



# Pseudo-Lignin Formation during Dilute acid Pretreatment for Cellulosic Ethanol



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## Abstract

Dilute acid-based pretreatment represents one of the most important pretreatment technologies to reduce biomass recalcitrance and it has been successfully applied to a wide range of feedstocks. During this type of pretreatment, the relative lignin content usually increases partially due to the loss of carbohydrates. More importantly, it has been reported that the increase of lignin content after dilute acid pretreatment is mainly due to the formation of pseudo-lignin. The exact reaction mechanisms leading to the formation of pseudo-lignin is still under investigation. However, it has been proposed that rearrangement of hydroxymethylfurfural (HMF) or furfural can produce aromatic type of compounds which can further undergo polymerization reactions to form a lignin-like polyphenolic structures termed as pseudo-lignin. This mini-review mainly covers recent advances in understanding the fundamentals of pseudo-lignin formation during dilute acid pretreatment, the impact of its formation on enzymatic hydrolysis, and how to suppress its formation during dilute acid pretreatment.

**Keywords:** Biomass recalcitrance; Pseudo-lignin; Dilute acid pretreatment; Enzymatic hydrolysis; Hydroxymethylfurfural; Furfural

**Abbreviations:** MW: Molecular Weight; Mw: Weight-average molecular weight; Mn: Number-average molecular weight; BTO: 1,2,4-benzenetriol; DMSO: Dimethyl Sulfoxide; HMF: Hydroxymethylfurfural

## Introduction

Increasing global energy demand and environment concerns have led to rapid development of converting renewable resources such as lignocelluloses biomass to biofuels such as cellulosic ethanol [1]. Relatively high costs associated with the bioprocess and the sub-optimal yield of ethanol production remains a great challenge due to the natural resistance of the plant cell wall to enzymatic deconstruction. As a result, a chemical or physical pretreatment is usually required prior to the enzymatic hydrolysis step to disrupt the lignin-hemicellulose matrix and increase cellulose accessibility, which subsequently increases the following hydrolysis efficiency [2].

Over the past decades, different pretreatment technologies have been developed to reduce biomass recalcitrance [3]. Among all the available pretreatment technologies up-to-date, dilute acid-based pretreatment using a variety of acids including sulfuric acid, nitric acid, or hydrochloric acid remains as one of the most important technologies for cellulosic ethanol. It is

normally performed with acid concentration less than 4wt% over a wide range of temperature (120 to 210 °C) [4]. It also has been applied on a wide range of feedstock such as poplar [5], switch grass [6], wheat straw [7], rice straw [8], bagasse [9], maize stems [10], and corn stover [11]. It is well known that this acidic type of pretreatment, in the absence of an organic solvent, is less effective in terms of lignin removal, and in fact, the relative content of Klason lignin is normally found to be increased after dilute acid pretreatment. For example, Foston et al. reported that the Klason lignin content significantly increased from ~25% to ~40% after dilute acid pretreatment of *Populus* [6]. This is of course partially due to the loss of carbohydrates especially the hemicellulose during pretreatment. However, Sannigrahi et al. reported that the formation of pseudo-lignin by the dehydration and polymerization of carbohydrates should be responsible for this unusual increase of lignin content [12]. In addition, it was also reported by Li et al. that only ~50% of the Klason lignin extracted from a hot water pretreated aspen was actual lignin [13].

Understanding the fundamentals of pseudo-lignin chemistry is important from the bioconversion process perspective. Optimization of current pretreatment technologies is often guided by carbohydrate loss during pretreatment and lignin residue content and/or structure after pretreatment. Lignin is well known to effect enzymatic hydrolysis negatively due to its physical barrier role and its unproductively binding to enzymes [14,15]. Therefore, development of novel low pH pretreatments with diminished pseudo-lignin formation will significantly reduce the enzyme loadings required for an efficient enzymatic

hydrolysis, hence improve the overall process economics. In conclusion, the formation of pseudo-lignin during any low pH pretreatment is unfavorable as it originates from carbohydrate degradation and more importantly, it may be even more detrimental to enzymatic hydrolysis compared to native lignin. This mini-review highlights recent advances in understanding the fundamentals of pseudo-lignin formation, the impact of its formation on enzymatic hydrolysis rate and yield, and how to suppress its formation during pretreatment.

### Structural Characterization of Pseudo-Lignin

**Table 1:** Pseudo-lignin yield during hydrothermal and dilute acid pretreatment of cellulosic substrates [18-20].

Sample	Pretreatment conditions	Klason lignin content (%)	Pseudo-lignin Yield (%)
Avicel cellulose	140 °C, 1 wt% H <sub>2</sub> SO <sub>4</sub> , 30 min	N/A	0
Avicel cellulose	160 °C, 1 wt% H <sub>2</sub> SO <sub>4</sub> , 40 min	N/A	0.51
Avicel cellulose	180 °C, 2 wt% H <sub>2</sub> SO <sub>4</sub> , 40 min	N/A	85.7
Poplar a-cellulose	170 °C, 0.10M H <sub>2</sub> SO <sub>4</sub> , 20 min	6.61	0
Poplar a-cellulose	180 °C, 0.10M H <sub>2</sub> SO <sub>4</sub> , 40 min	19.95	44.58
Poplar holocellulose	180 °C, 0.10M H <sub>2</sub> SO <sub>4</sub> , 40 min	37.37	51.3
Poplar holocellulose	180 °C, 0.20M H <sub>2</sub> SO <sub>4</sub> , 60 min	86.93	33.71
Bamboo holocellulose	170 °C, H <sub>2</sub> O, 30min	1.5	Trace
Bamboo holocellulose	170 °C, H <sub>2</sub> O, 90min	2	Trace
Bamboo holocellulose	170 °C, H <sub>2</sub> O, 150min	3.1	58.2
Bamboo holocellulose	170 °C, H <sub>2</sub> O, 240min	6.2	54.1

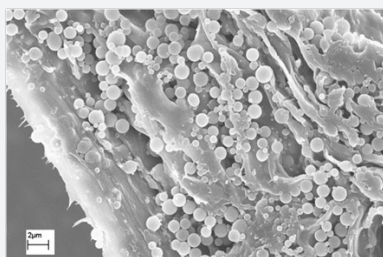
For characterization purposes, pseudo-lignin is normally produced and isolated from dilute acid pretreated lignin-free materials such as  $\alpha$ -cellulose and holocellulose. Table 1 shows some typical yields of pseudo-lignin isolated from different resources under different pretreatment conditions. A variety of analytical techniques including GPC, FTIR, NMR, SEM have been utilized to characterize pseudo-lignin. Molecular weight (MW) of isolated pseudo-lignin from different resources is shown in Table 2. In general, the MW of pseudo-lignin is much lower than that of milled wood lignin. For example, the weight average MW (M<sub>w</sub>) of milled poplar lignin and pseudo-lignin derived from dilute acid pretreated poplar holocellulose at 180 °C were found to be 10002g/mol and 5050g/mol, respectively [16,17]. Pretreatment

severity was not found to be a huge impact factor on the MW of pseudo-lignin (Table 2) [18-20]. In addition, MW of pseudo-lignin derived from dilute acid pretreated holocellulose was found larger than that of pseudo-lignin extracted from pretreated  $\alpha$ -cellulose (Table 2) [16]. FTIR and <sup>13</sup>C NMR analysis were also used to provide additional information on the chemical structure of pseudo-lignin, which indicated that pseudo-lignin was mainly composed of hydroxyl, carbonyl and aromatic structures [12]. These results clearly indicated that pseudo-lignin was a polyphenolic, lignin-like material with aliphatic, aromatic, and carbonyl structures derived from cellulose/hemicellulose fragments released during acid hydrolysis reactions.

**Table 2:** Weight-average (M<sub>w</sub>) and number-average (M<sub>n</sub>) of pseudo-lignin isolated from dilute acid pretreated cellulosic substrates [18,19].

Sample	M <sub>w</sub> (g/mol)	M <sub>n</sub> (g/mol)	PDI
Bamboo holocellulose pretreated at 170 °C, H <sub>2</sub> O, 150min	3410	1200	2.84
Bamboo holocellulose pretreated at 170 °C, H <sub>2</sub> O, 240min	5340	3320	1.6
Poplar a-cellulose pretreated at 180 °C, 0.10 M H <sub>2</sub> SO <sub>4</sub> , 40min	3440	1080	3.17
Poplar holocellulose pretreated at 180 °C, 0.10 M H <sub>2</sub> SO <sub>4</sub> , 40min	5080	1240	4.09
Poplar holocellulose pretreated at 180 °C, 0.20 M H <sub>2</sub> SO <sub>4</sub> , 60min	5970	1190	5

Lignin can be redistributed during dilute acid pretreatment, leading to the formation of lignin droplets of various morphologies [10,21-24]. During the dilute acid pretreatment, lignin was reported to coalesce on plant cell wall and then migrate into the bulk liquid phase in form of droplets or balls [21]. This kind of lignin aggregation normally requires the pretreatment temperature to exceed the lignin phase transition temperature. Similar to this kind of re-deposit lignin droplets, pseudo-lignin can be also exist as discrete spherical droplets on the surface of pretreated holocellulose with a range of sizes from 0.3 to 8.0  $\mu\text{m}$  [12]. Figure 1 illustrates a SEM image of pseudo-lignin deposition on surface of poplar holocellulose during dilute acid pretreatment.

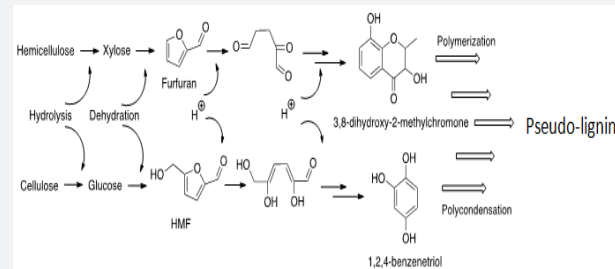


**Figure 1:** SEM image of pseudo-lignin deposition on surface of poplar holocellulose after dilute acid pretreatment [23].

### Reaction Mechanisms Leading to the Formation of Pseudo-Lignin

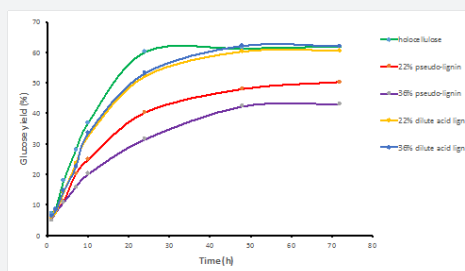
The exact mechanisms leading to the formation of pseudo-lignin are still under investigation due to the complexity of pseudo-lignin structure and the heterogeneity of reaction sources and media. However, the presence of high proportions of unsaturated carbons in pseudo-lignin structure strongly indicated that acid hydrolysis of carbohydrates polymers to their corresponding monosaccharides and the subsequent dehydration and fragmentation of sugars probably took place during the acid pretreatment. Hydroxymethylfurfural (HMF) and furfural can be produced from 6 and 5-carbon sugars such as glucose and xylofuranose via acid catalyzed dehydration reactions [25,26]. HMF and furfural can be further subjected to rearrangements to produce other aromatic compounds which might be the key intermediates for pseudo-lignin formation. For example, 3,8-dihydroxyl-2-methylchromone was reported as one of the main aromatic products in the acidic degradation of xylofuranose [27]. Similarly, hydrolytic ring-opening reaction of HMF was reported to generate 1,2,4-benzenetriol (BTO) in yields of 46% [28]. These intermediates can be then converted to pseudo-lignin via polymerization/polycondensation reactions. For instance, it has been reported that BTO could react with HMF or furfural to produce a three-dimensional polymer via acid catalyzed aromatic electrophilic substitution [18]. Figure 2 summarized the reaction mechanisms mentioned above, which highly suggested presence of acid and high temperatures are probably two crucial conditions for the pseudo-lignin formation. Understanding the reaction pathways leading to the formation of

pseudo-lignin will provide insights into how to suppress pseudo-lignin generation, though much work still needed to be done.



**Figure 2:** Proposed reaction pathways for pseudo-lignin formation.

### Impact of Pseudo-Lignin on Enzymatic Hydrolysis



**Figure 3:** Enzymatic hydrolysis time course of poplar holocellulose mixed with dilute acid pretreated lignin or pseudo-lignin [30].

Li and co-workers reported that the lignin droplets deposited on the surface of plant cell wall significantly inhibited cellulose hydrolysis, mainly through surface blockage [21]. Their study indicated the nonspecific binding of lignin droplets to enzymes was not the key source of inhibition. Similar to the lignin redeposit droplets, pseudo-lignin formed during dilute acid pretreatment can also exist as discrete spherical droplets on the surface of pretreated materials, and its formation is obviously not desired due to the fact that pseudo-lignin can directly decrease cellulose accessibility by blocking the surface binding sites. On the other hand, pseudo-lignin is also known to unproductively bind to cellulase and inhibit its action [29]. Kumar et al. studied the enzymatic hydrolysis of Avicel cellulose mixed with pseudo-lignin derived from pure xylose, and it was reported that even a small amount of pseudo-lignin addition could have a noticeable negative impact on enzymatic hydrolysis yield [20]. Further protein adsorption experiments revealed that pseudo-lignin bound to enzymes unproductively. A recent study by Hu et al. further demonstrated the formation of pseudo-lignin needed to be avoided as they proved that pseudo-lignin is much more detrimental to enzymatic hydrolysis than regular dilute acid pretreated lignin (Figure 3)[30]. More specifically, dilute acid pretreated lignin only inhibited enzymatic hydrolysis in its initial stage and had a nearly negligible impact on the overall conversion percentage after 48 h as shown in Figure 3, whereas pseudo-lignin addition could decrease enzymatic

hydrolysis yield up to 25% [30]. It is worth mentioning pseudo-lignin is insoluble in water, therefore the hydrophobic structural functionality of pseudo-lignin is probably responsible for its nonproductive association with enzymes.

### Suppression of Pseudo-Lignin Formation during Dilute Acid Pretreatment

Lignin redeposits droplets and pseudo-lignin only can be formed at elevated temperatures, therefore reducing the pretreatment severity is obviously one of the ways to reduce or avoid the formation of pseudo-lignin. However, as the pretreatment severity decreases, so do the efficient of pretreatment in terms of hemicellulose removal and cellulose accessibility increase. Compared to the typical batch pretreatment, flow through reactor system was shown to dramatically increase lignin removal as much as over 90% [31]. More importantly, its ability to constantly remove lignin into the aqueous phase effectively restricts the condensation reactions. As a result, flow through pretreatment can reduce the chances of pseudo-lignin formation [31,32]. Oxidative polymerization seems to play an important role in pseudo-lignin formation based on the proposed pathway, therefore performing dilute acid pretreatment under non-oxygen environment could be another possible alternative method. It was also reported that introduction of dimethyl sulfoxide (DMSO) to the acidic medium could effectively suppress HMF productions which is one of key intermediates during the pseudo-lignin formation [33]. A recent study modified a series of dilute acid pretreatment by using  $N_2$ , surfactant Tween-80, or DMSO-water mixture as the reaction medium to test these hypotheses for new methods of suppressing pseudo-lignin formation without significantly reducing the pretreatment severity [34]. As shown in Table 3, addition of  $N_2$  was not effective in terms of pseudo-lignin suppression although extra oxygen significantly facilitated pseudo-lignin formation as expected. Apparently, introduction of DMSO significantly reduced the pseudo-lignin content by ~30%. The coordination of HMF with water can be reduced in the presence of DMSO due to the stronger interaction of DMSO oxygen with water [35]. From the reaction mechanism perspective, the reduction of HMF-water coordination could protect the HMF molecule from further reactions to form pseudo-lignin [34].

**Table 3:** Klason lignin/Pseudo-lignin contents of various samples generated using modified dilute acid pretreatment of poplar holocellulose at 180 °C, 1.0wt%  $H_2SO_4$ , 40min [34].

Sample	Solids recovery (%)	Klason/pseudo-lignin content (%)
Control sample	18.9	42
O2 – pretreated	18.1	89.2
N2 – pretreated	19.1	48.7
Tween – pretreated	37.8	14.7
DMSO – pretreated	13.3	52.1

### Conclusion

Lignin-like materials originated from acid catalyzed dehydration of carbohydrate, termed pseudo-lignin, are responsible for the increased Klason lignin content after acid-based biomass pretreatment. Pseudo-lignin can be deposit on the surface of biomass during the dilute acid pretreatment in forms of discrete spherical droplets or balls, and it is detrimental to the subsequent enzymatic hydrolysis, even more detrimental than dilute acid pretreated lignin. Therefore, it became essential to develop techniques to effectively impeded pseudo-lignin formation. Current ongoing pseudo-lignin researches are still quite limited to carbohydrate-derived pseudo-lignins, it is quite possible that lignin would somehow react with carbohydrate degradation products via polycondensation reactions, contributing to the yield of pseudo-lignin. The understanding of the most fundamental chemistry associated with pseudo-lignin formation is crucial for the future bioethanol production. Therefore, future work is much needed to fully unlock the secret of pseudo-lignin chemistry.

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