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On the path to improve lignin depolymerization and functionalization into bio-based platform chemicals: a short review

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Abstract

This short review encompasses the last relevant studies that have been unveiling efforts to increase the efficiency of lignin depolymerization and functionalization into bio-based platform chemicals. One of the drawbacks upon lignin depolymerization is the undesired condensation reactions (repolymerization) that negatively affects the yields of lignin monomers. Some recent technologies have demonstrated to be effective on protecting lignin from repolymerization and enhancing depolymerization efficiency. Furthermore, functionalization of lignin aromatic monomers is needed to move towards a more sustainable chemical industry. As major example, the amination of lignin depolymerization products stands as hot research topic for future lignin valorization, the latest achievements being addressed in this review.

Keywords

Lignin; depolymerization, functionalization, stabilization, aromatic amines
Introduction

On November 15th 2022, the world population was projected to reach 8 billion people and this number is estimated to grow up to approximately 9 billion in the next 15 years [1]. Humanity faces a prime challenge of ensuring its own sustainability, where urgent actions to pave the way for overcoming current and future societal issues, including population health, climate change, resource management, food security and supply, energetic demand, among others, are required. This impetuous population growth versus inert world territorial area requests tremendous efforts on increasing efficient and sustainable use of resources. For a long last period, fossil-based resources have been extensively used to supply society needs of chemicals, materials and energy, but their inherent non-renewable and pollutant traits have changed a societal paradigm towards a more sustainable model of development based on the use and reuse of renewable bio-based resources [2].

A promising alternative to fossil-based resources falls upon biomass, in particular the widely available lignocellulosic biomass. The valorization of this resource constituted by three major components, cellulose, hemicelluloses and lignin, can assist fulfilling the commodities demand, but the technological development and its current cascade processing is still far from the ideal. Actually, major biomass processing approaches still relies on classical pulping processes (where cellulose fibers are the chief target for processing and conversion) and biofuels production (either from sugars to produce bioethanol, plant oils for biodiesel, or undifferentiated/residual biomass for pyrolysis/gasification). Hemicelluloses and lignin are still considered as residues or by-products from pulping processes and their valorization is impaired. Among them, lignin is attracting the attention of academia and industry and is now a priority for conversion and transformation into a new generation of bioproducts and fine chemicals [3].

The challenges of lignin valorization via a depolymerization strategy

Lignin is an aromatic biopolymer structuring lignocellulosic biomass and can reach approximately 1/3 of its weight. It is composed of polymerized monolignol units, including p-coumaryl, coniferyl and sinapyl alcohols covalently bonded through distinct C-O and C-C bonds [4]. The carbon atoms in the aliphatic side chains of those units are
usually labelled as α, β and γ, while those in the aromatic ring are numbered from 1 to 6. The covalent bonding at different positions leads to the formation of lignin subunits, such as β-aryl ether (β-O-4), resinol (β-β and γ-O-α), phenylcoumaran (β-5), among others [5]. Due to its unique physicochemical properties, particularly its aromatic character, lignin may provide a solid alternative to the aromatic hydrocarbon fraction of non-renewable crude oil.

In classical or new biomass pre-treatment and fractionation processes, the disruption of both lignin-lignin and lignin-polysaccharide chemical bonds enables the extraction of lignin (delignification). The type and extent of delignification set out the size of the extracted lignin macromolecules, the modification that took place during the extraction process and ultimately its chemical composition. Besides, the chemical structure of lignin varies from biomass source, species and geography. This leads to more or less heterogeneous samples with direct impact on the quality of lignin for further conversion and commercialization [6]. Indeed, the complexity and heterogeneity of extracted lignins is a transversal hurdle through the spectrum of lignin valorization, from the extraction, going to the conversion and finishing with downstream processing. Therefore, finding new strategies to selectively process lignin into more homogeneous fractions is probably the major challenge to accomplish a successful lignin transformation into desired aromatic bioproducts.

A solution relies on an efficient lignin depolymerization into monomers and oligomers as platform chemicals assisting chemical industry to move towards bio-based chemicals. However, lignin depolymerization is not simple and usually low yields are obtained. This is related to the instability of resulting products, which are highly reactive to each other forming condensed aromatic structures. For instance, the common hydrothermal and acid hydrolysis of lignin leads to the formation of Hibbert ketones, which are highly reactive to form new covalent bonds [7]. Therefore, stabilization of lignin during its extraction and functionalization after lignin depolymerization may offer an opportunity to reach a high yield of lignin products and fine tune lignin depolymerization into aromatic platform chemicals of interest.

This short review addresses and endorses some of the most relevant studies published in the last few years associated to technologies capable of stabilizing lignin towards high
depolymerization yields as well as studies covering functionalization of lignin monomers into important aromatic platform chemicals, such as aromatic amines.

**Lignin stabilization towards high depolymerization yields**

In order to avoid condensation reactions between lignin fragments, stabilization of lignin with external agents during its extraction seems to be an innovative and promising strategy to ensure high depolymerization yields. The reductive catalytic fractionation (RCF) of biomass is considered a lignin first approach covering the extraction of lignin reactive fractions through solvolysis and simultaneous stabilization through hydrogenolysis into desired aromatic monomers [8]. For instance, Rinaldi and co-workers have found that RCF (using 2-propanol/Raney® Ni/H₂) of poplar enables the production of lignin fragments in which β-O-4 linkages underwent selective hydrodeoxygenation to form β-O-4 linkages bearing a methylene group at the Cα position, stabilizing corresponding lignin fragments [9]. Luterbacher and coworkers mentioned that monomers yields close to the theoretical maximum of 50 % can be produced by RCF technology [10]. However, the reductive deoxygenation promoted by RCF leads to the production of mostly low value deoxygenated aromatics, such as benzene, toluene, xylene (BTX) and deoxygenated alkylated aromatics, yet important compounds to incorporate for instance in jet biofuels [11].

On the other hand, catalytic oxidation (e.g. with O₂ or H₂O₂ with or without catalyst) of lignin could play an essential role in producing value added compounds including functionalized phenolic derivatives. In general, oxidation processes enable the oxidation of the Cα–OH secondary alcohol in β-O-4 lignin subunits to Cα=O and CαOOH, impeding the formation of reactive benzylic carbocations that are highly prone to condensation reactions. Therefore, after depolymerization processes, aromatic aldehydes and acids, such as vanillin, syringaldehyde, vanillic and syringic acids are often found to be the major depolymerization products of oxidized lignins [12].

A more common way to stabilize lignin is the Organosolv process, which enables the etherification of the benzylic carbocation intermediate with an alcohol (e.g. ethanol and butanol), avoiding β-O-4 cleavage during biomass delignification. This phenomenon is favored of an excess amount of alcohol (> 95 wt% of the liquid feed mixture) with a
corresponding low water content (< 5 wt% of the liquid feed mixture). Barta and co-workers reported that further selective depolymerization of Organosolv lignin to monomers can yield up to 35% (considering a prior 18% of the lignin extracted from biomass), which is nearly 20% of theoretical yields based on the original lignin, but fourfold higher than the yield achieved from Kraft or Soda technical lignins [10]. In this line of research, an innovative approach towards benzylic alkoxylation with alcohols was recently presented by Deuss and coworkers through the application of self-acidified triethylammonium triflate ionic liquids to assist this reaction at room temperature [13].

Another promising protection of lignin macromolecules towards high depolymerization yields was recently presented by Barta and co-workers. A reversible functionalization reaction based on cyclic acetal formation using diols, such as ethylene glycol, was proposed by these researchers [14,15]. The ethylene glycol reacts with C2-aldehyde phenolic compounds formed during a delignification process, stabilizing them as acetals and avoiding any kind of dehydration and condensation reactions towards repolymerization [16], as represented in Figure 1. Recently, Luterbacher and coworkers also found similar stabilization using certain aldehydes [17]. In particular, this acetal-stabilized lignin was further depolymerized by hydrogenolysis over heterogeneous metal catalysts such as Pd, Ru or Ni yielding 42–50% of aromatic monomers based on the original lignin (hardwood) [10]. In the same line of research, Dong et al. demonstrated that eucalyptus wood fractionation with diol-based treatment (ethylene glycol or 1,4-butane diol) followed by hydrogenolysis of isolated lignins with a Ru/C catalyst in ethanol produced 15% aromatic monomer yield on native lignin basis, a value 5 times higher than ethanol-based Organosolv lignin depolymerization [18].
**Figure 1.** Acidolytic cleavage of an aryl ether bond in absence or presence of ethylene glycol (EG). Stabilization of C2-aldehyde compounds as acetals to avoid condensation reactions. Reprinted from [16] with permission from WILEY.

The technological development upon delignification processes demonstrated in the last years, clearly shows that non-aqueous systems may play a crucial role in upgrading lignin valorization. The cleavage of lignin chemical bonds is not favored in the presence of water, therefore studies on non-aqueous based treatments have been growing. In this context and also supporting the green chemistry approaches, Barta and co-workers displayed the performance of ternary deep eutectic solvents (DES) composed of diols and organic acids to promote controlled biomass delignification [19]. Similar observations to diol-based treatments were reported, namely on the stabilization of lignin macromolecules through acetal formation [19]. Indeed, the use of DES as green solvents for lignin valorization have attracted attention of the scientific community in the last few years. Recently, Da Costa Lopes and co-workers demonstrated that cholinium chloride based eutectic solvents might speed up the cleavage of β-O-4 aryl ether bonds towards fast and efficient biomass delignification as well as lignin depolymerization [20,21]. The authors showed by DFT calculations a possible nucleophilic substitution of the Cα-OH by the halide of the cholinium salt, forming an intermediate that energetically favors the cleavage of the aryl ether bond [20]. The same authors also demonstrated a high performance of acidic DES (cholinium chloride:oxalic acid) towards the depolymerization of Kraft lignin utilizing mild conditions, reaching up to a quarter of the initial lignin mass as monomeric and oligomeric compounds [21].

**Functionalization of lignin monomers: a case study of aromatic amines**

Apart from improving the depolymerization performance of lignin, functionalization of depolymerization products is of utmost importance to upgrade the lignin-based compound library. Figure 2 shows the reactive sites in lignin structure and possible functionalization reactions at the aromatic ring, at the phenolic groups, and at aliphatic chains of lignin units. Those reactions include amination, nitration, sulfonation, hydroxyalkylation, esterification, acetalization, phenolation, among others [22]. This functionalization reactions are most often dedicated to lignin modification by giving better physicochemical functionality to lignin macromolecules in the production of new
bio-based materials, such as polymers blends, composites, resins, among others [23]. However, despite the functionalization of lignin depolymerization products being still underdeveloped, probably due to the complexity of the depolymerization mixtures and subsequent limitations to fine tune the functionalization reactions, some recent studies have been paving the way to overcome these challenges. The amination of lignin aromatic monomers is a major example of such functionalization and has been explored in the last years.

Figure 2. Reactive sites and possible functionalization reactions that can be induced to lignin macromolecules or to lignin aromatic products after depolymerization. Reprinted from [22].

An example was the synthesis of 2- and 3-arylbenzomorpholines via cross-coupling/annulation between electron-rich 2-aminophenols and lignin-based 4-vinylphenol compounds [24]. In another work, benzylamines were tentatively produced from lignin [25]. Lignin β-O-4 model compounds were successfully transformed into benzylamines and phenols in the presence of organic amines and a Pd/C-based catalyst. The reaction pathway involved the following steps: i) dehydrogenation of Cα−OH; hydrogenolysis of the Cβ−O ether bond; and iii) reductive amination in the presence of a Pd/C catalyst. However, the authors faced the limitations of using lignin as the feedstock to perform these reactions, since very low yield of benzylamines were achieved (0.4%). The authors suggested that lignin oligomers were barriers for such reactions.
Recently, 1,4-cyclohexanediol and 1,4-cyclohexanediamine were shown to be produced from distilled dimers and oligomers, previously obtained by wood RCF treatment [26]. The dimers and oligomers were selectively transformed into dimethoxybenzoquinone (19.4 wt% yield), followed by its catalytic hydrogenation into 1,4-cyclohexanediol (86.5 mol% in respect to dimethoxybenzoquinone) and finally catalytic amination (with NH₃) into 1,4-cyclohexanediamine (> 99 mol% in respect to 1,4-cyclohexanediol), as depicted in Figure 3. The authors of this study emphasized the use of a RANEY® Ni catalyst and NH₃ in this process that hold great potential for future industrial synthesis of 1,4-cyclohexanediamine from renewable resources [26]. A similar approach was performed in the catalytical transformation of guaiacol and syringol, two major products of RCF liquor, using RANEY® Ni in both hydrogenation (H₂) and amination processes (NH₃) towards diamines [27] and cyclohexylamines [28]. In the last case, 4-propylcyclohexylamine was isolated up to 7 wt % on initial lignin basis [28].

![Figure 3. Concept presented by Barta and co-workers based on the catalytic transformation of lignin dimers and oligomers into 1,4-cyclohexanediol and 1,4-cyclohexanediamine. Reprinted from [26] with permission from the Royal Society of Chemistry.](image)

Few other studies have dwelt on other types of lignin monomer functionalization in the last years, including conversion into aromatic esters [29] as well as lignin C–C and C–O bond cleavages induced by heteroatoms X (N, Si, I and Li), leading to to functionalized products containing C–X and O–X bonds [30]. Yet, more fundamental research regarding the functionalization of lignin monomers must be performed to broaden the spectrum of fine chemicals produced from lignin and help chemical industry to move onto a more sustainable path.
Last but not least, downstream processing of non-functionalized or functionalized lignin monomers must be addressed in future research. An example was recently demonstrated by Rocha et al., who developed a process for the separation of vanillic acid from other lignin monomers through a scalable centrifugal partition chromatography process [31]. Furthermore, a recent review article has highlighted some downstream processing strategies for lignin-first approaches, including the separation and purification of fine chemicals, such as aromatic amines [32].

Conclusions

Recent literature has shown some advances on how lignin can be extracted to enhance depolymerization performance and achieve higher lignin monomer yields. In this context, technologies based on hydrogenation (RCF), alkoxylation (Organosolv) and acetal formation enable lignin depolymerization products stabilization to prevent condensation reactions and are now in the vanguard as lignin-first approaches. In the same line, studies showing new lignin monomers functionalization strategies are increasing to open up the spectrum of bulk and fine chemical compounds stemming from lignin as an alternative to the current fossil-based resources. As main example, the amination of lignin monomers has been developed in the last years resorting to (green) ammonia as nitrogen source. However, more studies tackling other chemical functionalization approaches of lignin monomers must be accomplished, while such functionalization should rely on more selective catalysis towards homogenous products and easier to handle in downstream processing for an effective commercialization.

Declaration of competing interest

There are no conflicts to declare.

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**References**


This work reports mechanistic insights related to Reductive Catalytic Fractionation (RCF) process as lignin-first approach underlining not only lignin stabilization in the RCF lignin oil but also elucidating structural features of carbohydrates occurring during the process.


This work encompasses a comprehensive review upon the latest strategies for the stabilization of biomass products after depolymerization process, showing crucial scientific insights towards the production of high yields of aromatic monomers.


This study shows the possibility of using oxidative catalytic fractionation of biomass as alternative treatment in the production of oxygenated aromatic compounds derived from lignin complementing alkylated aromatics from RCF process.


**This work reports a very interesting way to stabilize lignin macromolecules through acetal formation with ethylene glycol that enables high lignin depolymerization yields.**


**This study highlights a new concept for selective biomass fractionation and conversion by integrating RCF treatment of biomass followed by consecutive hydrogenation and amination stages towards the production of two bio-based platform chemicals derived from lignin.**


*This review study reveals the latest achievements on downstream processing of products coming from lignin-first approaches.
Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: