50	H ₂ O	4-allylsyringol	92	propylcyclohexane (58)	136,142
Pt/C and H ₃ PO ₄	batch	200	20	H ₂ O	guaiaicol	~78	cyclohexanol (~85)	282
Pd/C and HZSM-5	batch	200	50	H ₂ O	guaiaicol	100	cyclohexane (85)	139
Pd/C and HZSM-5	batch	200	50	H ₂ O	4-propylguaiaicol	97	propylcyclohexane (90)	139
Pd/C and HZSM-5	batch	200	50	H ₂ O	eugenol	97	propylcyclohexane (90)	139
Pd/C and HZSM-5	batch	200	50	H ₂ O	4-allylsyringol	95	propylcyclohexane (80)	139
Ru/HZSM-5	batch	200	50	H ₂ O	guaiaicol	99.9	cyclohexane (93.6)	293
Ru/HZSM-5	batch	200	50	H ₂ O	syringol	76.2	cyclohexane (57.2)	293
Ru/HZSM-5	batch	200	50	H ₂ O	4-propylguaiaicol	99.6	propylcyclohexane (89.5)	293
Ru/HZSM-5	batch	200	50	H ₂ O	4-allylsyringol	99.9	propylcyclohexane (85.4)	293
Rh/SiO ₂ -Al ₂ O ₃	batch	250	40	decane	guaiaicol	100	cyclohexane (57)	280
Ru/SiO ₂ -Al ₂ O ₃	batch	250	40	decane	guaiaicol	100	cyclohexane (60)	280
Ni/HZSM-5	batch	250	50	H ₂ O	guaiaicol	100	cyclohexane (74)	138
Ni/HZSM-5	batch	250	50	H ₂ O	4-propylguaiaicol	98	propylcyclohexane (84)	138
Ni/HZSM-5	batch	250	50	H ₂ O	eugenol	100	propylcyclohexane (80)	138
Ni/HZSM-5	batch	250	50	H ₂ O	4-allylsyringol	93	propylcyclohexane (78)	138
Ni/SiO ₂ -ZrO ₂	batch	300	50	dodecane	guaiaicol	100	cyclohexane (96.8)	294
Ni/SiO ₂ (55.5%)	batch	320	170	no solvent	guaiaicol	97.5	cyclohexane (~62)	291,292
NiCu/Al ₂ O ₃	batch	320	170	no solvent	guaiaicol	80.2	cyclohexane (~52)	291,292
NiCu/SiO ₂	batch	320	170	no solvent	guaiaicol	87	cyclohexane (~62)	291,292
NiCuLa/ZrO ₂ -SiO ₂	batch	320	170	no solvent	guaiaicol	85.6	cyclohexane (~63)	291,292

Table 2. continued

catalyst	reactor	T (°C)	P (bar)	solvent	substrate	conv. (%)	product (sele. %) ^a	ref
Ru/CNT	batch	220	50	dodecane/H ₂ O	guaiacol	N. R.	cyclohexane (92) ^e	295
Ru/CNT	batch	220	50	dodecane/H ₂ O	4-propylguaiacol	N. R.	propylcyclohexane (94) ^e	295
Ru/CNT	batch	220	50	dodecane/H ₂ O	eugenol	N. R.	propylcyclohexane (94) ^e	295
Ru/CNT	batch	220	50	dodecane/H ₂ O	4-allylsyringol	N. R.	propylcyclohexane (80) ^e	295

^aNumbers in brackets are selectivity determined by GC. ^bIsolated yield. ^cN. R. means not reported. ^datm means atmospheric pressure at room temperature. ^eNumber in brackets means GC yield.

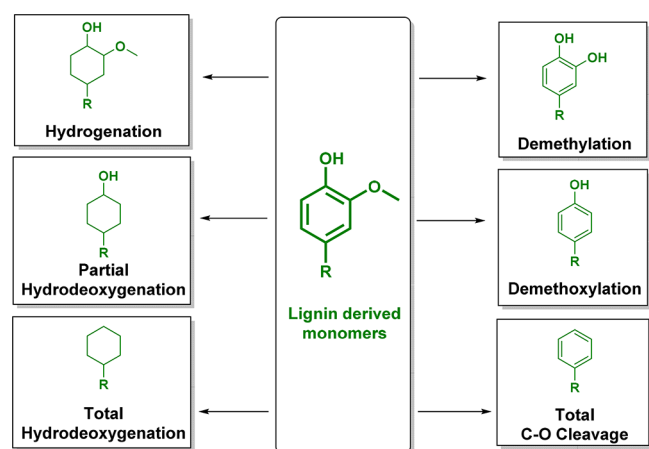


Figure 29. Strategies for defunctionalization of lignin-derived monomers.

hydrogenation of arenes without promoting extensive hydrodeoxygenation.²⁸¹ This method was also efficient in the hydrogenation of realistic lignin-derived aromatic compounds while preserving the phenyl- and benzyl C–O bonds.

Another interesting route for defunctionalization of lignin-derived monomers is the selective hydrodeoxygenation to oxygenated products such as cyclohexanols that should involve a combination of hydrodemethoxylation and aromatic ring hydrogenation with retention of the hydroxyl group. Cyclohexanol is an important precursor of polymer building blocks like caprolactam, caprolactone, and adipic acid.^{297,298} Alkyl-substituted cyclohexanols could open a new way for synthesizing alkylated variants of these polymer building blocks since the presence of alkyl groups allows for tuning the polymer's physical properties such as crystallinity, melting point, elasticity, etc.^{279,288} Both noble and non-noble metal catalysts have been used and high cyclohexanol selectivity was mainly achieved with Pt,²⁸² Ru,^{282–285,290} Co,^{286,287} and Ni^{218,279,287–289} based catalysts. Methods using Pt/C and Ru/C give similar selectivity (68% vs 70%) in the hydrogenation/deoxygenation of guaiacol at 200 °C.²⁸² Furthermore, a bifunctional RuZrLa catalyst showed significant activity and selectivity for the hydrogenation/deoxygenation of both guaiacol and lignin-derived monomers.²⁸³ Over 88% yield of cyclohexanols were obtained from lignin-derived methoxyphenols after hydrotreatment at 200 °C for 4 h in water. Nakagawa and co-workers successfully used a Ru catalyst combined with MgO at significantly decreased reaction temperature.²⁸⁴ Addition of MgO to the reaction media suppressed the unselective C–O dissociation, and cyclohexanol and methanol were obtained in high yield (>80%) at 160 °C. However, MgO was not stable during the reaction when using water as solvent and acidic substrates. An optimized catalyst system, namely Ru-MnO_x/C,²⁸⁵ was found to be an easy-to-handle alternative to promote selective demethoxylation. This

catalyst gave cyclohexanol from guaiacol in higher yield than Ru/C combined with MgO.

Several groups focused on using less expensive, Co- or Ni-based catalysts, which are familiar to industry. Liu et al.²⁸⁶ investigated a series of cobalt-based catalysts on various supports for the catalytic conversion of lignin-derived phenols to cyclohexanols. Among these catalysts, Co/TiO₂ showed the best HDO activity and high yield of propylcyclohexanol (>99.9%) was achieved under 1 MPa H₂, 200 °C for 2 h. Zhou and co-workers²⁸⁷ studied the catalytic activity of γ -Al₂O₃ and ZSM-5 (Si/Al = 25, 38) supported non-noble metal (Co and/or Ni) catalysts for the HDO of guaiacol. The introduction of Co into Ni/ γ -Al₂O₃ could enhance the acidity, reducibility, and metal particle dispersion of the catalyst, which resulted in increase of catalytic activity. The maximum guaiacol conversion was observed when water was used as solvent with a selectivity of 70.9% of cyclohexanol. Sels et al. developed several supported Ni catalysts, such as Ni supported on CeO₂ for the conversion of lignin-derived guaiacols into the corresponding cyclohexanols in yields above 80%.²⁸⁸ Furthermore, using commercial base metal catalyst Ni/SiO₂–Al₂O₃ a propyl-cyclohexanol yield of 85% was obtained at 250 °C.²⁷⁹ However, the drawback of using Ni/SiO₂–Al₂O₃ was shown to be methane formation.

Raney nickel is widely used in current industrial processes owing to its low cost, easy preparation, and high activity.²⁹⁹ Wang and Rinaldi pioneered the use of isopropanol as H-donor and solvent in combination with Raney Ni for the defunctionalization of lignin monomers.²¹⁸ Under low-severity conditions (80–120 °C), excellent yield (78%–95%) of cyclohexanols was obtained.

Another promising strategy to achieve high yield of cyclohexanols at mild conditions was the use of Raney Ni as electrode in electrocatalytic hydrogenolysis/hydrogenation.²⁸⁹ Selective cleavage of aryl ether (C–O) bond followed by reduction of the aromatic ring at ambient pressure and 75 °C was observed in aqueous solution. Another example of a hydrogenation/hydrodeoxygenation strategy was using a Ru/ACC electrocatalyst.²⁹⁰ Similar electrochemical efficiencies for reducing guaiacol, phenol, and syringol were seen; however, temperature was found to influence the electrochemical efficiency. Guaiacol reduction increased from 8% at 25 °C to 17% at 50 °C but then dropped back to 10% at 80 °C. Solution pH also affected catalyst activity and product selectivity, with acidic conditions favoring guaiacol conversion, electrochemical efficiency, and cyclohexanol selectivity.

Despite their importance as precursor for the polymer intermediate caprolactone,³⁰⁰ cyclohexanones are rarely reported products in one-pot catalytic conversion of lignin-derived monomers. Cyclohexanones can be obtained from cyclohexanols by dehydrogenation reaction using Cu/ZrO₂²⁸⁸ or as an intermediate in the isomerization of the partial-hydrogenation product cyclohexenol (ketone/enol tautomerism).²⁹² When testing the performance of several Ni-based catalysts obtained by coprecipitation and impregnation techniques in the hydro-

Table 3. From Lignin-Derived Monomers to Catechol, Phenol, and Benzene by Heterogeneous Catalysts

catalyst	reactor	T (°C)	P (bar)	solvent	substrate	conv. (%)	product (sele. %)	ref
α -MoC _{1-x} /AC	batch	340	atm	H ₂ O	guaiacol	36	catechol (94)	302
MoO ₂ /AC	batch	340	atm	H ₂ O	guaiacol	33	catechol (93)	302
MoN/SBA15	batch	300	50	decalin	guaiacol	44	phenol (26)	303
MoN-A	batch	300	50	decalin	guaiacol	95	phenol (90)	304
1Mo/C	fixed-bed	350	40	no solvent	guaiacol	74.1	phenol (78.5)	305
NiMo/Al ₂ O ₃	packed-bed	450	20.7	no solvent	4-propylguaiacol	~95	4-propylphenol (~70)	306
α -MoC _{1-x} /AC	batch	340	atm	tetralin	guaiacol	53	phenol (84)	302
MoWBO _x /AC	fixed-bed	400	40	methanol	vanillic acid + syringic acid	100	p-hydroxybenzoic acid (71.6)	307
MoC _x /C	batch	300	5	hexane	guaiacol	99	phenol (76)	308
MoC _x /C	batch	300	5	hexane	syringol	91	phenol (37)	308
NiMo/Al ₂ O ₃	packed-bed	450	20.7	no solvent	4-propylguaiacol	~95	4-propylphenol (~70)	306
Re/ZrO ₂	batch	300	50	decalin	guaiacol	~50	phenol (~35)	309
WP/SiO ₂	packed bed	300	50	no solvent	guaiacol	60	phenol (100)	310
Au/TiO ₂	batch	300	65	toluene	guaiacol	100	phenol (49.6)	311
CoMoS	fixed bed	300	40	no solvent	guaiacol	50	benzene (42)	312
CoMoS/TiO ₂	fixed bed	300	40	no solvent	guaiacol	~95	benzene (~60)	313
10Mo/C	fixed-bed	400	40	no solvent	guaiacol	100	benzene (83.5)	305
Ni ₂ P/SiO ₂	fixed-bed	300	1.4	no solvent	guaiacol	99.5	benzene (71.9)	314
Ni ₂ P/SiO ₂	packed bed	300	50	no solvent	guaiacol	80	benzene (60)	310
Ru/C	fixed-bed	400	40	no solvent	guaiacol	100	benzene (69.5)	305
Ru/LaCO ₃ OH	batch	240	2	H ₂ O	guaiacol	95.6	benzene (~79)	315

deoxygenation of guaiacol, Bykova et al.²⁹² found that large amount of cyclohexanone can be obtained at 320 °C from 1-cyclohexen-1-ol through keto–enol tautomerism.

Another defunctionalization strategy is the selective cleavage of C–O bonds (either demethylation or demethoxylation of full defunctionalization) without hydrogenation of the aromatic ring and yielding catechols, phenols, and benzenes, respectively, which are important aromatic compounds. These processes are generally operated at high temperatures (>300 °C), frequently in continuous flow reactors to avoid hydrogenation of aromatic ring.

Total hydrodeoxygenation of bioderived phenols to hydrocarbons is the most effective method for upgrading of bio-oils.^{30,274,275,277} Many studies were conducted to develop catalysts with high catalytic activity and stability, low hydrogen consumption, and high selectivity toward direct removal of oxygen with the aim to convert oils originating from catalytic pyrolysis processes.^{2,301} Most of the studies use guaiacols and syringols as the model compounds and guide for the potential upgrading of lignin-derived monomers.

Lercher and co-workers developed a series of catalytic methods for the one-pot hydrodeoxygenation through multistep reactions consisting of hydrogenation, dehydration, or hydrolysis and hydrogenation of functionalized aromatics to alkanes, which use the combination of a hydrogenation catalyst (Raney Ni, Pd/C or Pt/C) with a homogeneous/heterogeneous acid (H₃PO₄, Nafion, or HZSM-5).^{136,137,139,142} Excellent cycloalkane yields, above 80%, were reported from lignin-derived monomers in the case of Pd/C and HZSM-5. Another strategy is the use of solid acid support for the development a bifunctional catalyst such as Ru supported on HZSM-5, which exhibited excellent hydrodeoxygenation activity toward the conversion of lignin-derived phenolic monomers.²⁹³ It was shown that both the presence of Bronsted acid site supplied by HZSM-5 for dehydration and the metal Ru for hydrogenation were crucial to achieve good selectivity. Several lignin-related C6–C9 phenolic monomers could be converted to cyclohexanes in high yield at 200 °C. The high activity of this catalyst was attributed to the strongly acidic

site on the surface of HZSM-5 as other acidic support like SiO₂–Al₂O₃ gave much lower yield (~60%) with Ru and Rh at even higher temperature (250 °C).²⁸⁰ Other than noble metal catalysts, bifunctional Ni catalyst also showed excellent activity for hydrodeoxygenation of lignin-derived monomers. However, higher temperature (250–320 °C) and pressure (50–170 bar) were normally required.^{291,292,138,294}

Most of the systems for HDO of phenols were conducted in a single solvent such as water or *n*-decane. Biphasic systems have notable advantages in protecting the products from further degradation by extraction/separation into another phase. In 2015, Fu and co-workers²⁹⁵ found that biphasic systems with the combination of water and dodecane used showed superior advantages over monophasic systems in HDO reactions. By means of a Ru/CNT catalyst designed by this group, full conversion of eugenol and 98% alkane selectivity (94% propylcyclohexane and 4% propylcyclopentane) was achieved at 220 °C and 50 bar H₂.

Catechol is an important chemical that can be used directly or as a precursor for the production of pesticides or other fine chemicals such as perfumes and pharmaceuticals.²³³ So far, only a few synthetic procedures exist for transformation of substituted phenols into catechols; however, these normally suffer from low selectivity, in particular for meta-substituted phenols.²³² Instead of using phenols, a more sustainable route from lignin via guaiacol and subsequent demethylation to catechol would be desired. A method for demethylation of aryl methyl ethers using iodocyclohexane in DMF under reflux condition was described by Zuo et al.³¹⁶ who obtained catechol with 91% isolated yield in 4 h from guaiacol. Waghmode et al. developed a method for selective cleavage of aryl methyl ethers in the presence of a protic acid (HBr) and a catalytic amount of phase-transfer catalyst (Aliquat-336).²³² Another method that provided full conversion of guaiacol and 89% yield of catechol was developed reported by Yang et al. This system relied on heating guaiacol in hydrochloric acid solution at 280 °C under 10 bar hydrogen.³¹⁷ Generally, the selective demethylation of guaiacols with heterogeneous catalysts is very challenging due to the more favorable demethoxylation

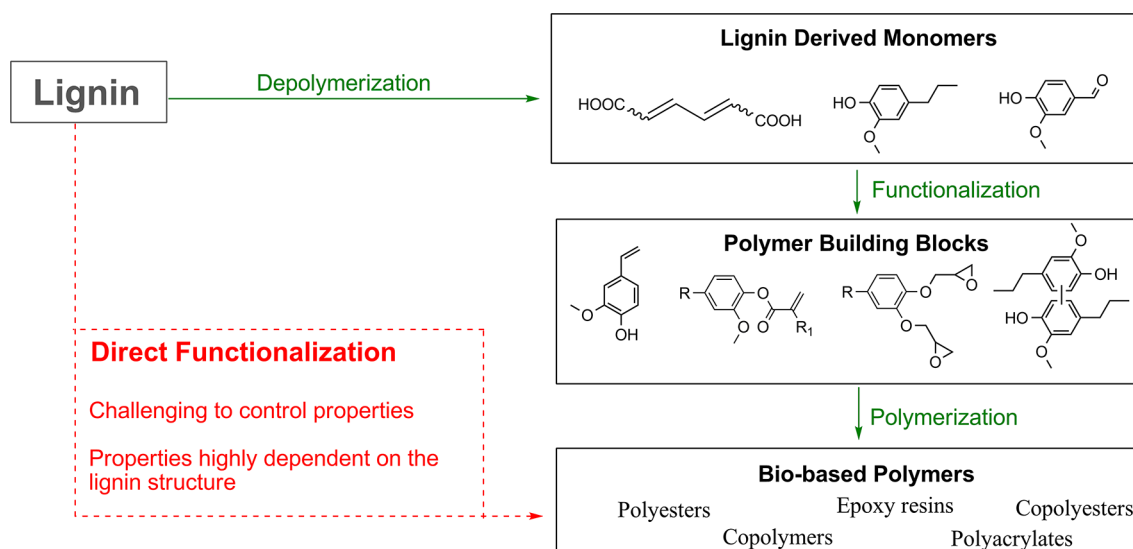


Figure 30. General strategies for production of polymers from lignin.

reaction that generally yields phenol as the main product. As shown in Table 3, the heterogeneous catalyst α -MoC_{1-x}/AC is a unique choice for obtaining catechol in high selectivity, albeit at lower conversion values.

4-Alkylphenols are interesting candidates to serve as replacements for petroleum-derived phenols in several applications^{143,230} and can also be used as the intermediates for the production of phenols.²³¹ Several groups have studied the possibilities to obtain phenols by demethoxylation of guaiacols (Table 3) including the most widely applied molybdenum-based catalysts^{302–308} as well as Re/ZrO₂,³⁰⁹ WP/SiO₂,³¹⁰ and Au/TiO₂,³¹¹ however, these often suffer either from low activity or low selectivity.

Benzene could be produced from guaiacol by total C–O bond cleavage generally through phenol as intermediate. Molybdenum-based catalysts including CoMoS,³¹² CoMoS/TiO₂,³¹³ and 10Mo/C³⁰⁵ and Ni₂P-supported catalysts^{310,314} were successfully applied in this reaction to give high benzene selectivity. This reaction could also be successfully performed with an increase in reaction temperature to 400 °C by using Ru/C as catalyst.³⁰⁵

Notably, in combination of Raney Ni with HZSM-5, Rinaldi and co-workers²¹⁷ pioneered the selective formation of fully defunctionalized aromatics from model compounds and pyrolysis oil components, via a unique transfer hydrogenation/dehydration/rearomatization sequence under mild conditions.

Recently Zhao and co-workers³¹⁵ synthesized a hydrothermally stable Ru/LaCO₃OH catalyst in which Ru nanoparticles were partially encapsulated by LaCO₃OH by a strong metal–support interaction. This conferred high catalyst stability and activity for the hydrogenolysis of several biomass-derived model compounds. Under aqueous conditions at 240 °C and 0.2 MPa H₂, 75.8% yield of benzene was obtained from guaiacol at nearly full substrate conversion. Notably, high conversion (>95%) and >70% benzene selectivity was found even after eight runs, highlighting the exceptional stability of this catalyst.

3.3. Conclusions

Several selective functionalization and defunctionalization strategies were reported that could be potentially applied in the downstream processing of lignin-derived monomers. However, a significant knowledge gap exists due to the predominant use of model compounds that are significantly

simpler in structure than the monomers currently found from lignin depolymerization methods (Figure 23). This necessitates the study of the existing methods using more complex substrates as well as the development of novel methods that would allow for good functional group tolerance.

Regarding the functionalization of the phenol moiety in guaiacol derivatives, new catalysts are desired that would allow one to directly install C–C and C–N bond starting from aromatic alcohol moieties (especially in the vicinity of a methoxy substituent) since known transformations generally use protecting groups (Figure 27) which decrease the overall atom economy of such reactions. In addition, new catalysts are needed for the direct functionalization of an aromatic methoxy group, which is highly abundant in lignin-derived monomers. Regarding 4-propanolguaiacol (**M10G**) that can be obtained in high yield from lignin, the functionalization of the aliphatic alcohol in the presence of a phenol needs to be investigated, since the availability of such methods is very limited.

Several powerful methods have been identified for the selective defunctionalization of simpler lignin-derived aromatics that will be further evaluated and potentially upscaled. Future research should focus on the development of non-noble metal catalysts that might operate at milder reaction conditions as well as the development of one-pot, tandem depolymerization and defunctionalization strategies to obtain bulk chemicals directly from lignin.

4. LIGNIN-DERIVED MONOMERS TO BIOBASED POLYMERS OR POLYMER BUILDING BLOCKS

The world plastics production has markedly increased from 230 Mton/year in 2005 to 322 Mton/year in 2015.^{318,319} Nearly 50–55% of this quoted polymer production volume is attributed solely to polyethylene and polypropylene, which currently are not easily or cost effectively bioderivable,³²⁰ although second generation bioethanol serves as promising future alternative. Interestingly, biobased polyethylene can be produced via ethylene by ethanol dehydration (Braskem Company, plant production capacity of 200000 tons per year started in 2010 in Brazil),³²¹ even though this currently appears most feasible in places where the cost of sugars is low, such as Brazil.³²² Several commercial examples of biobased polymers are available but

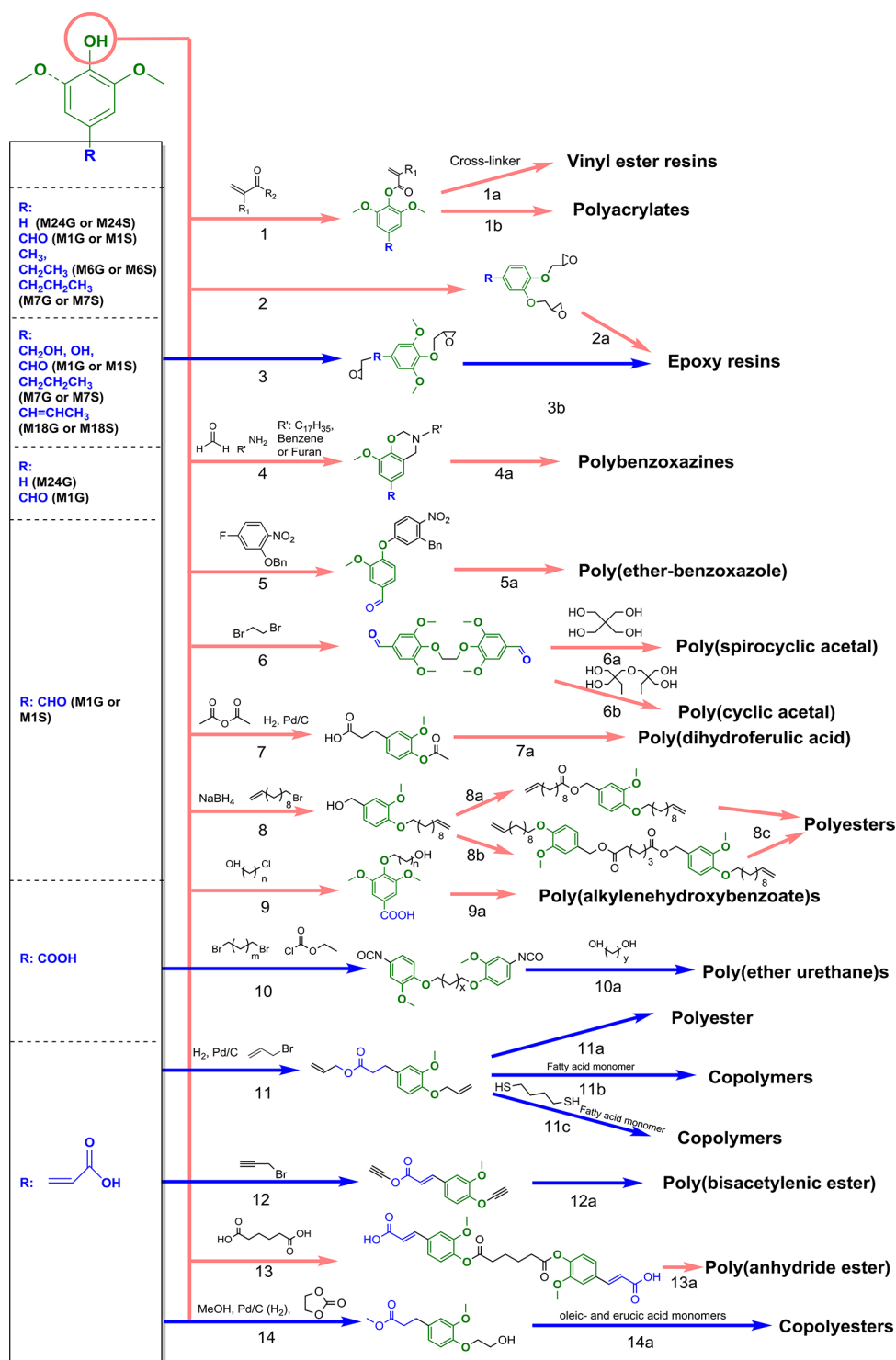


Figure 31. Polymers produced from lignin-derived monomers by functionalization of only the phenol moiety or both the phenol moiety and the side chain.

related mostly to different kind of polymers such as starch plastics,³²³ poly(lactic acid) (PLA, Natureworks LCC), polyhydroxyalkanoate (PHA, Metabolix and Archer Daniels Midland Company), polyamide 11 (PA11, Arkema), partially biobased epoxy resins (Solvay Epiceroland DowGTE technologies), or polyethylenefuranoate (PEF, Avantium, pilot scale).³²⁴ In spite of these existing examples, only a small fraction of the worldwide manufacture of polymers is bioderived (1.7 Mton/year in

2014).³²⁵ Thus, new strategies are needed in order to facilitate the production of polymers from renewable resources.³²⁶

To this end, the search of suitable biobased starting materials for polymer production and, specifically, the development of biobased polymers from lignin or lignin-derived monomers has drawn an enormous interest in recent years.^{325,327}

Lignin can be directly used for the production of polymers^{325,327–330} (e.g., polyurethanes, phenol–formaldehyde resins, polyesters, and phenolic and epoxy resins) typically by

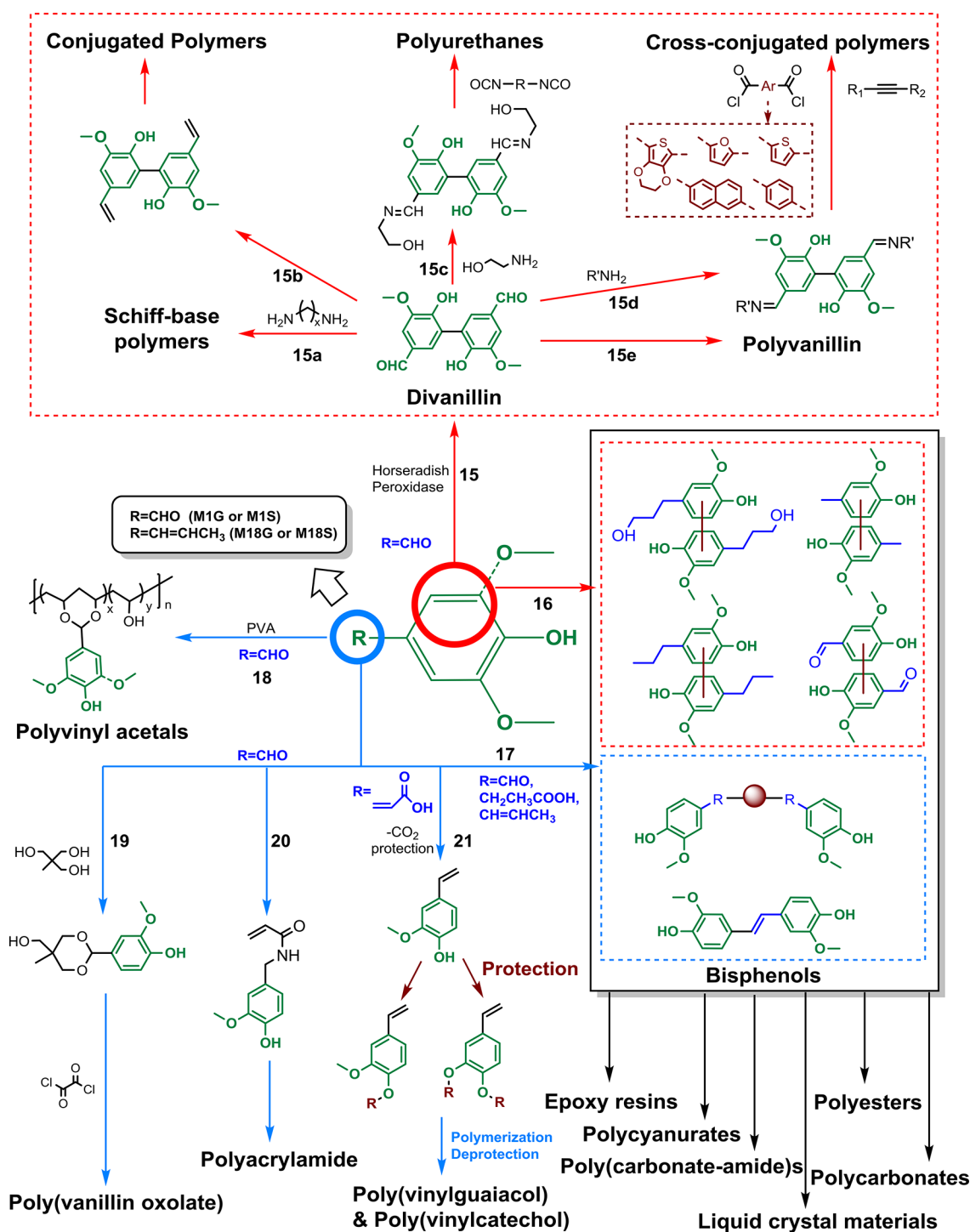


Figure 32. Polymers produced from lignin-derived monomers by functionalization of the aromatic ring or only the side chain.

functionalization of the hydroxyl groups in its structure or used as copolymers, blends, and composites.^{331,332} The limitations of these applications are related to the relatively ill-defined structure/composition of the starting material, where the properties of the obtained polymers may depend on the origin of lignin, method of extraction, and fragmentation processes present during synthesis and functionalization (Figure 30).³³³ Another limitation is that lignin is often used in minor amounts for these blends and composites since the main building blocks of these polymers still originate from petroleum.

Lignin-derived monomers, however, are well-defined small molecules, frequently aromatic in nature.³³² This aromatic structure provides valuable properties such as rigidity, hydrophobicity, as well as resistance against fire, essential for many applications. They are preferably obtained through a mild lignin depolymerization methodology, retaining most of the functionality present in the natural feedstock, which results in a highly modular structure and various possibilities for further functionalization. Indeed, numerous novel structures and polymers have been produced in the recent years.^{327,328,330,334} Herein, we will give a summary of methods that were used to transform lignin-

derived monomers to polymers. Further, we specifically describe the properties of reported polymers that were produced recently (2016–2017). The properties of polymers published before 2016 are summarized in the excellent review by Cramail and co-workers³³³ and others.^{327,330,335}

4.1. From Lignin-Derived Aromatic Monomers to Polymers

Figure 31 and Figure 32 show the various possibilities of functionalization of lignin-derived aromatic monomers (discussed in section 2), including modification of the phenol functionality and aromatic ring functionalization. In addition, the side chain can participate in several reactions depending on its nature, which will be influenced by the applied depolymerization method.

4.1.1. Modification through the Phenol Functionality and/or Side Chain. Several polymer materials were reported by modifying the phenol group only (Figure 31). For example by functionalization with acrylates (route 1), several polyacrylates (route 1b) were obtained from vanillin (M1G), guaiacol (M24G), or 4-alkylguaiacols^{336–338} or vinyl ester resins (route 1a) by using a cross-linker.^{339–342} Furthermore, the synthesis of epoxy resins was reported using vanillin (M1G), vanillic acid (M20G), vanillyl alcohol,^{343–347} or 4-(1-propenyl)guaiacol (M18G)³⁴⁸ from direct functionalization of both phenol and the side chain (route 2 and 3). Abu-omar and co-workers produced several novel biobased epoxy nanocomposites from 4-propylguaiacol (M7G) by functionalization of phenol and –OMe group.^{349,350} Next, benzoxazines were produced with a one-pot method from phenolic derivative, primary amine, and formaldehyde (route 4), which underwent ring-opening polymerization (route 4a) to polybenzoxazines.^{351–354} Biobased poly(ether benzoxazoles) could be obtained through reacting vanillin (M1G) with 5-fluoro-2-nitrophenol followed by hydrogenation and thermal treatment (route 5 and 5a).³⁵⁵ Aromatic dialdehydes prepared by the reaction of lignin derivatives with 1,2-dibromoethane using sodium hydroxide and potassium iodide in water (route 6) were condensed with pentaerythritol (route 6a) and ditrimethylolpropane (route 6b) to produce a new class of cyclic polyacetal ether thermoplastics.³⁵⁶ Poly(dihydroferulic acid), which exhibits thermal properties functionally similar to those of polyethylene terephthalate (PET), could be synthesized from vanillin (M1G) and acetic anhydride (route 7 and 7a).³⁵⁷ Firdaus et al.³⁵⁸ prepared bis-unsaturated esters from M1G and fatty acids (route 8). Then all the monomers were polymerized via the acyclic diene metathesis (ADMET) or thiol–ene methodologies (route 8c). Polyalkylenehydroxybenzoates and poly(ether urethane)s were produced by functionalization of only the phenol group (route 9 and 9a)³⁵⁹ or both phenol and carboxyl groups (route 10 and 10a)³⁶⁰ in vanillic acid. Although ferulic acid (FA) is not included in the product table from depolymerization strategies, we have also included related routes. Various polyesters could be produced from FA.³⁶¹ For instance, FA could be transformed to a α,ω -diene derivative in a two-step sequence (route 10), with subsequent preparation of the respective polyesters via ADMET reaction (route 11a). Following the same method, several copolymers were also produced but reacting with fatty acid monomers (route 11b) or via thiol–ene addition with 1,4-butanedithiol (route 11c). After reaction with propargyl bromide by using FA, a bisacetylenic monomer was obtained (route 12), and it was polymerized by the oxidative coupling polymerization to obtain a novel polyetherester (route 12a).³⁶² Uhrich and co-workers reported the synthesis of polyanhydride esters. In this

study, a diacid monomer was first synthesized (route 13) and then polyanhydride esters were obtained by polycondensation with triphosgene (route 13a). Meier and co-workers³⁶³ synthesized a series of novel copolyesters with different ratios of aliphatic (obtained from oleic and erucic acid via thiol–ene addition) and aromatic (hydroxyethylated methyl ester derivative of ferulic acid) monomers (route 14 and 14a).

4.1.2. Modification through the Aromatic Ring or Side Chain.

Divanillin. Divanillin, which can be easily synthesized by oxidative dimerization of vanillin by horseradish peroxidase (route 15),³⁶⁴ is a useful intermediate for synthesis of other polymer building blocks. For instance, Razzaq and co-workers reacted divanillin with alkyl diamines (1,2-diaminoethane, 1,3-diaminopropane, and 1,6-diaminohexane) in ethanol; after reflux the Schiff base polymers with a degree of polymerization between 25 and 32 were obtained (route 15a).³⁶⁵ Divanillin was converted to α,ω -dienes and then a conjugated polymer was obtained by ADMET polymerization (route 15b).³⁶⁶ Vanillin is also a useful chain extender after its dimerization and further modification with ethanolamine in the synthesis of biobased polyurethanes (route 15c).³⁶⁷ These vanillin-derived diimines were converted into conjugated pyrrole-based polymers by a transformation exploiting a catechyl-substituted phosphonite-mediated multi-component polymerization with commercial diacid chlorides and simple alkynes or alkenes (route 15d).³⁶⁸ Importantly, this study reported, for the first time, a cross-conjugated polymer composed of both components of lignocellulosic biomass by using vanillin and furan-based acid chlorides. Polyvanillin, which is a functionalized polymer using totally renewable resources can be simply synthesized by electrochemical reductive polymerization of divanillin in aqueous sodium hydroxide (route 15e).³⁶⁹

Sustainable Bisphenols. To generate thermoplastics such as polycarbonates and thermosetting resins from lignin-derived monomers, bisphenols are usually required. There are two strategies to produce bisphenols using lignin-derived monomers as starting materials. The first is a coupling on the aromatic ring of two phenolic monomers with formaldehyde,^{349,370–373} by enzymatic dimerization^{366,374} or electrophilic aromatic condensation³⁷⁵ (route 16). An alternative strategy is the functionalization of the side chain, which includes formation of stilbenes^{267,376,377} or coupling of two phenolic monomers with a cross-linker^{378–382} (route 17). After obtaining the bisphenol precursor, a series of polymers including polycarbonates,^{370,376} epoxy resins,^{378,380,382} polyesters,^{374,379,383} polycyanurates,^{370,372,376} poly(carbonate–amide)s,³⁸⁴ and liquid crystal materials³⁸¹ could be produced with simple modification of the bisphenol structure.

Diverse Side Chain Modifications. Polymers with only functionalization of the side chain are also possible. Miller and co-workers reported a series of polyvinyl aromatic acetals, which were obtained from the condensation of commercially available poly(vinyl alcohol) (PVA) and sustainable aromatic aldehydes including vanillin (M1G), syringaldehyde (M1S), and other 11 aldehydes (route 18).³⁸⁵ Polymeric nanoparticles based on poly(vanillin oxalate) (PVO), were developed by Lee and co-workers (route 19).³⁸⁶ These nanoparticles presented great potential as novel antioxidant therapeutics and drug delivery systems. Roger and co-workers synthesized the acrylamide derivative from vanillin by a three step process, and then the obtained acrylamide monomer was polymerized by free radical polymerization (route 20).³⁸⁷ Decarboxylation of ferulic acid results in 4-vinylguaiacol, which was easily and quantitatively transformed into novel-biobased styrene monomers by Take-

Table 4. Thermomechanical Properties of Lignin Derivative-Based thermosets

entry	resins	lignin derivatives	T_g (°C)	T_{dec} (°C)	curing procedure	ref
1	epoxy resins	4-(1-propenyl)guaiacol (M18G)	78–120 ^a	$T_{max} = 322–412^c$	150 °C for 1 h	348
2	epoxy resins	mixtures of phenolics	99–113 ^b	$T_{max} = 261–303^{df}$	(1) 110 °C for 1 h (2) 150 °C for 1 h	343
3	epoxy resins	4-propylguaiacol (M7G)	40–139 (T_g) ^c	$T_{5\%} = 193–297^{df}$	(1) 55 °C for 2 h (2) 75 °C for 2 h (3) 95 °C for 2 h	349
4	epoxy resins	hydrogenolysis products derived from softwood lignin (mixture used)	59–135 ^a	$T_{5\%} = 220–325^{df}$	(1) 40 or 80 °C for 24 h (2) 120 °C for 24 h (3) 150 °C for 24 h	394
5	epoxy resins	vanillyl alcohol and guaiacol (M24G)	100–158 (T_g) ^c	$T_{max} = 352–392^{df}$	(1) 90 °C for 5 h (2) 160 °C for 2 h	375
6	epoxy resins	vanillyl alcohol and guaiacol (M24G)	81–103 ^c	$T_{max} = 345–365^{df}$	(1) 90 °C for 5 h (2) 160 °C for 2 h	395
7	epoxy resins	4-hydroxybenzaldehyde, vanillin (M1G), syringaldehyde (M1S), 4-methylguaiacol, 4-propylguaiacol (M7G), 4-methylcatechol	82–167 (T_g) ^c	$T_{5\%} = 220–269^{df}$	(1) r.t. for 8 h (2) 60 °C for 4 h (3) 80 °C for 4 h	396
8	epoxy network	4-propylguaiacol (M7G) + deprotected lignin	130–141 (T_g) ^c	$T_{5\%} = 273–297^{df}$	(1) 55 °C for 2 h (2) 75 °C for 2 h (3) 95 °C for 2 h	397
9	epoxy resins	vanillin (M1G)	166–214 ^a	$T_{5\%} = 286–356^e$	(1) 160 °C for 2 h (2) 200 °C for 2 h (3) 230 °C for 2 h	382
10 ^g	epoxy resins	lignin-derived C2-acetals	67–134 ^d	N. R.	N. R.	378
11	cyanate ester resins	4-propylguaiacol (M7G)	193–231 ^h	$T_{5\%} = 375–389^{df}$	(1) 150 °C for 1 h (2) 210 °C for 24 h (3) 280 °C for 4 h	370
12	vinyl ester resins	phenyl methacrylate, 2-methoxyphenyl methacrylate, and 4-propyl-2-methoxyphenyl methacrylate	125–155 (T_g) ^c	$T_{max} = 392–427^{df}$	(1) 90 °C for 4 h (2) 180 °C for 2 h	341
13	poly-vanillin methacrylate	vanillin methacrylate	102 ^a	250–480 °C ^{d,j}	65 °C for 6 h	340
14 ⁱ	polymer on the methacrylate-modified Fe ₃ O ₄ NPs	vanillin methacrylate	N. R.	N. R.	N. R.	342

^aDSC under nitrogen. ^bDSC under air. ^cDMA. ^dTGA under nitrogen. ^eTGA under air. ^fTGA under argon. ^gCuring made directly during DSC analysis and occurring around 140 °C. ^hTMA under nitrogen. ⁱMicrospheres used as adsorbents, thermal properties not reported. ^jDecomposition temperature range.

shima and co-workers³⁸⁸ (route 21). Herein the phenolic functions in 4-vinylguaiacol and 4-vinylcatechol were protected with silyl groups and subjected to controlled radical polymer-

ization to give a series of polymers with controlled molecular weights.

4.2. Properties of Polymers Obtained from Lignin-Derived Monomers

4.2.1. Lignin-Derived Thermosets. Epoxy Thermosets. A thermoset polymer is a material undergoing degradation with increasing temperature instead of behaving like a fluid.³⁸⁹ Thermosets represent less than 20% of plastic production³⁹⁰ and are usually synthesized from a polymeric chain reacting with a cross-linker in order to provide a three-dimensional structure.³⁹¹ These polymers are extremely interesting due to the possibility of easily varying their properties, which not only depend on the nature and molecular weight of the polymer material but also on the cross-linking density that is adjustable. Thus, a broad range of different properties can be potentially reached.³⁹¹ In fact, thermosets have been employed in several applications such as packaging, electronics, coatings, adhesives, and composites thanks to their usually high modulus, strength, and good thermal and chemical resistance.³⁹² Among the various classes of thermosets, epoxy resins have been broadly investigated. These materials represent approximately 70% of the market of thermosets due to their superior chemical and heat resistance, adhesion, and mechanical properties.³⁹⁰

Several aromatic structures mentioned in section 2 (e.g., Vanillin **M1G**, 4-propylguaiacol **M7G**, and 4-(1-propenyl)guaiacol **M18G**) can be obtained from lignin and lignocellulose. Interestingly, they can be employed to produce several polymers. For instance, François et al.^{348,393} used 4-(1-propenyl)guaiacol (**M18G**) to synthesize its diglycidylether (DGE-isoEu) (Figure 31, route 3) which was subsequently cured in the presence of several anhydride and acid hardeners (e.g., maleic anhydride, MA) to prepare thermosetting resins (Figure 31, route 3b). After obtaining DGE-isoEu in 92% yield, epoxy resins were synthesized by heating mixtures of DGE-isoEu (Table 4, entry 1) with curing agents and 2-ethyl-4-methylimidazole (EMID) as catalyst. Nanoindentation measurements showed an instantaneous and relaxed modulus ranging from 4.15 to 5.54 GPa and a hardness parameter that varies between 230 and 400 MPa, values of the same order of magnitude as petroleum-based resins. Fache et al.³⁴³ employed model mixtures of depolymerization products of lignins from both softwood and hardwood directly to prepare epoxy resins (Figure 33). First, the phenolic functionalities were

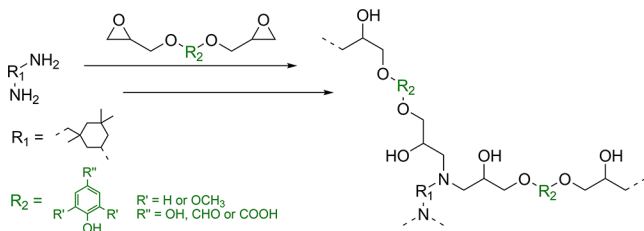


Figure 33. Synthesis of cross-linked thermosets by epoxy/amine reaction and epoxy polymers from model mixtures of G- and GS-type monomers. Adapted with permission from ref 348. Copyright 2016 Royal Society of Chemistry.

subjected to Dakin oxidation followed by glycidylation to produce a mixture of epoxy monomers. Subsequently, the resins were prepared using isophorone diamine (IPDA) as hardener, obtaining a homogeneous glassy material after curing (Table 4, entry 2). The thermo-mechanical properties determined by dynamic mechanical analysis (DMA) showed characteristics of high-performance epoxy thermosets.

Zhao et al.³⁴⁹ used 4-propylguaiacol (**M7G**) to synthesize several starting monomers differing in molecular weight orientation of functional group and number of epoxy groups to explore systematically the differences in the final material properties (Figure 31, route 2; Figure 32, route 16). They demonstrated that the epoxy resins obtained from the new monomers in the presence of diethylenetriamine (DETA) improved in thermomechanical properties increasing the cross-linking density (Table 4, entry 3). In particular, the use of an oligomer derived from modification of 4-propylguaiacol (**M7G**) through phenol–formaldehyde reaction led to the highest cross-linking density with an α -relaxation temperature (T_{α}) of 139 °C and a high degradation temperature ($T_{5\%} = 297$ °C in contrast with 193–245 °C). Importantly, T_{α} value is slightly higher than the 137 °C of traditional DGEBA/DETA epoxy resins (diglycidyl ether of bisphenol A/epoxy prepolymer cured with diethylenetriamine), showing the possible effective replacement in terms of this parameter.

Van de Pas and Torr³⁹⁴ used the oil from mild hydrogenolysis of pinewood to react with epichlorohydrin to give epoxy prepolymers (Figure 34). After fractionation in diethyl ether, they obtained two fractions named hydrogenolysis epoxy prepolymers (LHEP) and oligomeric lignin hydrogenolysis epoxy prepolymers (LHOEP). Blending these with bisphenol A diglycidyl ether (BADGE) or glycerol diglycidyl ether (GDGE) and curing with DETA or IPDA they obtained epoxy resins. Interestingly, the use of BADGE or GDGE and different curing agent leads to a pronounced effect on the final thermomechanical properties (Table 4, entry 4). In particular, this study evidenced that blending LHEP and LHOEP with BADGE and curing with IPDA gave mechanical properties similar to the industrial BADGE control resin while increased flexural modulus and strength were observed if cured with DETA. However, lower T_g (68–104 °C) were detected in this case, indicating that IPDA enhanced the resin thermal properties reaching T_g of the order of 100–135 °C. When LHEP and LHOEP were blended with GDGE, similar mechanical properties were detected while T_g around 60 °C were obtained, indicating a restriction in the use of these materials to lower temperature applications.

Hernandez et al.³⁷⁵ prepared bisguaiacol through condensation of vanillyl alcohol and guaiacol (**M24G**) to then obtain diglycidyl ether of bisguaiacol (Figure 32, route 16). Furthermore, three single aromatic diglycidyl ethers were synthesized from vanillyl alcohol, gastrodigenin, and hydroquinone. Once cured with a diamine (4,4'-methylenebis(cyclohexanamine)), they found a positive influence of methoxy and methylene moieties on the thermomechanical properties of the final material. The methoxy groups improved the modulus of cured resins; however, a lower T_g (100–124 vs 131–149 °C) was found (Table 4, entry 5). Subsequently, the diglycidyl ethers of gastrodigenin, vanillyl alcohol, bisguaiacol, and hydroquinone were employed by Mauck et al.³⁹⁵ to be reacted with the cellulose-derived 5,5-methylenedifurfurylamine as curing agent and obtain epoxy amine thermosets (Table 4, entry 6). These new highly bioderived thermosetting epoxy and amine resins were characterized by good thermogravimetric and thermomechanical properties comparable with a commercial BPA-epoxy resin demonstrating the possibility of its replacement.

Zhao et al.³⁹⁶ prepared a series of triphenylmethane-type polyphenols (TPs) from guaiacols [4-methylguaiacol and 4-propylguaiacol (**M7G**)] and aldehydes [4-hydroxybenzaldehyde (**M1P**), vanillin (**M1G**) and syringaldehyde (**M1S**)] (Figure 35).

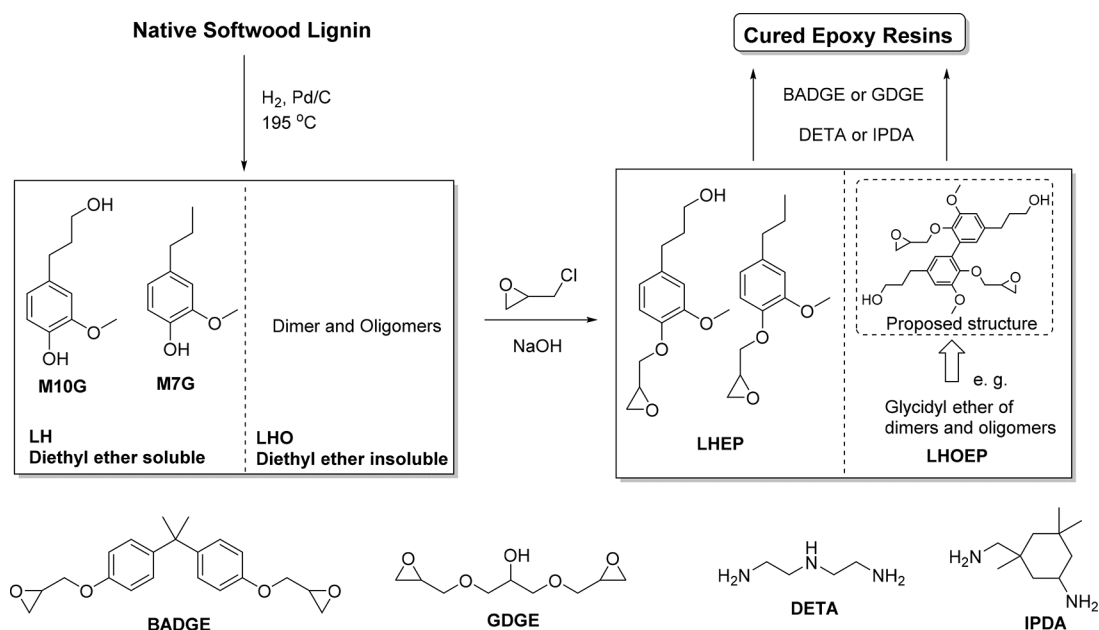


Figure 34. Approaches to prepare cured epoxy resins from lignin hydrogenolysis products and the cured epoxy resin specimens. Adapted from ref 394. Copyright 2017 American Chemical Society.

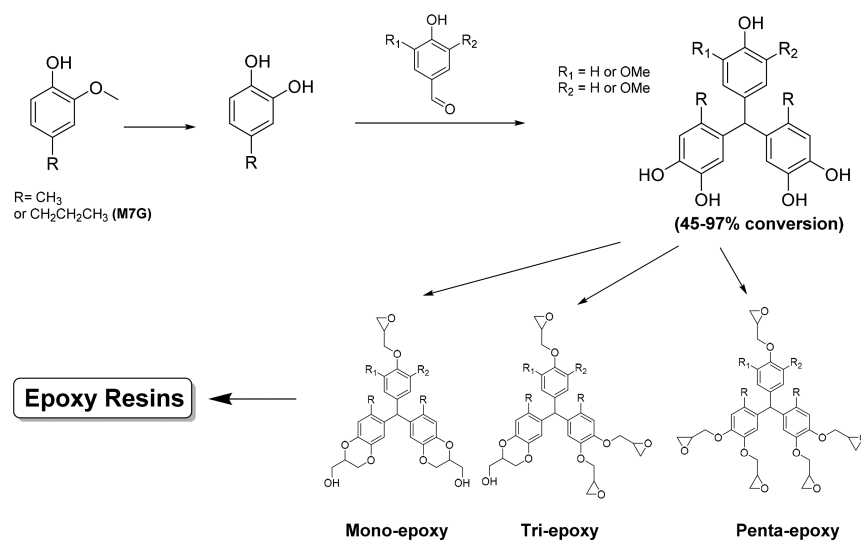


Figure 35. Synthesis route of fully renewable triphenylmethane-type polyphenols and corresponding polymers from lignin-derived aldehydes and para-substituted guaiacols. Adapted from ref 396. Copyright 2017 American Chemical Society.

Afterward, the polyphenol was epoxidized and cured or reacted with a modified linoleic acid followed by epoxidation and curing to obtain the final resin (Table 4, entry 7). Interestingly, the presence of the long chain of linoleic acid acted as plasticizer decreasing both T_g and storage modulus from 167 to 82 °C and from 12.3 to 3.6 GPa, respectively. They also prepared epoxy resin, employing both lignin-derived phenols (LDPs) and lignin itself.³⁹⁷ This procedure involved demethylation of lignin followed by the addition of 4-propylguaiacol (M7G) and formaldehyde solution to make a deprotected lignin incorporated novolac polyphenol (DLINP). Consequently, the DLINP was reacted with epichlorohydrin and cured with diethylenetriamine (DLINEN). Interestingly, the obtained polymer (DLINENs) were characterized by thermal and mechanical properties similar to the neat polymer prepared exclusively with LDPs in terms of degradation temperature ($T_{5\%} = 273\text{--}287\text{ }^\circ\text{C}$ vs 297

°C) and glass-relaxation temperature ($T_g = 130\text{--}141\text{ }^\circ\text{C}$ vs 139 °C) (Table 4, entry 8).

Wang et al.³⁸² reported the synthesis of vanillin-based epoxy resins characterized by flame retardant properties thanks to phosphorus introduction using the coupling agent [4,4-diaminodiphenylmethane (DDM)] or *p*-phenylenediamine (PDA) (Figure 32, route 17) to produce materials with similar or improved mechanical and thermal properties compared with the commercial DGEBA (Table 4, entry 9).

Kaiho et al.³⁷⁸ studied the synthesis of lignin-based epoxy resins with controlled glass transition temperature starting from selectively depolymerized lignin containing a C2-acetal structure. The C2-acetals were subjected to (1) transacetalization with tetraol di(trimethylolpropane) (DTMP) to introduce a flexible structure or (2) generation of a phenylanthracene structure via aldol condensation and intramolecular annulation to introduce a

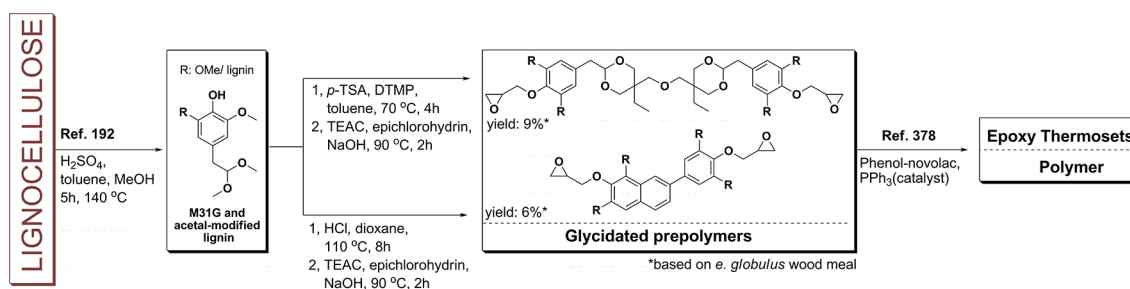


Figure 36. Synthesis of lignin-based epoxy resins by using lignin-derived monomer (M31G) and acetal-modified lignin.

rigid structure (Figure 36). Afterward, the phenolic hydroxyl group underwent glycidylation providing the corresponding reactive epoxide. Subsequently, phenol novolac and triphenylphosphine (TPP) were mixed with the monomer producing the final epoxy resins (Table 4, entry 10). Notably, the resin containing DTMP showed lower flexural strength and impact strength compared to the phenylanthralene.

Other Lignin-Derived Thermosets. Koelewijn et al.³⁷⁰ proposed the synthesis of cyanate ester thermosets starting from 4-propylguaiacol (M7G) (Figure 32, route 16). Specifically, they prepared *m,m'*-bisguaiacols from methyl-, ethyl-, and propylguaiacols studying the effect of the alkyl chain systematically (Table 4, entry 11). Importantly, the highest decomposition and glass transition temperature were detected with 4-propylguaiacol (M7G). Bassett et al.³⁴¹ studied the effect of impurities in reactive diluents prepared from lignin model compounds on the properties of commercial vinyl ester resins (VER) (Figure 31, route 1a). VER are in fact usually blended with diluents like styrene to reduce resin viscosity for liquid molding processing and increase polymer performance.³⁹⁸ Thus, the lignin-derived diluents (phenyl methacrylate, 2-methoxyphenyl methacrylate, and 4-propyl-2-methoxyphenyl methacrylate) were tested as possible styrene replacement (Table 4, entry 12). The use of pure compounds led to a material with properties comparable to the industrial one while the impure VER markedly deteriorated the material.

Zhang et al.³⁴⁰ employed vanillin methacrylate as monomer to produce polymeric microspheres containing reactive aldehyde groups. Interestingly, they demonstrated the effective functionalization with glycine obtaining Schiff-base chelating microspheres which were proven to be efficient as adsorbent of Cu²⁺ used as a representative of heavy metal ions (over 130 mg/g) (Table 4, entry 13). Subsequently, the same group prepared the same microspheres introducing methacrylated-Fe₃O₄ NPs as magnetic moiety enabling an easy separation from liquid medium.³⁴² Interestingly, the microspheres were proven to be effective adsorbents for paraanisidine (representative for amines) and proposed as suitable materials for immobilizing enzymes (Table 4, entry 14).

4.2.2. Lignin-Derived Thermoplastic Polymers. A thermoplastic polymer is a material which behaves as a fluid above a specific temperature.³³⁵ Thermoplastic materials are employed in several applications depending on their chemical nature and thus final properties. Important industrial examples are polyamides (PA, nylon), polypropylene (PP), polyethylene (PE), poly(vinyl chloride) (PVC), polystyrene (PS), poly(methyl methacrylate) (PMMA, Plexiglas), and poly(ethylene terephthalate) (PET) which are polymers frequently used for fibers, containers, automotive parts, insulators, furniture, foams, packaging, medical equipment, and so on. However, their synthesis is usually based on fossil fuel-derived monomers which

results in the strong necessity of finding alternative routes.³²⁷ As mentioned in section 2, vanillin (M1G), guaiacol, and syringyl-derivatives and ferulic acid can be derived from lignin or lignocellulose in high yields. Remarkably, they have been also broadly investigated in order to produce materials characterized by thermo-mechanical properties comparable to those of traditional petroleum-based polymers.

Zhou et al.³³⁸ prepared high glass-transition temperature methacrylate polymers from vanillin (M1G) and syringaldehyde (M1S) via four methacrylate monomers [syringaldehyde methacrylate (SMA), syringaldehyde acrylate (SA), vanillin methacrylate (VMA), and vanillin acrylate (VA)] that underwent free radical polymerization providing the corresponding polymers (PSMA, PSA, PVMA, and PVA) (Figure 31, route 1b). Remarkably, the final materials presented improved or similar thermal properties compared to biobased polylactic acid (PLA), petroleum-based polystyrene (PS), and polymethylmethacrylate (PMMA). In particular, glass transition temperature was found to be much higher in the new syringaldehyde-derived polymers compared to the traditional PLA, PS, and PMMA (95–180 °C vs 48–110 °C) (Table 5, entry 1). Furthermore, all the prepared materials presented an increased initial degradation temperature (T_{onset}) compared to PLA and PMMA (300–320 vs 296 and 280 °C, respectively).

Holmberg et al.³⁹⁹ employed guaiacyl methacrylate (GM), creosyl methacrylate (CM), 4-ethylguaiacyl methacrylate (EM), and vanillin methacrylate (VM) from guaiacol (M24G), creosol, 4-ethylguaiacol (M6G), and vanillin (M1G), respectively (Figure 31, route 1) to obtain the equivalent polymers (PGM, PCM, PEM, and PVM) via reversible addition–fragmentation chain transfer (RAFT) polymerization (Figure 31, route 1b). Interestingly, they also reported the synthesis of two heteropolymers with different amounts of the four monomers mining a biomass-derived oil. Remarkably, the authors reported measurable differences in glass transition ($T_g = 111–139$ °C), thermal degradation ($T_{\text{max}} = 281–327$ °C), and viscoelastic properties (zero-shear viscosity, $\eta_o = 730–25000$ kPa s), depending on the starting monomer or on the relative composition in the heteropolymers (Table 5, entry 2). Following this research, the same group³³⁷ then used syringyl methacrylate and related monomers to prepare homo- and heteropolymers (Figure 31, route 1b) with controllable glass transition temperature ranging from 114 to 205 °C and zero-shear viscosities ranging from ~0.2 kPa·s to ~17000 kPa·s at 220 °C, highlighting the wide applicability of these systems (Table 5, entry 3).

Takeshima et al.³⁸⁸ utilized 4-vinylguaiacol derived from ferulic acid to synthesize polyvinylguaiacol and polyvinylcatechol via controlled radical polymerization using various protecting groups (Figure 32, route 21). The solubility of polymers before and after deprotection in several solvents as well as the glass

Table 5. Thermomechanical Properties of Lignin Derivative-Based Thermoplastics

entry	lignin-derived monomers	polymerization method	final polymers	M_n (g/mol)	\bar{D}	T_g (°C)	T_m (°C)	T_d (°C)	ref
1	syringaldehyde (M1S) and vanillin (M1G)	free radical polymerization	lignin-based (meth)acrylate polymers	7600–14600	1.89–4.07	95–180 ^a	N. R.	$T_{max} = 340–360^c$	338
2	guaiacol (M24G), cresol, 4-ethylguaiacol (M6G), vanillin (M1G)	RAFT polymerization	(meth)acrylate polymers	15000–41000	1.12–1.39	111–139	N. R.	$T_{max} = 281–327$	399
3	syringyl methacrylate	RAFT polymerization	poly(syringyl methacrylate), SM-containing heteropolymers	11000–38000	1.32–1.74	114–205 ^b	N. R.	$T_{onset}(\text{initial degradation}) = 256–303^d$	337
4	ferulic acid (FA)	RAFT+ living radical polymerization	poly(vinylcatechol) and poly(vinylguaiacol)	2200–41500	1.06–1.59	21–190 ^c	N. R.	N. R.	388
5	syringic acid (M20S), vanillic acid (M20G), ferulic acid (FA), and <i>p</i> -coumaric acid	ring-opening polymerization (ROP)/polycondensation	N. R.	1500–60700	1.6–6.3	(–48)–113 ^c	36–354	$T_{5\%} = 209–343^c$	400
6	vanillin (M1G)	N. R.	divanillin-ethanol amine conjugate-based polyurethane	N. R.	N. R.	(–68.08)–(–67.2) ^a	N. R.	$T_{5\%} = 329.59–341.54^c$	367
7	vanillic acid (M20G) and syringic acid (M20S)	N. R.	poly(ether urethane)s	32100–36100	1.6–1.9	49–74 ^a	N. R.	$T_{10\%} = 304–308^c$	360
8	12 aromatic aldehydes including vanillin and syringaldehyde	N. R.	polyvinyl acetals	22300–46000	N. R.	114–157 ^c	N. R.	$T_{95\%} = 185–308^c$	385
9	4-propylguaiacol (M7G)	N. R.	polycarbonates	2503–5182	N. R.	99–125 ^a	205–305 ^a	$T_{5\%} = 346–376^c$	370
10	vanillin (M1G)	N. R.	poly(ether- <i>o</i> -hydroxyamide) and following cyclodehydration to poly(ether benzoxazole)	N. R.	N. R.	N. R.	N. R.	>400 ^c	355
11	vanillin-based monomers	phosphonite-mediated multicomponent polymerization	vanillin-derived fluorescent polymers	3000–12700	1.8–2.3	N. R.	N. R.	N. R.	368

^aDSC under nitrogen. ^bDSC under air. ^cTGA under air. ^dTGA under nitrogen. ^eAtmosphere not specified.

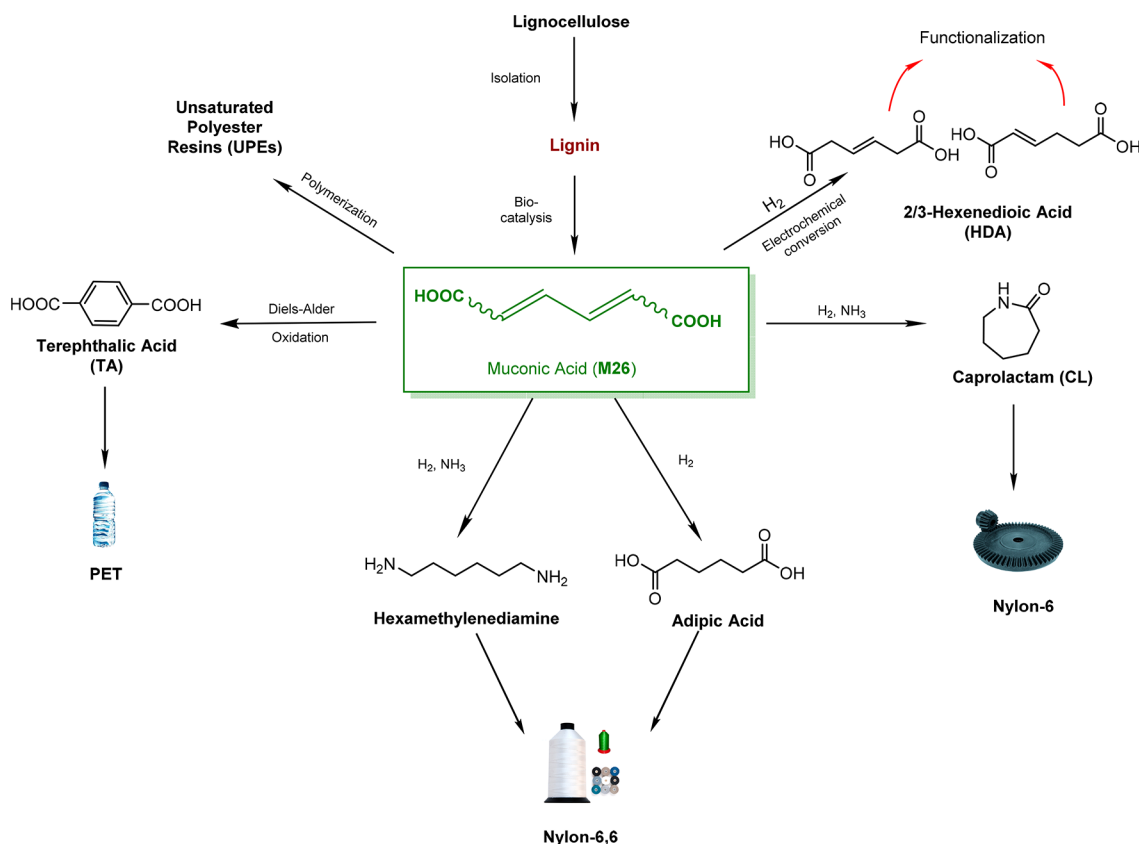


Figure 37. Strategies for transformation of muconic acid to biobased polymers or polymer building blocks.

transition temperature were reported, the latter varied in a wide range [from 21 to 190 °C being the lowest for poly(bis-(triethylsilyl)-protected vinylcatechol) (poly(TES₂VC))] showing that trialkylsilyl groups tend to decrease the T_g of the polymers by enhancing the mobility of the polymer chain (Table S, entry 4).

Miller and co-workers⁴⁰⁰ prepared several polymers via copolymerization of lactones (L-lactide or ϵ -caprolactone) and bioaromatics (hydroxy-acid derived from syringic acid (M20S), vanillic acid (M20G), ferulic acid (FA), and *p*-coumaric acid) through concurrent ring-opening polymerization/polycondensation strategies to obtain new materials with promising properties. In fact, the introduction of bioaromatics in poly(lactic acid)(PLA) was reported to increase the T_g from 50 to 62–107 °C and to improve the thermal stability [$T_{95\%}$ from 207 °C (PLA) up to 323 °C]. An analogous effect was verified introducing bioaromatics in polycaprolactone (PCL) [T_g from –60 °C (PCL) to –48–105 °C and $T_{95\%}$ from 255 °C (PCL) up to 325 °C] (Table S, entry 5).

Gang et al.³⁶⁷ used a dimerized and modified vanillin (M1G) [divanillin-ethanol amine conjugate (DVEA)] to partially replace the traditional 1,4-butanediol as chain extender to produce polyurethanes (PU) with increased percentage of biocontent (Figure 32, route 15c). Notably, the final materials containing DVEA presented similar strength and thermal stability but improved Young's modulus (8.02–9.67 MPa vs 7.53 MPa of control PU) and strain (644.82–770.86% vs 522.57% of control PU) (Table S, entry 6).

Kuhire et al.³⁶⁰ synthesized biobased-aromatic diisocyanates [bis(4-isocyanato-2-methoxyphenoxy)alkane and bis(4-isocyanato-2,6-dimethoxyphenoxy)alkane] from vanillic acid (M20G) and syringic acid (M20S) to prepare polyether urethanes by

reaction with aliphatic diols (1,10-decanediol and 1,12-dodecanediol) (Figure 31, route 10) and found that thermal stability was mainly determined by the stability of urethane linkages. The highest T_g and degradation temperature ($T_{10\%}$) values corresponded to the use of vanillic acid instead of syringic acid which involved a higher number of methoxy groups that increased the conformational barrier to chain rotation (Table S, entry 7).

Rostagno et al.³⁸⁵ studied the synthesis of polyvinyl aromatic acetals from the condensation of commercially available poly(vinyl alcohol) (PVA) and sustainable aromatic aldehydes [12 aromatic aldehydes including vanillin (M1G) and syringaldehyde (M1S)] (Figure 32, route 18). Importantly, the T_g values in the obtained polymers reached 114–157 °C compared to 75 °C of PVA. Remarkably, the possible degradation of two of the polymers prepared (namely 63.3% and 54% acetalization) was tested in aqueous acidic medium (pH = 1, 2, 3, and 5) verifying that even though they were not degraded at pH = 5, they were efficiently hydrolyzed at pH = 1, 2, and 3 (conditions in the stomach of mammals, fish, and birds) with regeneration of biodegradable PVA and benign aromatic small molecules (Table S, entry 8).

Koelwijn et al.³⁷⁰ synthesized a bisphenolic polymer precursor [*m,m'*-methylenebis(4-*n*-propylguaiaicol) (*m,m'*-BGF-4P)] from 4-propylguaiaicol (M7G) which displayed a markedly reduced potency to activate human estrogen receptor in comparison with commercial bisphenols (Figure 32, route 16). Notably, this molecule was employed as precursor to obtain a thermoplastic polycarbonate (PC3) which was compared with the corresponding polycarbonates from *m,m'*-bis(4-methylguaiaicol) (named PC1) and *m,m'*-bis(4-ethylguaiaicol) (named PC2) and with the commercial PC-BPA. Importantly, PC3 is reported to have the slowest tendency to crystallize and improved

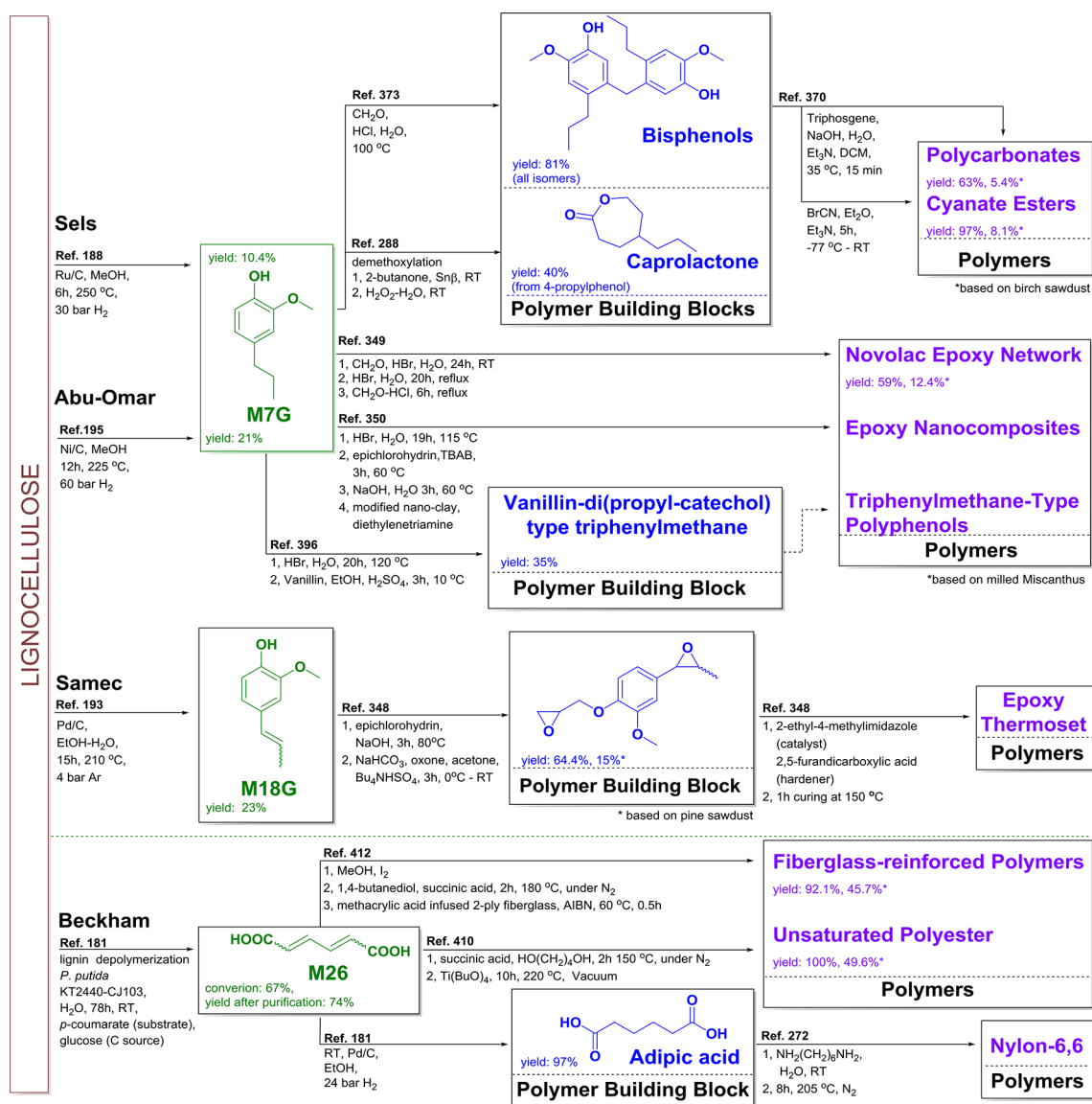


Figure 38. Polymer materials obtained in feasible starting from lignin.

solubility in common solvents even though its glass transition temperature resulted to be lower than PC-BPA, PC1, and PC2 (99 °C vs 145–150, 125, and 116 °C, respectively) (Table 5, entry 9).

Sun et al.³⁵⁵ investigated the synthesis of polyether benzoxazole (PEBO) from modified vanillin (Figure 31, route 5a). In particular, this polymer was obtained from a precursor poly(ether *o*-hydroxy amide) (PEHA) by cyclodehydration with following analysis of thermo-mechanical properties. Interestingly, no evident glass transition was observed possibly due to the rigid benzoxazole structure in PEBO. Moreover, an improved Young's modulus and tensile strength was reported compared to commercial equivalent polymers (Table 5, entry 10).

Kaysner and co-workers³⁶⁸ studied the synthesis of cross-conjugated fluorescent polymers from vanillin-based monomers with tunable properties (Figure 32, route 15d and Table 5, entry 11). In particular, optical properties such as UV/vis absorbance and fluorescence were investigated showing that these lignin-based polymers were blue-emitting compounds and structural modifications modulated this emission. These materials were

stated to be of potential relevance in polymer-based LED production.

4.3. From Lignin-Derived Muconic Acid to Polymers or Polymer Building Blocks

As mentioned in section 2.1, muconic acid (M26) is considered an important biomass-derived chemical. As shown in Figure 37, M26 can be converted to a wide range of commodity chemicals currently produced from fossil resources such as adipic acid, caprolactame, and terephthalic acid.⁴⁰¹

Adipic acid is a bulk chemical of which approximately the 85% is converted together with hexamethylenediamine (HMDA) to obtain nylon-6,6 where the remainder was used for polyurethanes and adipic esters.^{402,403} Thus, the result of catalytic conversion of M26 to these two chemicals is particularly appealing. In this context, M26 plays an important role since its possible conversion to both adipic acid and HDMA was demonstrated. Niu et al.⁴⁰⁴ reported an efficient *cis,cis*-M26 hydrogenation to adipic acid by using Pt/C as catalyst. An excellent 97% yield of adipic acid was obtained at room temperature after 2.5 h. Vardon et al.²⁷² investigated the

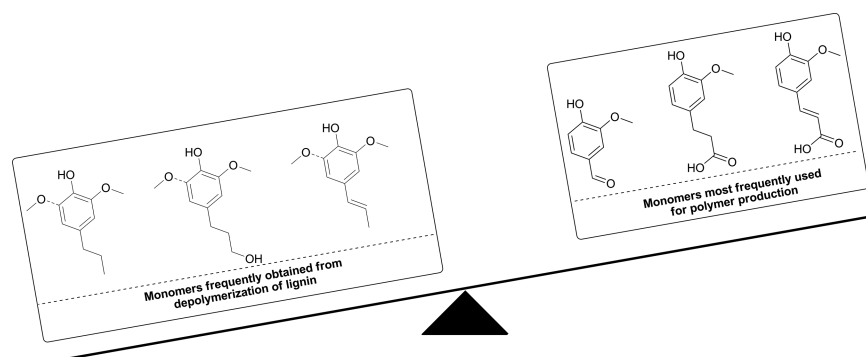


Figure 39. Monomers frequently originating from lignin depolymerization methods (left) and monomers very frequently used for polymer production (right).

separation and purification of **M26** after biological synthesis and achieving a purity of 99.8% which is pure enough for further polymer synthesis. Catalysts screening in batch reactor for hydrogenation of **M26** to adipic acid by using different supported metal catalysts (Pt, Ru, Rh, and Pd on activated carbon or SiO_2) found that Rh/C showed the best activity and stability. A complete conversion and 99.8% purity could be achieved as well even in a trickle bed reactor. Interestingly, they were able to polymerize the synthesized adipic acid with HMDA and obtained a polymer which has similar properties to nylon derived from petrochemical adipic acid. Instead of using hydrogen gas, Matthiesen et al.⁵⁵¹ investigated the electrocatalytic hydrogenation of *cis,cis*-**M26** by hydrogen generated in situ from water. They demonstrated that *trans,trans*-**M26**, *trans*-3-hexenedioic acid, and adipic acid can be produced depending on metal and conditions chosen. However, high selectivity could be obtained mostly for *trans*-3-hexenedioic acid (up to 95% by using Pb at a conversion of $\sim 75\%$). Adipic acid was only observed when using Ni with less than 10% selectivity.

Caprolactam which is usually used to produce nylon-6 fibers and resins⁴⁰⁵ is another relevant chemical which can be derived from of **M26**. Frost et al.⁴⁰⁶ provided a valid synthesis from the three isomers of **M26** (*cis,cis*-, *cis,trans*-, and *trans,trans*-) using Pd/ Al_2O_3 in dioxane at 250 °C. After 2 h, the highest yield (55%) was reached from *cis,cis*-**M26** at a conversion of 79%. Terephthalic acid (TA), another bulk chemical mainly used to produce polyethylene terephthalate (PET),⁴⁰⁷ can be obtained from **M26** as reported by Burk et al.⁴⁰⁸ In particular, the *trans,trans*-**M26** or *cis,trans*-**M26** can be converted to terephthalic acid in a two-step process via Diels–Alder reaction with acetylene at 200 °C followed by oxidation in air or oxygen. The Diels–Alder reaction between muconate and acetylene proceeds via cyclohexa-2,5-diene-1,4-dicarboxylate as intermediate, which is subsequently exposed to air or oxygen to rapidly convert to TA. In 2016, Lu et al.⁴⁰⁹ proposed a synthetic route from *trans,trans*-**M26** to diethyl terephthalate (DET) through a cascade reaction combining esterification, Diels–Alder cycloaddition, and dehydrogenation by using ethanol and ethylene as reactant. Basically, the esterification step improves the solubility of reaction products in ethanol and modifies the electronic properties of *trans,trans*-**M26** promoting the Diels–Alder reaction with ethylene. Various metals were tested for the hydrogenation step, achieving the highest yield in DET (80,6%) with Pd/C at 200 °C.

Apart from its use as a precursor, **M26** can be exploited as a monomer itself. For instance, Rorrer et al.⁴¹⁰ studied its application as unsaturated polyester resins (UPEs) which are

considered interesting materials suitable for coatings, drug delivery systems, tissue engineering, and insulating materials.⁴¹¹ In particular, they incorporated *cis,cis*-**M26** into four succinate-based polyesters showing how thermal properties such as the glass transition temperature of the polymer can be tuned depending on **M26** loading. Furthermore, they demonstrated the applicability of these polymers fabricating a material characterized by a shear modulus typical of fiberglass composites. Subsequently, the same authors synthesized a family of copolymers incorporating maleic anhydride, fumaric acid, *cis,cis*-muconate ester, and *trans,trans*-muconate ester into poly(butylene succinate) at various loadings. Then, the obtained copolymers were cross-linked with styrene, methacrylic acid, and a blend of methacrylic and cinnamic acid in the presence of woven fiberglass mats to produce a series of fiberglass-reinforced polymers (FRPs).⁴¹² When UPEs and methacrylic acid were used for the preparation of the composites, a greater UPE resin/fiberglass compatibility was observed compared to when styrene was employed even though the final FRP was characterized by lower shear and storage moduli. To overcome this problem, a certain amount of cinnamic acid (20% mol) was incorporated, resulting in a significant improvement of these properties and enabling a fully renewable system.

4.4. Conclusions

The possibility of producing polymers from lignin-derived aromatics has generated significant advances in polymer chemistry. Most groups have utilized pure and well-defined starting materials obtained from commercial sources for the synthesis of novel polymers, especially thermosets and thermoplastics that have shown comparable or even better properties than those conventional materials. Several researchers were engaged in the development of both lignin depolymerization methods as well as the synthesis of lignin-derived polymers. Related examples summarized in Figure 38 show that a number of interesting polymer materials can be obtained in feasible quantities starting from lignin.

However, a discrepancy still exists regarding the monomers used for the synthesis of polymers (Figure 39). Novel methodologies are needed that would deliver higher yields of aromatic compounds, which have been widely studied as starting materials for polymer synthesis. In turn, the actual monomers that can be obtained in high yield offer new possibilities for the synthesis of emerging materials and polymers.

Furthermore, catalytic methods typically deliver mixtures of aromatic compounds, which can be directly used for polymer synthesis, thereby eliminating tedious purification steps; however, reproducibility regarding the starting material and the

composition of these product mixtures should be clarified. And last, the biobased polymers are not automatically biodegradable, therefore more insight into the biodegradability, toxicity, and properties of the novel polymers is desired.

5. COMPOUNDS WITH PHARMACOLOGICAL ACTIVITY FROM LIGNIN-DERIVED MONOMERS

Phenols, lignans, and neolignans are a large group of natural products derived from the pool of compounds originating from the Shikimate pathway.⁴¹³ They possess a wide range of biological activities and have been used for a long time both in ethnic^{414,415} as well as lead compounds for the development of new drugs.⁴¹⁶ Furthermore, such structural moieties can be found in already existing pharmaceuticals as well as compounds with pharmacological activity. From a synthetic point of view, these molecules can be synthesized from lignin-derived monomers, since these already contain the required functional groups on the aromatic ring and side chain.

5.1. Natural Products Synthesized from Lignin-Derived Monomers

5.1.1. 4-(1-Propenyl)-syringol, 4-(1-Propenyl)-guaiacol and Isomers. Lignin-derived trans-4-(1-propenyl)-syringol *E*-**M18S** that could be directly obtained through Pd-catalyzed transfer hydrogenolysis of birch lignocellulose in ethanol in high yield (49%)¹⁸⁷ serves as suitable starting material for the synthesis of polysphorin (**PN1**) in 2 steps.⁴¹⁷ **PN1** was isolated from *Piper polysphorum* *C* in China and from the leaves and stems of *Rhaphidopora decursiva* in Vietnam⁴¹⁸ and shows in vitro antimalarial activity.⁴¹⁹ The *E*-**M18S** can be converted in one step to neolignan Eusiderin K (**PN2**) that can be methylated to Eusiderin J (**PN2-Me**).⁴²⁰ Primarily due to the 1,4-benzodioxane moiety, **PN2** and **PN2-Me** show cytotoxic and hepatoprotective activity⁴²¹ and have been isolated from *Viola elongata* or *Licaria chrysophylla*.^{422,423}

M18G is a starting material for the synthesis of variety of natural products. For instance, the sodium salt of *E*-**M18G** can be converted to (–)-virolin (**PN3**) that was isolated from the leaves of *Viola surinamensis*⁴²⁴ and shows activity against parasites in mice.⁴²⁵

Licarin A (**PN4**), present in various tropical or subtropical plants or nutmeg,^{426–428} exhibits a wide range of beneficial pharmacological effects,^{429–431} including free-radical scavenging⁴³² and cytotoxicity against tumor cells.⁴³³ **PN4** can be easily synthesized in one-step through an enzymatic oxidative coupling of *E*-**M18G** with outstanding 98% yield.⁴³⁴ Licarin A can be further converted to (±)-acuminatin (**PN4-Me**),⁴³⁵ a natural product isolated from various *Piper* plant species^{436,437} displays a variety of biological activities.^{438,439}

5.1.2. Syringaldehyde and Related Compounds. Syringaldehyde (**M1S**) is a lignin-derived lignin monomer, which can be nearly quantitatively methylated to the corresponding derivative with 96% yield.^{440,441} (–)-Rhaphidocursinol B (**PN5**), first isolated from *Rhaphidophora decursiva* Schott (Araceae),^{419,442} can be obtained from methylated syringaldehyde (**M1S**) in only three steps.⁴⁴³ **PN5** was found active against *Plasmodium falciparum*, the parasite responsible for the most severe form of malaria.^{444,445} Another antimalarial agent prepared from **M1S** and the TBS ether of sinapyl alcohol is Nitidanin (**PN6**)⁴⁴⁶ that was isolated from the tropical plant *Grewia Bilamellata* Gagnep (Tiliaceae).⁴⁴⁷

Daphneticin (**PN7**) was isolated as a racemic compound from the roots and stems of *Daphne tangutica*.⁴⁴⁸ The plant is used

extensively in Chinese traditional medicine as a remedy for the treatment of rheumatism and toothache and also shows cytotoxicity against Walker-256-Carcinoma Ascites cells.⁴⁴⁹ **PN7** can be obtained in 9 steps from **M1S**.⁴⁵⁰

The high yield (82%) cobalt/Schiff base-catalyzed oxidation of **M1S** was presented by Bozell and co-workers to 2,6-dimethoxy-1,4-benzoquinone (**M2S**), which can be isolated from direct lignin oxidation as well.^{451,452} This compound is starting material for the 6 step synthesis⁴⁵³ of Ladanein (**PN8**), an antiviral flavone identified from *Lamiaceae* extracts.⁴⁵⁴ Interestingly, **PN8** has shown potential against enveloped viruses such as the hepatitis C (HCV), as a safe flavonoid-based alternative.^{455,456}

5.1.3. C2-Aldehydes and Alcohols. The acetal of C2 aldehyde **C2AldG** was obtained in high yield by acidolysis in conjunction with ethylene glycol treatment of lignin.¹⁶⁶ Interestingly, **C2AldG** was found as a key ingredient in the synthesis of quebecol [2,3,3-tri-(3-methoxy-4-hydroxyphenyl)-1-propanol] (**PN9**), which was isolated in 2011 from maple syrup and named after the world largest maple syrup producer region, Quebec.⁴⁵⁷ Maple syrup is obtained by thermal evaporation of the sap⁴⁵⁸ collected from the sugar maple (*A. saccharum*) tree, and maple syrup extracts have antioxidant, antimutagenic, and anticancer properties.^{459,460} Quebecol, a compound derived from natural resources and consumed for decades without showing any toxicity shows activity against various cancer cell lines including the human breast adenocarcinoma (MCF-7).⁴⁶¹ Thus far, a sufficient quantity of pure quebecol could not be isolated to conduct detailed biological evaluation, but a patent exists that shows its synthesis from lignin-derived building blocks involving **C2AldG** as well as vanillin (**M1G**).⁴⁶²

Alcohol **C2AlcS** should be easily obtained by reduction of the syringyl derivative of **C2AldG**, and it has been reported as product from lignin depolymerization. Raphanuside (**PN10**) can be found in *Descurainia sophia*⁴⁶³ and was used for anticough and antiasthmatic purposes and moreover show anticancer activity, and it can be synthesized from **C2AlcS** in eight steps.^{464,465}

5.1.4. Dihydroferulic Acid and Derivatives. 4-Propanol-guaiacol (**M10G**) is a building block that can now be obtained in high yield in one step from lignocellulose, owing to the novel catalytic lignocellulose fractionation strategies.^{185,194} These methods have also reported the corresponding dihydroferulic acid methyl ester (**M28G**) in tangible quantities.¹⁹⁵ **M28G** can be converted to dihydroferulic acid (**C3AcidG**) through hydrolysis.⁴⁶⁶ These compounds are versatile starting materials for the synthesis of a variety of natural products as summarized below.

(–)-Arctigenin (**PN11**) is a phenylpropanoid isolated from a variety of plants which shows phagocytic activity on leukemia cells^{467–469} and synergistic effects in combination with cisplatin against several cancer cell lines.^{470,471} Furthermore, the cytotoxicity of doxorubicin in combination with (–)-arctigenin against several multidrug-resistant cells showed improved results.⁴⁷² Other effects are also known.⁴⁶⁹ The synthesis of **PN11** was reported from 3,4-dimethoxycinnamic acid in a convergent nine-step synthesis resulting in 19% overall product yield.⁴⁷³ This synthesis route proceeded through the methylated^{474,475} analogue of alcohol **M10G**, and **M10G-Me** could be directly used as the starting material.

(+)-Imperanene (**PN12**) is a novel phenolic compound that has been isolated from *Imperata cylindrical* and used extensively in traditional Chinese medicine as diuretic and anti-inflammatory agents.⁴⁷⁶ From the reported synthesis, it is recognized that **M28G** can directly be used, giving an overall yield of 17%.⁴⁷⁷

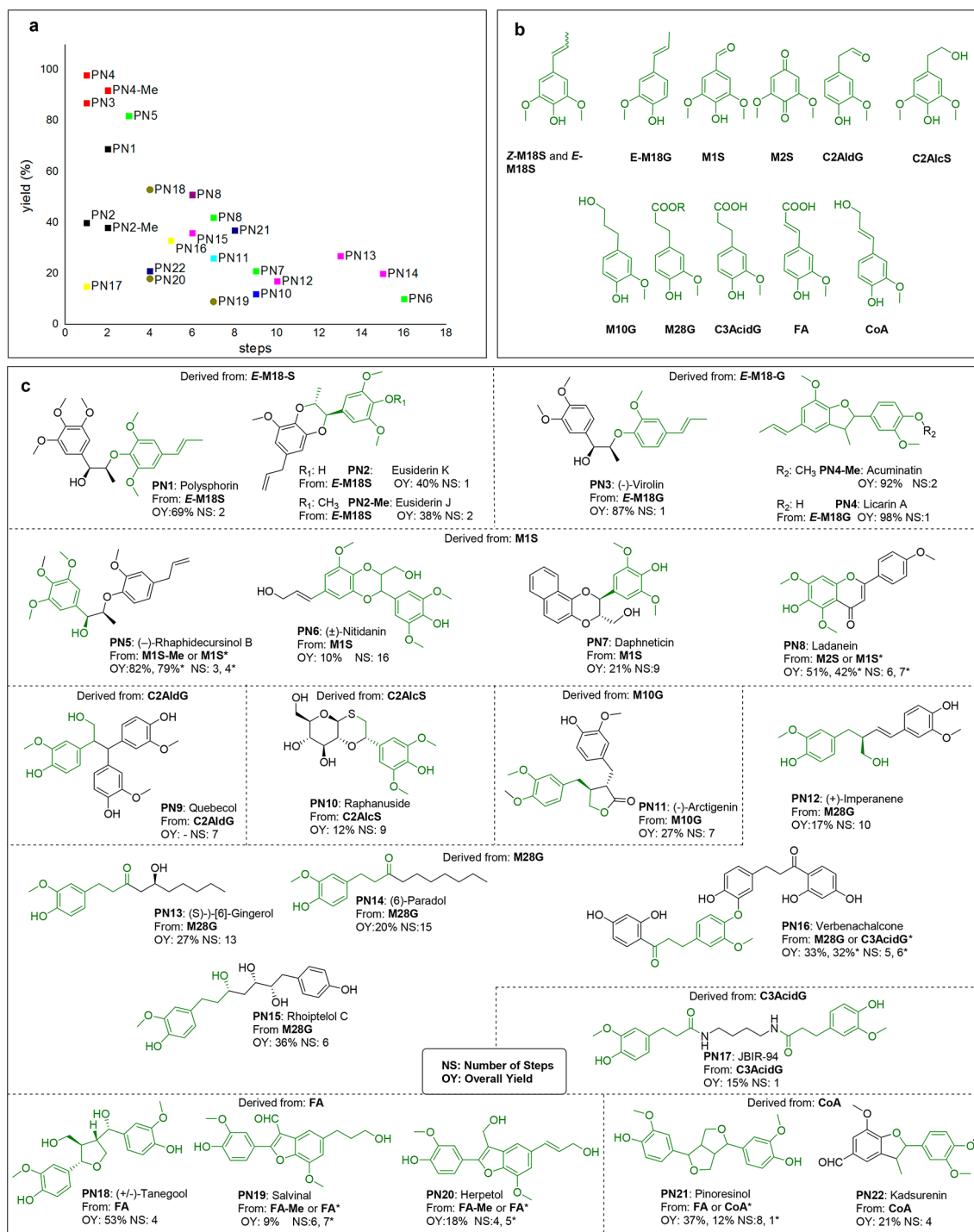


Figure 40. Summary of structures of natural products obtained from lignin-derived monomers. (a) Number of steps required to synthesize the natural products versus overall yield of the process. (b) Monomers used as starting material. (c) Chemical structures of natural products separated by dotted line based on different starting material.

Ginger is a widely used spice and a food supplement throughout the world, and widely applied in traditional Chinese and Japanese medicine.⁴⁷⁸ Its major ingredient, (+)-(S)-[6]-gingerol (PN13), has been found to exhibit diverse pharmacological activities such as antioxidant, anti-inflammatory, anti-tumor, and antibacterial effects.⁴⁷⁹ (S)-[6]-Gingerol can be synthesized from ferulic acid (FA) in 15 steps and from M28G in 13 steps, with overall 27% yield.⁴⁸⁰ (6)-Paradol (PN14) shows anti-inflammatory effect and can be synthesized from PN13 in a two-step procedure.⁴⁸¹

Rhoiptelol C (PN15) was first isolated from the fruits of *Rhoiptelea chiliantha*.⁴⁸² The molecule shows strong phenol oxidase inhibitor effect and has potential for future use in the development of environmentally friendly pesticides.⁴⁸³ PN15 was synthesized in eight steps from vanillin and can be obtained from M28G in 6 steps.⁴⁸⁴

Verbenachalcone (PN16) was isolated from *Verbena littoralis* (Verbenaceae) and displays a biological effect as enhancer of nerve growth factor (NGF) in specific cells⁴⁸⁵ and can be

synthesized from **C3AcidG** in 6 steps with 32% yield or from **M28G** in 33% overall yield in five steps.⁴⁸⁶

Streptomyces strains are producing a wide variety of compounds that serve as antibiotics, including the recently reported JBIR-94 (**PN17**).⁴⁸⁷ This phenolic compound can be synthesized from ferulic acid in four steps and from dihydroferulic acid **C3AcidG** in only one step with 15% yield without any protecting group.⁴⁸⁸

5.1.5. Ferulic acid and Its Derivatives, Monolignols.

Ferulic acid (**FA**) is usually obtained by extraction^{489,490} but was also seen as product in lignin depolymerization mixtures.⁴⁹¹ Although a direct, high yield production of **FA** from lignin is not known at the moment, we will include a few examples of natural products that can be obtained from ferulic acid.

Tanegool (**PN18**) can be found in various plants including *Magnolia fargesii*, *Taxus yunnanensis*, or *Patrinia villosa* originating mainly in East Asia and North America.^{492,493} It shows diverse pharmacological activity, including a great potential in the prevention of Alzheimer's disease.⁴⁹⁴ **PN18** can be synthesized from **FA** in four steps in 53% overall yield based on recovered starting material.⁴⁹⁵

Ferulic acid (**FA**) can be quantitatively esterified.¹⁶⁷ Salvinal (**PN19**), first isolated from *Salvia mitorrhiza*, can also be obtained from the methyl ester of **FA** through a six-step synthesis route.⁴⁹⁶ In traditional Chinese medicine, water extracts have been used to treat acute myocardial infarction and angina pectoris.⁴⁹⁷

Herpetol (**PN20**) featuring a benzofuran skeleton was isolated from *Herpetospermum caudigerum* and possesses anti-inflammatory and free radical scavenging properties.⁴⁹⁸ It can be synthesized in four steps from the methyl ester of **FA** with 18% overall yield.⁴⁹⁶

Similarly to ferulic acid, monolignols are also not direct products from common lignin depolymerization routes. However, the structural variants of the natural products shown below, synthesized from monolignol **CoA**, have been observed on lignin acidolysis studies as part of mixtures.¹⁶⁶

The substance (+)-pinoresinol (**PN21**) is a compound present in the lignan fraction of several plants, such as the seeds of the species *Forsythia* or sesame (*Sesamum indicum*).^{499,500} In a traditional human diet, extra virgin olive oil is an excellent source of pinoresinol up to a concentration of 100 mg/kg.⁵⁰¹ Pinoresinol has cytotoxic activity against human colon cancer cell lines (SW480 and HCT116).⁵⁰² It had been synthesized in one step from coniferyl alcohol **CoA** in 12% yield⁵⁰³ or in an eight-step synthesis in 37% yield from **CoA**.⁴⁹⁵

(7*S*,8*S*)-Kadsurenin M (**PN22**) is a Chinese traditional drug used as a remedy for inflammation and rheumatic conditions.⁵⁰⁴ It was synthesized from vanillin (**M1G**) in five steps. In the procedure, methylated derivative of **CoA** was an intermediate which was converted in three steps to **PN22**; the procedure does not report on the yields of each step.⁵⁰⁵ Guaiacol type phenylalkylalcohol-phenols can be chemoselectively quantitatively methylated;^{474,475} and the methylated **CoA** compound can be chlorinated with 95% yield,⁵⁰⁶ based on **CoA** the synthesis would take four steps with 21% overall yield.

Structures and overall yields of natural products obtained from lignin-derived monomers described in this section are summarized in Figure 40.

5.2. Pharmaceutical Products from Lignin-Derived Monomers

Actual pharmaceutical products (**PD**) can also be obtained from lignin-derived monomers (**E-M18G**, **M1S**, **C3AcidG**) and ferulic acid (**FA**). Tofisopam (marketed under brand names Emandaxin and Grandaxin) (**PP1**) is an anxiolytic agent without addiction potential and without the sedative-hypnotic side effects generally associated with the use of 1,4-benzodiazepines.^{507,508}

According to the 2017 report of the European Medicines Agency (EMA), the lead producer of **PP1** in the EU is Hungary.⁵⁰⁹ Methylated **E-M18G** can be dimerized to 4-(1-propenyl)-guaiacol (**M18G**) by an acid-catalyzed cycloaddition reaction.⁵¹⁰ It can be further converted by oxidation to the corresponding diketone with 88% yield.⁵¹¹ The diketone is then transformed to Tofisopam by hydrazine hydrate in a single step.⁵¹² The calculated yield for the four steps starting from **E-M18G** is 40%. The original patent used the same synthesis strategy.^{513,514}

Trimethoprim (**PP2**) is a classical antibacterial agent that serves as selective inhibitor of bacterial dihydrofolate reductase.⁵¹⁵ It is used alone or in combination with sulfamethoxazole to treat a wide range of bacterial infections in humans and poultry. According to the 2017 report of the European Medicines Agency (EMA), the lead producer of **PP2** in the EU is Estonia.⁵⁰⁹ **PP2** was sold in more than 140 tons as a veterinary antimicrobial agent in the countries of EU, Iceland, and Switzerland in 2014.⁵⁰⁹ More than 80 tons of **PP2** were sold in 2010 for human treatment in the U.S. alone,⁵¹⁶ and in the same year in China, more than 3000 tons⁵¹⁷ of **PP2** were produced for the global market, which shows a huge demand due to antimicrobial and antimalarial applications. **PP2** can be synthesized from the methylated derivative of syringaldehyde (**M1S-Me**) with overall 85% yield in three steps.⁵¹⁷ **M1S** can be nearly quantitatively (96%)^{440,441} transformed to the methylated derivative, and based on this, the overall yield of **PP2** from **M1S** is 82% in four steps.

Donepezil (**PP3**) is a drug used in the treatment of Alzheimer's disease. Since its first approval by the FDA in 1996, this blockbuster drug generated more than 2 billion USD sales in 2010, just in the U.S. After the original patent expired in 2010, generic competitors made **PP3** less expensive and more accessible for patients in 5 and 10 mg doses.⁵¹⁸ According to the 2017 report of the European Medicines Agency (EMA), the lead producer of **PP3** in the EU is the United Kingdom.⁵⁰⁹ Several synthetic procedures exist for the synthesis of **PP3**.^{519,520} In a short synthetic route, dihydroferulic acid **C3AcidG** can undergo ring closure, and upon methylation it can be turned into 5,6-dimethoxy-2,3-dihydro-1*H*-inden-1-one (**DMI**) with 63% yield from **FA** in three steps.⁵²¹ **PP3** can be obtained upon a one-step catalytic alkylation of **DMI**, according to the procedure developed by Glorius et al. with 40% yield which means 25% overall yield in this four step synthesis from **FA**.⁵²²

PP4 (lead EU producer, Hungary⁵⁰⁹) is used in combination with other APIs such as carbidopa, constituting the least expensive (less than 319\$ annual treatment cost) Parkinson's disease medication.⁵²³ Parkinson's disease is affecting more than 2 million people in our world, and it is projected to grow to 2.89 million cases worldwide by 2022.⁵²¹ Several synthesis routes have been established to synthesize **PP4**.⁵²⁴ The most well-known example is the Monsanto process which utilizes asymmetric hydrogenation.^{525,526} Another interesting approach to get **PP4** is based on the demethylation of **FA** to caffeic acid with 62% yield.⁵²⁷ Caffeic acid can aminate in the presence of NH_3 with a plant-derived phenylalanine ammonia-lyase enzyme to yield L-DOPA (**PP4**) close to 100% yield and excellent enantioselect-

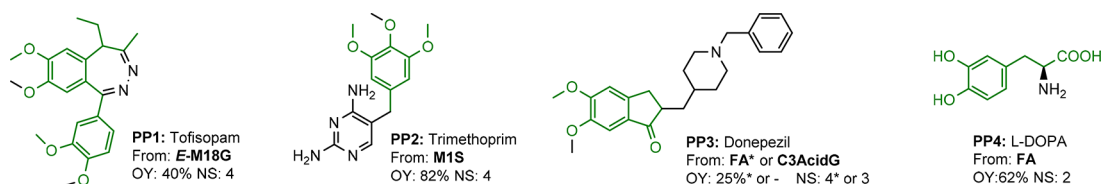


Figure 41. Summary of structures of pharmaceutical products obtained from lignin-derived monomers.

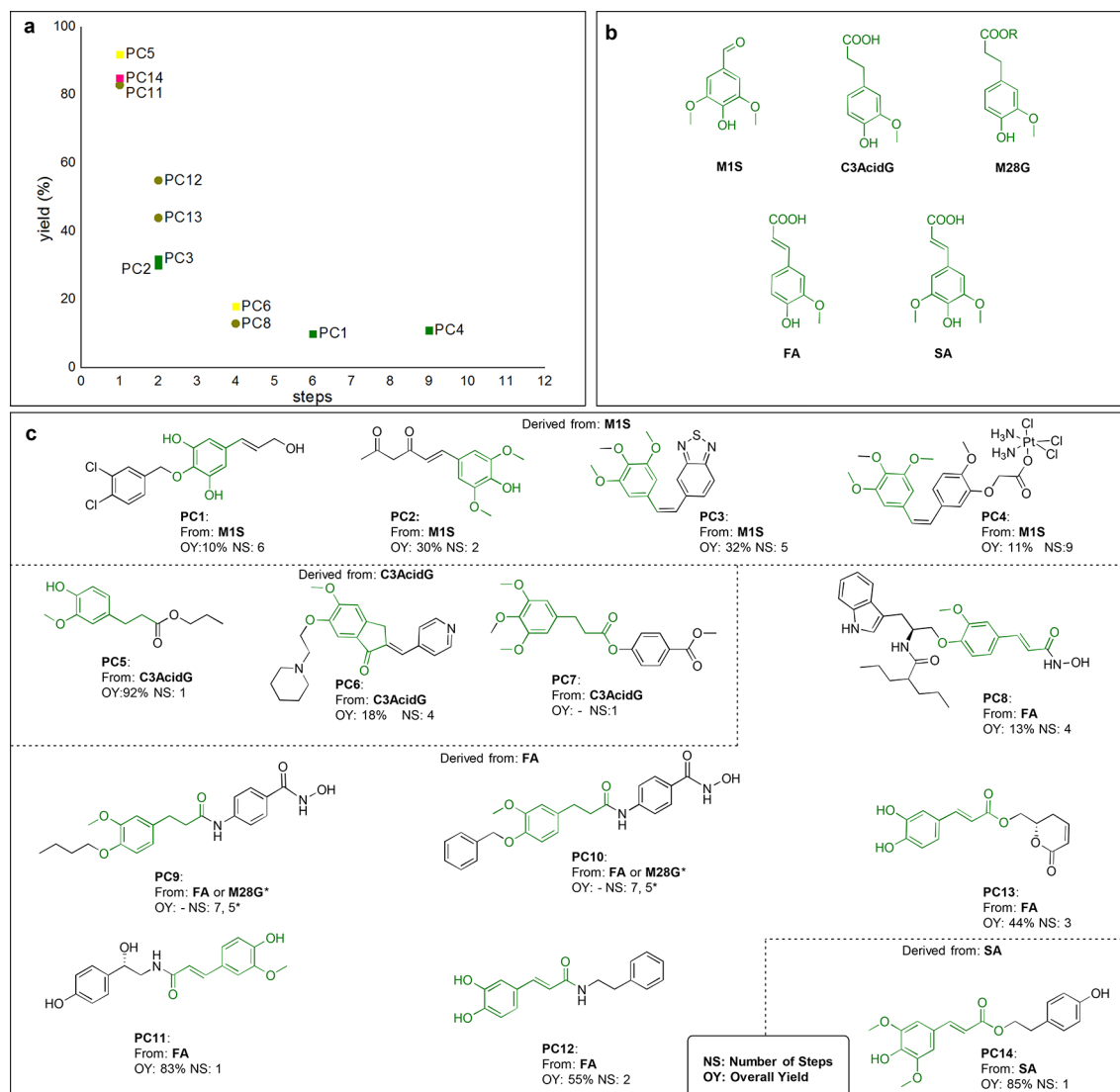


Figure 42. Summary of structures of drug lead compounds obtained from lignin-derived monomers. (a) Number of steps required to synthesize the drug lead compounds versus overall yield of the process. (b) Monomers used as starting material. (c) Chemical structures of drug lead compounds separated by dotted line based on starting material.

tivity, which means 62% overall yield for the two-step procedure.⁵²⁸

Structures and overall yield of all these pharmaceutical products are summarized in Figure 41.

5.3. Drug-Leads from Lignin-Derived Monomers

Drug-leads are chemical compounds that possess favorable pharmacological and biological effects (Figure 42). Their properties can usually be tuned by chemical modifications to yield drug candidates before those enter into clinical trials.⁵²⁹ However, the probability for a drug candidate to succeed as an active pharmaceutical ingredient is typically low, which significantly contributes to the development cost.⁵³⁰

5.3.1. Syringaldehyde and Related Compounds. Drug lead candidate PC1 exhibited significant cytotoxicity to several human tumor cell lines in the micromolar range and showed 20 times more potency than the control cisplatin. PC1 was synthesized from M1S in 6 steps with 10% yield.⁵³¹

Curcumin, 1,7-bis(4-hydroxy-3-methoxyphenyl)-1,6-heptadien-3,5-dione, is the primary bioactive compound isolated from turmeric, the dietary spice made from *curcuma longa*. Curcumin is a potent anti-inflammatory and antiproliferative agent.⁵³² Moreover no cancer cell type has yet been found where curcumin lacks antiproliferative effects, and this effect is selective toward tumor cells showing minimum effect on normal cells.⁵³³

Next to the natural analogues (e.g., demethoxycurcumin and bisdemethoxycurcumin), numerous derivatives have been synthesized in an attempt to find “super curcumin”.⁵³⁴ It was found that PC2 showed higher antiproliferative effect than curcumin.⁵³⁵ PC2 can be synthesized from MIS in two steps with 30% yield.

Combretastatin derivatives also show antitumor activity, and the Z isomer of PC3 was the most potent derivative in the paper presented by Riant et al.⁵³⁶ It was synthesized from methylated MIS in four steps with 33% yield. MIS can be quantitatively (96%) methylated^{440,441} which means five steps to PC3 from MIS.

The Z isomer of platinum containing combretastatin derivative PC4 also show antitumor activity with higher cytotoxicity but with lower toxicity and lower resistance than cisplatin in HepG-2 cancer cells.⁵³⁷ It can be synthesized in eight steps from the methylated MIS with 11% overall yield. MIS can be quantitatively (96%) methylated,^{440,441} which means nine steps from MIS with overall yield around 11%.

5.3.2. Dihydroferulic and Dihydrosinapic Acid Derivatives. The propylester of dihydroferulic acid (PC5) is able to totally inhibit the growths of *Aspergillus fumigatus* and *Aspergillus flavus* in the concentration as low as 6.4 mM. It was synthesized in one step from C3AcidG with 92% yield.⁵³⁸

The inhibitory activity of PC6 on acetylcholinesterase enzyme was 14-fold of that of donepezil (PP3).⁵³⁹ It can be synthesized from C3AcidG in four steps with 18% yield.

AV170 (PC7), derivative of dihydrosinapic acid C3AcidS, exhibited the most pronounced reduction in peptide hydrolysis activity and was four times more effective for certain applications compared to the previously reported beta-lactone inhibitors (gold standard); this might open possibilities to obtain new antimicrobial agents.⁵⁴⁰ The compound was purchased, but the yield from C3AcidS is inaccessible.

5.3.3. Ferulic and Sinapic Acid Derivatives. Ferulic acid (FA) can serve as the starting material for the synthesis of several lead compounds. For example, PC8 exhibited potent in vitro and in vivo antitumor activity, which was synthesized from FA with 13% yield in four steps.⁵⁴¹ Derivatives PC9 and PC10 have been shown to be nearly as potent as the positive control drug Zolozin in in vitro histone deacetylase (HDACs) activity assays. Inhibition of HDACs is considered as a potent strategy for cancer therapy. PC9 and PC10 can be synthesized from FA in seven steps or from M28G in five steps with unpublished yields.⁵⁴² Furthermore, the amide (PC11) that is selectively cytotoxic to white blood cancer cells has been synthesized from FA in one step with 83% yield.⁵⁴³

Ferulic acid FA can be demethylated to caffeic acid,⁵²⁷ which can undergo condensation with phenylethylamine to yield a promising drug candidate, the insulin sensitizer⁵⁴⁴ and antioxidant⁵⁴⁵ KS370G (PC12) with 88% yield.⁵⁴⁶

FA can be demethylated to caffeic acid with 62% yield.⁵²⁷ Some simplified analogues of the natural product (–)-tarchonanthalactone showed anticancer activity in different cell lines, including the highly drug-resistant human pancreatic carcinoma cell line.⁵⁴⁷ Caffeic acid derivative PC13 was the most active compound from the tested analogues.

(–)-Oleocanthal is a bioactive compound isolated from virgin olive oil. Tyrosol sinapate (PC14) is a semisynthetic analogue of (–)-oleocanthal. Tyrosol sinapate (PC14) which shows several biological effects including anticancer activity.⁵⁴⁸ It can be synthesized from SA in one step with 85% yield.

5.4. Conclusions

Compared to polymers, pharmaceuticals are produced on much lower scales, therefore the possibility to source them from renewables is considered much less important. Nonetheless, lignin-derived, highly functionalized aromatics appear to be possible entry points into the synthesis of pharmaceuticals; however, this approach must show clear advantages over existing methods. Such a goal is for example the possibility to significantly reduce waste (improve atom economy and E factor)^{235,237} by minimizing the number of reaction steps in total syntheses.

Due to their inherent structure and natural origin, several aromatics are very common starting materials for the synthesis of natural products (e.g., FA, monolignols). These however are not directly obtained by lignin depolymerization methods. Several monomers, on the other hand, especially those obtained by reductive depolymerization methods (e.g., alkyl-guaiacols or phenols), are not generally encountered starting materials for the synthesis of natural products, pharma intermediates, or drug candidates.

Some of the transformations described in section 5 proceed in biorenewable and/or environmentally benign solvents. For example, PN4 was synthesized in the mixture of water and methanol, PP2 in methanol, PC2 was synthesized in ethyl acetate while PC5 in propanol. For the synthesis of Tanegool (PN18), 2,2,2-trifluoroethanol, acetone, and hexanes were used; the latter could be replaced with heptane. The THF used in several syntheses such as PC14 could be substituted with 2-Me-THF⁵⁴⁹ or CPME.⁵⁵⁰ However, most of the synthesis routes in the examples detailed above utilize traditional solvents such as dichloromethane (DCM) or dimethylformamide (DMF). Effort should be devoted to search for biobased solvent alternatives possibly also from lignin, as this would have significant environmental benefits.

6. CONCLUDING REMARKS

In this review, a comprehensive overview of catalytic processes that are capable of delivering products in high yield and good selectivity from preisolated lignin or lignocellulose as starting material was provided. This gives insight into the creative solutions that were found to tackle the great challenges related to the robust and refractory structure of this intriguing aromatic biopolymer, especially in the past 5 years. Most of the new catalytic methods have focused on the selective cleavage of C–O bonds in the most abundant β -O-4 moieties. Considering this strategy, and the natural abundance of β -O-4 linkages, high theoretical efficiencies were already reached. In order to further improve product yields, new research should focus on the development of selective catalysts for cleaving moieties that are mutually connected by two bonds and via stronger C–C linkages. Several of the new methods have recognized the importance of suppressing recondensation reactions, which typically lead to decreased product yields especially when acid or base and elevated temperatures are used. Also in these cases, high theoretical efficiencies were reached, and further challenges will involve addressing engineering solutions for possible upscaling and in depth mechanistic understanding. Several research groups have identified the significance of the processing parameters (temperature, additives) for lignin fractionation, as a major factor influencing product yield and selectivity. Future challenges will relate to the implementation of these novel lignin isolation methods in existing biorefinery schemes. The elegant, catalytic lignocellulose fractionation methods pioneered by several groups

have overcome the undesired modification of the native lignin structure and found well-defined products in improved yields. Future research in this area will focus on solving challenges related to catalyst separation from the cellulose and hemicellulose and their valorization.

A summary of well-defined products (Figure 23), including interesting, unexpected structures (M7-M10, M17, M18, M20, and M21), originating from the novel catalytic methods developed recently, will provide a starting point for designing new lignin-based products, revisiting the idea of lignin-derived platform chemicals. While phenol or BTX are still highly interesting targets, future research should also focus on defining new strategies for the valorization of these emerging, more functionalized structures, for the production of tangible products. Given the large scale and importance of the field of biobased polymers, it would be highly desired to find novel applications that take advantage of the inherent complexity of lignin-based aromatics, especially to add extra functions or improve existing properties.

About a decade ago, “cracking” the recalcitrant lignin structure appeared to be a daunting task, which was met with considerable skepticism on the one hand and enthusiasm on the other. Today, owing to the remarkable achievements in catalysis research, it became possible to derive well-defined compounds from lignin in acceptable quantities, among which several structures will emerge as future lignin-derived platform chemicals, and there is a much clearer understanding of the challenges that still need to be tackled in order to enable the full implementation of lignin as sustainable starting material for the production of drop-in chemicals, polymers, or emerging functional materials. This will require close collaboration across multiple disciplines and a dialogue between academia and industry. Without any doubt, the new, exciting developments achieved thus far project a bright future for lignin valorization for years to come.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acs.chemrev.7b00588.

Structure, codes, and names of identified lignin monomers (Table S1) (PDF)

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Notes

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Bálint Fridrich was born in Budapest, Hungary. He obtained his bachelor's degree in Chemical Engineering in 2015 and master's degree from the Budapest University of Technology and Economics in 2016 with highest distinction. During his university studies he worked on the “Conversion of non-edible biomass waste streams to optically active platform molecules” in the research group of Prof. László T. Mika. He then moved to the Leibnitz Institute of Catalysis (LIKAT) in Rostock, Germany to work in Prof. Matthias Beller's group as a visiting student. Starting from November 2016, he is in the group of Katalin Barta, exploring the topic “Sustainable catalysis for value-added chemicals from biomass”. Bálint received several scholarships, including a Fellowship granted by the Hungarian Republic (2015) and National Talent Program (2017) from the Hungarian Ministry of Human Capacities. He was recently awarded with the Pro Scientia Medal from the Hungarian National Scientific Student Council. In his free time, he enjoys road cycling and geography, and also likes travelling, exploring museums and libraries.

Alessandra De Santi was born in Viareggio, Italy, in 1992. She obtained her bachelor's degree in Chemistry for Industry and Environment from the University of Pisa (Italy) in 2014. As an undergraduate, Alessandra's work was developed under the guidance of Dr. Elisa Passaglia (ICCOM-CNR U.O.S. of Pisa) focusing on modification of cationic and anionic clays and their dispersion at nanoscale in poly(lactic acid) matrix. In 2017, Alessandra received her master's degree in Industrial Chemistry from the University of Pisa. Her master's research project dealt with the catalytic conversion of biobased molecules such as furfural and was performed as part of a joint project under the supervision of Prof. A. M. Raspolli Galletti (University of Pisa) and Prof. H. J. Heeres (University of Groningen). In 2017, Alessandra joined the group of Katalin Barta as Ph.D. student and her research focuses on the catalytic conversion of lignin and lignocellulose.

Saravanakumar Elangovan was born in Ramanathapuram and grew up in Thogur, a small village in Tamilnadu, India. He completed his M.Sc in chemistry at St. Joseph's college, Trichy and worked as a research associate in Syngene International Ltd, Bangalore, India. In 2012, he moved to France to perform an International Master program in Molecular Catalysis and Green Chemistry at the University of Rennes. He then started his PhD studies under the guidance of Prof. Christophe Darcel and Prof. Jean-Baptiste Sortais at the University of Rennes and with Prof. Matthias Beller and Dr. Kathrin Junge at Leibniz Institute for Catalysis (LIKAT), Rostock, Germany. His doctorate was focused on well-defined iron and manganese catalysts for reduction and dehydrogenation reactions. He is currently a postdoctoral researcher at the Stratingh Institute for chemistry, University of Groningen, in the group of Katalin Barta working on several research directions related to sustainable catalysis and green chemistry.

Katalin Barta is Associate Professor at the Stratingh Institute, University of Groningen. She studied chemistry at ELTE Budapest (Hungary) and carried out her master's research in alternative solvents in the group of István T. Horváth. She was also Erasmus research student at the University of Leeds. Then she moved to RWTH-Aachen (Germany), to pursue her PhD research under the guidance of Walter Leitner in asymmetric catalysis and ligand design. During postdoctoral research (2008-2010) with Peter Ford at University of California, Santa Barbara she worked on the conversion of renewable resources. After, she was Associate Research Scientist (2010-2012) at Yale University, the Center for Green Chemistry and Engineering (New Haven, USA) with P. T.

Anastas where she worked on catalytic conversion of renewable resources, with special focus on lignin valorization. She established her independent research group at the Stratingh Institute for Chemistry, the University of Groningen in 2013. Combining various fields, the research interests in the Barta group are broadly in Sustainable and Green Chemistry, focusing on the development of novel homogeneous and heterogeneous catalytic strategies for the conversion of all main components of lignocellulose, utilizing Earth abundant metals.

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