HIGH VALUE LIGNIN DERIVATIVES, POLYMERS, AND COPOLYMERS, AND USE THEREOF IN THERMOPLASTIC, THERMOSET, AND COMPOSITE APPLICATIONS

FIELD OF THE INVENTION

Disclosed herein are methods of forming modified lignins of controlled thermal stability and reactivity and methods of incorporating such modified lignins into polymer systems, as well as the formed, reactive modified lignins and the polymer systems incorporating the modified lignins.

BACKGROUND

Lignin is a highly abundant biopolymeric material (second only to cellulose) and can be derived from wood via processes that have been used for many years. Lignin is an amorphous, highly branched polyphenolic macromolecule with a complex structure, and the material typically forms about1/3 of the dry mass of woody materials. The general structure of native lignin is shown in FIG. 1; however, lignin structure is known to be significantly altered when lignocellulosic material (e.g., wood or other plant materials) are treated under conditions intended to separate the lignin from the cellulose.

Lignin provides structure to woody materials and is the component responsible for the strength of wood against mechanical stress. The physical and chemical properties of lignin can vary depending upon the wood species, the botanical origin, and the region from which the wood is harvested, and the process by which the lignin is isolated. Lignin typically is obtained from pulping processes such as used in the paper and biorefinery industries where the lignin is separated from cellulosic fibers. Large quantities of modified lignin are made available yearly from pulping processes as well as bio-ethanol digestion and saccharification processes. For example, the global production of isolated lignin from sulphite processes is about 1 million tons/year, and Kraft processes provide around 100,000 tons/year of lignin. The "technical lignin" arising from such methods has undergone severe hydrolytic degradation imparting a highly reactive structure and a relatively low molecular weight. This can render technical lignins

unsuitable for many value added applications despite its aromatic and somewhat polymeric nature.

Previously, the majority of produced technical lignin (~90%) has been used as a combustion fuel to provide energy for heat or power production. Lignin also has been used as an additive in various low volume and niche applications, such as being used as a dispersant, in concrete admixtures, as a binder in mining operations (e.g., copper, carbon black, and coal), and as an adhesive. Efforts to use lignin as a source of valuable carbon fiber have also been made with limited success. The common feature for such previous commercial uses of lignin is that, in all cases, the lignin only serves as an additive to produce relatively low added value products.

Most efforts to utilize lignin previously have been limited by various factors that impart in lignin characteristics that define it as an unreliable precursor to polymer production. This is because lignin (and more specifically technical lignin) offers relatively unpredictable polymerization characteristics, depending upon its source, the pulping (or other process) from which the lignin arises, and the degree of delignification to which the plant materials were subjected. More specifically, the highly functional character of lignin (i.e., rich in phenolic and aliphatic OH groups, as well as reactive benzylic carbons) induces a variety of potential polymerization sites and heat instability in such materials. Both factors promote gelation processes under polymerization conditions or when the temperature increases close to and/or above the glass transition temperature (Tg). Heating of lignin at an elevated temperature converts it to a condensed from and makes it rigid and less reactive. The irreversible formation of such gels precludes lignin from becoming and being considered as an integral part of modern synthetic polymer and composite production lines. In addition, the relatively low molecular weight (a few thousands) for lignin derived from commercial pulping and biorefinery operations makes lignin unsuitable for higher end applications, such, for example, high performance, heat stable engineering thermoplastic applications.

Chemically, lignin has a variety of functional groups, namely hydroxyl, methoxyl, carbonyl and carboxyl groups. Phenolic hydroxyl groups in the aromatic rings are the most reactive functional groups in the lignin and can significantly affect the chemical reactivity of the material. Higher end uses of lignin have not previously been achieved because of its structure complexity, augmented reactivity, and thermal instability. To improve upon this limitation, different types of modifications have been proposed with objectives to increase its chemical

reactivity, reduce the brittleness of lignin-derived polymers, increase its solubility in organic solvents, and improve the ease of processing the lignin. For example lignin modification with propylene oxide for preparation of engineering plastic and polyurethane foam has been proposed. This type of modification results in the formation of lignin polyol derivatives, which in turn improves the solubility and uniformity of the lignin. During the modification, the majority of phenolic hydroxyl groups are converted to aliphatic hydroxyl units. Thus, more reactive hydroxyl groups become readily available. Previous methods have consisted of mixing the solid lignin into pure propylene oxide in the presence of a base (usually KOH) at a temperature of 150-200 °C for 1 to 2 hours.

In general, lignin is a green biomaterial which has a great market potential in renewable energy and biopolymeric materials. Despite the previous attempts in the field, new methods and materials utilizing lignin are desirable.

BRIEF SUMMARY OF THE INVENTION

The present invention provides reactive modified materials that are stabilized and rendered better suited for industrial applications. Specifically, the invention provides methods for selectively protecting and/or masking reactive functional groups on lignin such that the reactivity of the lignin is controlled and modulated as desired. Thus, in certain embodiments, the invention can be characterized as providing a reactive modified lignin. Specifically, such reactive modified lignin can comprise a lignin having a content (e.g., about 5% or greater) of its initial reactive functional groups thereon protected with a masking moiety. Preferably, the masking moiety can be less reactive than the functional group that is masked.

The reactive modified lignin according to the present invention can be characterized in that it exhibits characteristics associated with thermal stability and polymerization stability such that heating of the modified lignin at a temperature of about 20 °C above its glass transition temperature (Tg) increases that molecular weight of the modified lignin by no more than about 10%. Further, the reactive modified lignin can be characterized as exhibiting a thermal stability such that weight loss of the modified lignin is less than 5% when heating to a temperature of greater than 225 °C. Moreover, the modified lignin can exhibit a glass transition temperature (Tg) that varies with the percentage of reactive functional groups that are masked with the masking moiety. The thermal properties and molecular weight distributions of copolymers

produced from such protected lignins can vary in accordance with the degree of protection, and this provides means for modulating the properties of an otherwise intractable polymer.

The types of reactive functional groups that are masked can vary. The reactive functional groups that are masked can be selected from the group consisting of hydroxyl, methoxyl, carbonyl, and carboxyl, and combinations thereof. Specifically, the reactive functional group can be present on a phenol group of the lignin, more specifically it can be a phenolic OH group.

The masking moiety likewise can be selected from a variety of materials. For example, the masking moiety can be selected from the group consisting of optionally substituted alkyl, optionally substituted alkenyl, optionally substituted alkynyl, and combinations thereof.

In further embodiments, the invention can provide lignin polymers prepared from the reactive modified lignins, as described herein. Such lignin polymers may have a molecular weight of, for example, about 5,000 Da or greater.

Still further, the invention can provide various polymer systems that comprise a reactive modified lignin as disclosed herein. For example, the polymer system can be such that the reactive modified lignin is covalently bonded within a three-dimensional network polymer. Moreover, the polymer system can be a copolymer of the reactive modified lignin and a further monomer. Yet further, the polymer system can be a linear polymer.

Further to the above, the invention can provide methods of preparing polymer systems. For example, such method can comprise reacting a reactive modified lignin as disclosed herein with a second material under conditions such that the modified lignin covalently bonds with the second material. Specifically, the second material can be a three-dimensional network polymer. Further, the second material can be a monomer.

The invention also provides methods for preparing the initial, reactive modified lignin. An exemplary method can comprise reacting a starting lignin with a masking moiety under conditions such that a content (e.g., about 5% or greater) of the reactive functional groups on the starting lignin react with the masking moiety and become masked by the moiety. Preferably, the masking moiety can be less reactive than the functional group that is being masked.

The source of the lignin used according to the present invention can vary. In certain exemplary embodiments discussed herein, technical Kraft lignin from softwoods was utilized, but the invention is not limited to only such sources. Rather, the methods and products disclosed herein can encompass the use of a large variety of lignin sources, including hardwoods and

annual plants. The present invention beneficially can allow for the use of lignin in applications that significantly exceed the traditional sources of the pulp and paper industry and into those produced from modern biorefinery operations. These can include organosolv, steam explosion, ethanol and other alcohol pulping, and acidic pulping processes.

Further, the invention can be characterized in that technical lignins can be structurally modified so as to form lignins of modulated reactivity by the selective masking procedures discussed herein. The thus formed, masked lignins exhibit modulated characteristics making them highly useful components for network and linear polymers and composite materials. As such, the present invention provides a significant advancement in lignin chemistry that provides significant flexibility in choosing lignin source and in tuning the eventual polymer properties to desired and pre-defined characteristics. This is all achieved while simultaneously preventing the lignin from becoming a gel during polymerization, which is a phenomenon that has previously significantly limited the usefulness of technical lignins in preparing high value polymers.

In further embodiments, the invention can be characterized in relation to the ability to prepare lignin derivatives of increased thermal stability. In particular, fractionation methods can allow for identifying and isolating lignins of desired characteristics (e.g., molecular weight and functionality). In one embodiment, the invention thus provides a method that comprises the following steps: at least partially dissolving a lignin in a suitable solvent; separating a soluble lignin fraction from an insoluble lignin fraction; and modifying the lignin from the soluble fraction by covalently incorporating a masking moiety into the structure thereof

BRIEF DESCRIPTION OF THE DRAWINGS

Having thus described the invention in general terms, reference will now be made to the accompanying drawings wherein:

FIG. 1 is a chemical structure representative of a typical lignin material;

FIG. 2 is the quantitative ^{31}P NMR spectra of partially oxypropylated lignin (a) and a starting, unprotected lignin (b);

FIG. 3 is a gel permeation chromatogram for a starting Kraft lignin, a 65% propargylated derivative of the same lignin, and a copper mediated chain extended analog of the propargylated derivative, wherein the time to maximum elution is indicative of molecular weight;

FIG. 4 is a chart showing thermogravimetric weight loss for a starting Kraft lignin, two lignin derivatives propargylated at different levels, and a copper mediated chain extended, fully propargylated lignin;

FIG. 5 is a chart showing Differential Scanning Calorimetric (DSC) data indicating that the glass transition temperatures of lignin derivatives, propargylated to various degrees, increases monotonically;

FIG. 6 is a chart showing thermogravimetric weight loss for a sample of a starting Kraft lignin, a sample of a reactive modified lignin, and samples of two protected and chain extended lignin derivatives;

FIG. 7 is a chart showing thermogravimetric analytical data for a sample of acetone soluble Kraft lignin (ASKL), an ASKL sample that was modified via treatment with NaOH in DMSO at 160 ºC for 10 hours, and a sample of the treated ASKL copolymerized with difluorodipheyl sulfone (DFDPS), the chart illustrating the improved thermal stability of the modified lignin and the copolymerized lignin

FIG. 8 is a quantitative ^{31}P NMR spectra of a Kraft lignin showing the content of phenolic OH and aliphatic OH present in the material;

FIG. 9 is a quantitative ^{31}P NMR spectra of unmodified Kraft lignin compared to Kraft lignin with varying degrees of methylation

FIG. 10 is a quantitative ^{31}P NMR spectra of unmodified Kraft lignin compared to Kraft lignin with varying degrees of oxypropylation;

FIG. 11 is an FTIR spectra of an unmodified Kraft lignin, a fully methylated lignin, and a fully oxypropylated lignin;

FIG. 12 is a chart showing DSC curves for methylated lignin (B) and oxypropylated lignin (A)

FIG. 13 is a chart illustrating changes in Kraft lignin, fully methylated lignin, and fully oxypropylated lignin after heating at temperatures above Tg;

FIG. 14 is a chart showing the effect of heating on molecular weight distribution of fully methylated Kraft lignin before and after heating at 150 ºC;

FIG. 15 is a chart showing the effect of heating on molecular weight distribution of fully propylated Kraft lignin before and after heating at 150 ºC; and

FIG. 16 is a chart showing the comparative effect of heating at 150 °C on the molecular weight distribution of sample of Kraft lignin, a sample of fully methylated lignin, and a sample of fully oxypropylated lignin.

DETAILED DESCRIPTION OF THE INVENTION

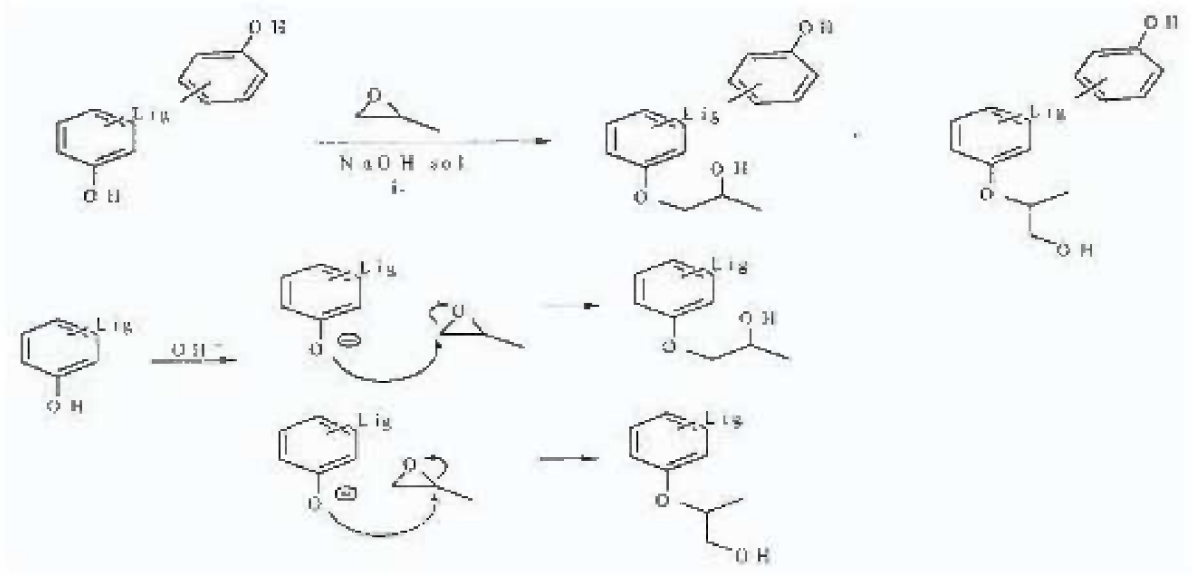
The present invention beneficially overcomes limitations in the usefulness of lignins, particular technical lignins, through the application of chemistries that modify the lignin and provide it in a new form that provides increased usefulness. The modified lignins can be incorporated into polymer systems in a manner not previously recognized.

In one embodiment, the invention provides means for modifying the reactive properties of lignin by at least partially masking reactive functional groups (e.g., phenolic OH groups) on the material. The resulting material is a protected lignin that exhibits stable and consistent properties, and previous, limiting characteristics of lignin (e.g., rapid, irreversible gelation) are eliminated. The protected lignin can then be utilized as an integral component in high end uses, such as linear, long-chain, high performance and heat stable polymers, copolymers, and blends. Such polymer systems are particularly characterized in that the lignin is incorporated into the polymer by covalent bonding rather than simply functioning as an additive to the system. Thus, the invention provides for reactive modified lignin (i.e., lignin that has been chemically altered such that the reactivity of the lignin is modified and such that the reactivity is controllably modulated). The reactive modified lignin provides predictable and uniform properties and may be produced from a variety of sources, plant feedstocks, and processing conditions.

Chemical processes leading to the formation of technical lignins (such as pulping methods that separate the lignin from cellulose) rely upon scission of alkyl-aryl ether bonds. As a result, technical lignins are rich in phenolic hydroxyl (OH) groups. Such phenolic OH groups can be a primary functional group on technical lignin in that the phenolic OH groups can account for the majority of covalent bonding by the material. As such, the present disclosure may particularly describe processes and materials in relation to modification of the phenolic OH functional groups. Such discussion should not be viewed as limiting the scope of the invention, which can relate to masking of functional groups generally on technical lignin, including methoxyl, carbonyl, and carboxyl groups, as well as OH groups other than phenolic OH.

Reactive lignin functional groups can be modified through reaction with a variety of moieties. For example, methyl chloride and ethyl chloride can be used to mask a reactive functional group with an alkyl moiety. Methylation is particularly described in the Experimental section below. Propylene oxide in alkaline media likewise can be used to form an oxypropylated lignin with a reactive OH group. Preferably, the oxypropyl OH is less reactive than the functional phenolic OH group originally present. An exemplary reaction mechanism for reacting a phenolic OH on lignin with propylene oxide is shown below in Scheme 1. The formed, oxypropylated lignins are provided with various degrees of protection.

Scheme 1

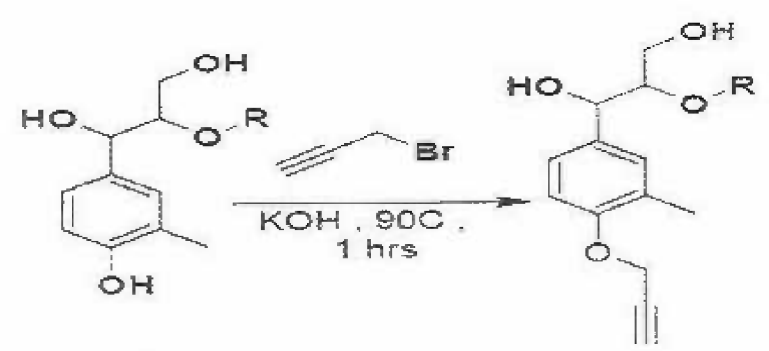


Quantitative ^{31}P NMR spectra of partially oxypropylated lignin (a) and the starting, unprotected lignin (b) are shown in FIG. 2. As seen in FIG. 2, the significant peak between 130 to 145 ppm indicative of phenolic OH groups in spectrum (b) of the non-modified lignin is significantly lessened in spectrum (b), and a new signal at 145.8 ppm is indicative of the newly formed aliphatic OH groups on the oxypropyl-protected lignin. Quantitative integration of the spectra indicated that the amount of newly formed aliphatic OH in the protected lignin accounted for the depleted phenolic OH in the protected lignin compared to the non-protected lignin. Thus, through accurate monitoring using such spectral data, the present invention allows for the formation of reactive modified lignins with a controllable degree of protection and a controllable

degree of pendant reactive functionality to allow for further chemical modification, which can be particularly useful for integration of the reactive modified lignin into various polymer systems.

In further embodiments, the invention provides means for synthesizing lignin polymers useful as a functional component in a three dimensional network polymer. For example, reactive modified lignin protected with an alkynyl moiety (e.g., a propargyl moiety) can be particularly useful for addition to network polymers through covalent bonding. An exemplary reaction mechanism for forming a propargyl reactive modified lignin is shown below in Scheme 2.

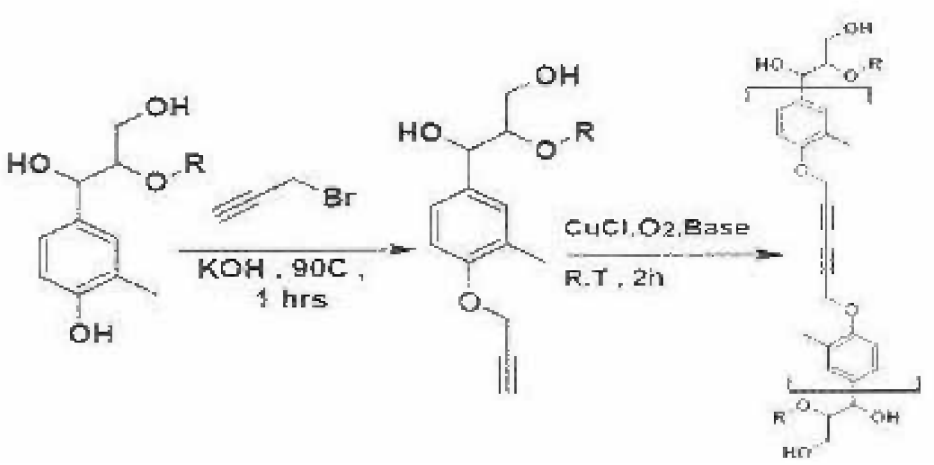
Scheme 2



In exemplary embodiments, lignin that was reactive modified with a propargyl moiety was evaluated as a non-polar matrix for the creation of pendant unsaturated moieties, which can be useful for incorporation into advanced polymeric composite and transportation applications – e.g., tires. Such lignin derivatives can be readily used in a variety of industrial applications, can be implemented on a large scale, and can provide a desirably low price modification of polymer systems. In one embodiment, a propargyl reactive modified lignin (as well as further lignin derivatives) can undergo chain extension to provide even further types of lignin derivatives.

For example, as shown in Scheme 3, copper mediated oxidative coupling of propargyl reactive modified lignin can be used to form a biphenol structure with pendant unsaturated moieties. This can be particularly useful since thermosets that are produced from various biphenols have been shown to have a glass transition temperature above 300 °C with excellent isothermal thermo-stability in air and nitrogen. Such materials also may be useful in relation to their mechanical properties, low water absorption, low dielectric constants, and low dissipation factors. The pendant unsaturation present within the propargyl lignin derivatives may be subsequently used in covalently incorporating lignin (e.g., via vulcanization schemes in rubber) into a variety of existing and new 3D network polymer systems.

Scheme 3



Reactive modified lignins can be characterized by an increased molecular weight in relation to technical lignin. For example, Table 1 shows the molecular weight of a starting Kraft (technical) lignin, a 65% propargylated Kraft lignin (e.g., prepared according to Scheme 2), and a 65% propargylated Kraft lignin that has been chain extended (e.g., according to Scheme 3). As seen therein, the propargyl reactive modified lignin exhibits an approximate 33% increase in MW over the technical lignin, and the chain extended reactive modified lignin exhibits and approximately 8.5 fold increase in MW compared to the technical lignin. This is further illustrated in the chromatogram shown in FIG. 3.

Table 1

Sample	Molecular Weight (Da)
Starting Kraft Lignin	2,000
65% Propargylated Kraft Lignin	3,000
Chain Extended, 65% Propargylated Kraft Lignin	17,000

The reactive modified lignin also can impart isothermal thermo-stability. This is seen in Table 2, which provides thermogravimetric weight loss data for a starting Kraft lignin, two lignin derivatives propargylated at different levels, and a copper mediated chain extended fully propargylated lignin. Compared to the starting lignin, the 2% and 5% weight loss for each of the derivatives and the fully chain extended product are significantly augmented. This is further

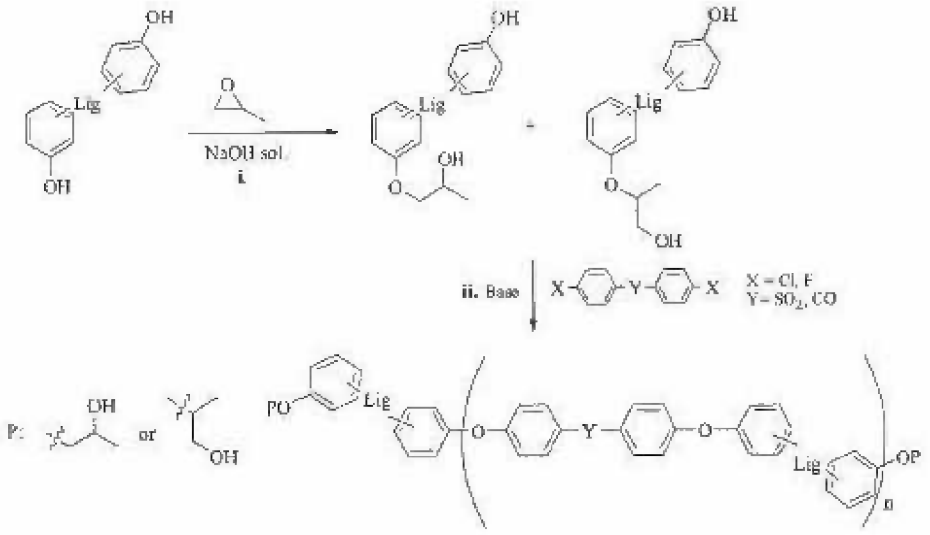
illustrated in FIG. 4. Changes in glass transition temperature in relation to the extended lignin as derivatized is illustrated in FIG. 5 (i.e., in relation to propargyl reactive modified lignin).

Table 2

Sample	2% Weight Loss	5% Weight Loss
Starting Kraft Lignin	162 °C	225 °C
14% Propargylated Kraft Lignin	160 °C	230 °C
75% Propargylated Kraft Lignin	188 °C	270 °C
Fully Propargylated Kraft Lignin, Chain Extended	218 °C	315 °C

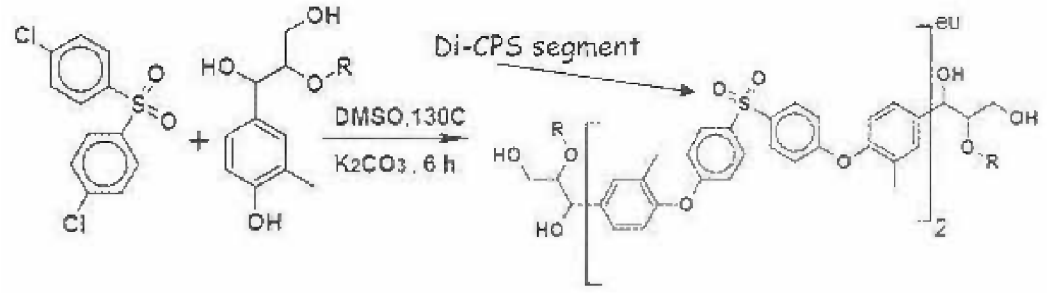
In further embodiments, reactive modified lignin (including chain extended lignins) can be useful as a component in linear long-chain high performance and heat stable polymer and copolymer systems, polymer blends, and composite materials. The invention thus improves the ability to utilize the inherent branched nature of lignin in modulating the thermal transitions (i.e., polymer properties that depend on the available free volume of the system) of lignin and its copolymers, blends, and composites. Partially protected lignin ethers (e.g., lignins modified at the OH functional group) can be reacted with activated diphenols as shown in Scheme 4. Such reaction schemes can be useful in the synthesis of melt and heat stable aromatic polyethers. Appropriate selection of the leaving groups (X and Y in Scheme 4) present on the activated diphenol allows for customizable reactions with adjustable kinetics and polymer chain lengths.

Scheme 4



Additional examples of reactions useful in the preparation of linear polymer systems with beneficial properties are shown in Scheme 5 and Scheme 6. The reaction of bis(4-chlorophenyl) sulfone (Di-CPS) with oxypropylated lignin (R) shown in Scheme 5 proceeded smoothly when carried out in DMSO. Referring to Scheme 6, the reaction of partially oxypropylated and methylated lignins with 4,4'-difluorobenzophenone (Di-FBP) was found to be significantly more facile than the analogous reaction depicted in Scheme 5 using the diphenyl sulfone. These copolymers were also found to be of higher molecular weight, as shown below in Table 3 showing the weight average molecular weights for the starting Kraft lignin, the partially oxypropylated derivative, and the respective chain extended products created with the two sets of activated biphenols. Changes in glass transition temperature in relation to the chain extended lignins are illustrated in FIG. 6.

Scheme 5



Scheme 6

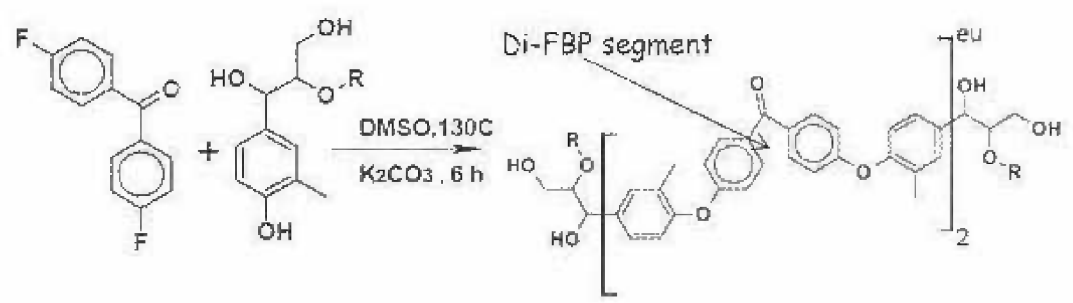


Table 3

Sample	Kraft Lignin	Protected Lignin	Protected and Extended Di CPS	Protected and Extended Di FBP
Molecular Weight (Da)	2,000	2,500	14,000	16,000

The present invention still further provides various solvent fractionation processes that can be used with technical lignin to provided lignin fractions of variable molecular weight and functionality. More specifically, the fractionation processes can utilize a variety of ketones and various alcohols to allow for lignin fractions of variable functionality, branching, and molecular weight to be produced. These fractions, when subjected to the protection protocols otherwise discussed herein, provide further means for controlling and creating linear, branched, and network polymer and copolymer compositions, including through use of the chemistries already described herein. Exemplary means for using solvent fractionation to separate lignins of variable molecular weight are shown in Example 6.

EXPERIMENTAL

The present invention will now be described with specific reference to experimental work carried out to evaluate methods of preparing modified lignin and the modified lignin and other materials that were prepared. The experimental disclosure is not intended to be limiting of the invention and is rather provided as exemplary embodiments.

EXAMPLE 1

Oxypropylation of Kraft Lignin

Kraft lignin (2 g, containing 3.86 mmol/g of total phenolic-OH) was dissolved in 25 ml of 0.4M KOH solution. Propylene oxide (1.9 mmol) was added into the lignin solution. The mixture was heated at 40 ºC for 12 hours with stirring. The reaction was stopped and the lignin was precipitated by adding dilute hydrochloric acid. The precipitated lignin was washed with excess water and dried in a vacuum oven. The degree of oxypropylation was measured by phosphorus NMR.

EXAMPLE 2

Propargylation of Oxypropylated Kraft Lignin (65% Masking of Phenolic OH)

Oxypropylated lignin (300 mg) prepared as described in Example 1 was dissolved in 10 ml of water containing KOH (1 mmol) with an initial pH of 13.7. Propargylbromide (0.4 mmol) was added into the lignin solution at room temperature. The mixture was heated to 90 °C and kept at this temperature of 1 hour with stirring (final pH = 9.8). The final product was precipitated using dilute HCl and washed with excess water.

EXAMPLE 3

Copper Mediated Oxidative Coupling of Propargylated Lignin

Propargylated lignin (150 mg) prepared as described in Example 2 was dissolved in 6 ml of dry pyridine. Copper chloride (15 mg) was dissolved in 2 ml pyridine and stirred with bubbling air to induce oxidation. Copper chloride solution in pyridine was then added to the lignin solution and stirred at room temperature for 30 minutes. The final solution was poured into 30 ml MeOH, and the precipitated lignin was separated and washed five times with MeOH and once with deionized water.

EXAMPLE 4

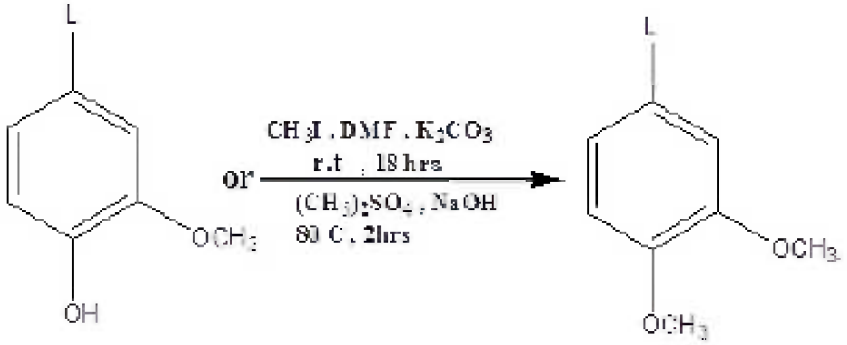
Co-Polymerization of Partially Oxypropylated Lignin with Bis(4-chlorophenyl) Sulfone or 4,4'-Difluorobenzophenone

Oxypropylated lignin (300 mg, 35% masking of phenolic OH) was dissolved in 10 ml of dry DMSO. Potassium carbonate (0.8 mmol) was added, and the mixture was heated at 100 °C for one hour. The respective dihalide (0.4 mmol) was then dissolved in 1 ml DMSO and added to the lignin solution of a period of 1 hour at a temperature of 130 °C. The mixture was maintained at 130 °C for six hours. The final product was recovered by acidification, washing with water, and centrifugation. The product was then dried in a vacuum oven.

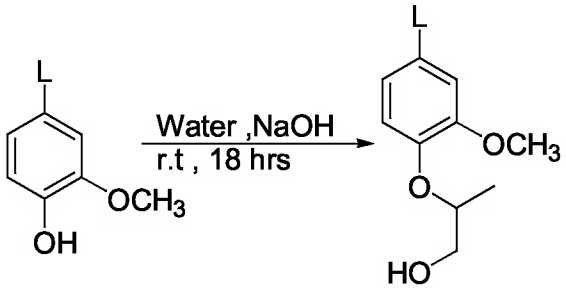
EXAMPLE 5

Methylation and Oxpropylation of Kraft Lignin

A sample of commercially available Kraft lignin (indulin) was used as a starting material. Methylation of lignin (as shown below) was carried out by mixing with dimethyl sulfate at 80 °C for two hours in NaOH alkali solution (10 mL/g). During methylation, sodium hydroxide was added to maintain a constant pH >12. Thereafter, the reaction mixture was acidified (pH 2.5) with 2N HCL, and the solid precipitate was washed with water and freeze dried.



Oxypropylation of Kraft lignin (as shown below) was carried out by reaction of lignin with propylene oxide in 0.5M NaOH solution (10 ml/g) at 40 °C for 18 hours. Thereafter, the mixture was acidified (pH= 2.5) with 2N HC1, filtered, and solid precipitate was washed with water and freeze dried.



EXAMPLE 6

Fractionation of Lignin

Kraft lignin (indulin) (10 g) was dissolved in 150 mL of acetone and was stirred at room temperature for 4 hours. The residue was then filtered, and the dissolved fraction was separated from the un-dissolved fraction. After solvent evaporation the two fractions were further dried in

a vacuum oven. The fraction including acetone soluble Kraft lignin (ASKL) was determined to be 35% by weight of the original material and of distinctly different hydroxyl group and molecular weight distribution as determined by quantitative ^{31}P NMR and gel permeation chromatography respectively. The weight average molecular weight of the acetone soluble fraction was found to be about 1200 g/mol, while that of the precipitated (undissolved) fraction was about 20,000 g/mol. Figure 7 shows a series of thermogravimetric analytical data for the ASKL, its control counterpart (ASKL treated with NaOH in DMSO at 160 °C for 10 hours), and the copolymer of ASKL with difluorodipheyl sulfone (DFDPS). The remarkable thermal stability of the copolymer is obvious where only about 4% of its weight was lost after exposure at 350 °C while the starting Kraft lignin lost about 32% of its weight at the same temperature.

EXAMPLE 7

Characterization of Reactive Modified Lignin

The present invention can utilize specific means to rapidly arrive at a quantitative estimate of the reactive functional groups in lignin prior to and after protection, chain extension, and/ or other modification. Specifically, the present invention encompasses quantitative ^{31}P NMR equipment and methods of use thereof for quantifying the reactive functional groups in a lignin sample.

Quantitative ^{31}P NMR of all lignin samples was obtained using published procedures. See Granata et al., *J. Agric. Food. Chem.* 1995, 43, 1538-1544; Corradini et al., Lignin-poly (vinyl alcohol) blends studied by thermal analysis, *Polymer Degradation and Stability* 66 (1999) 199-208; and Akim et al., *Holzforschung* 2001, 55, 386-390; the disclosures of which are incorporated herein by reference in their entireties. Dried lignin (40 mg) was dissolved in 500 μL of anhydrous pyridine and $CDCL_3$ mixture (1.6:1, v/v). 200 μL of endo-N-hydroxy-5-norbornene-2,3-dicarboximide (e-NHI) solution (9.23 mg/mL in pyridine and $CDCL_3$ (1.6:1, v/v) as the internal standard and 50 μL of chromium(III) acetylacetonate solution (5.6 mg/mL in the pyridine and $CDCL_3$ solution) as a relaxation reagent was added. Then, 100 μL of phosphitylating reagent II (2-chloro- 4,4,5,5-tetramethyl-1,3,2-dioxaphospholane, TMDP) was added and transferred into a 5 mm NMR tube for subsequent NMR acquisition. NMR spectra were acquired using on a Bruker 300 MHz spectrometer equipped with a Quad probe dedicated to ^{31}P, ^{13}C, ^{19}F, and ^{1}H acquisition.

Fourier transforms infrared (FT-IR) spectra were obtained for powdered solid lignin on KBr discs using a Bruker Tensor Series FT-IR Spectrometer. The Spectra was collected from 4000 to 400 cm-1 with 64 scans and 4 cm-1 resolution.

Gel Permeation Chromatography measurements were carried out with Waters pumps equipped with UV and RI detectors using THF as the eluant at a flow rate of 0.6 mL/min. at 35 °C. Two Ultrastyragel linear columns linked in series (Styragel HR 1 and Styragel HR 5E) were used for the measurements. Standard monodisperse polystyrenes were used for the calibration. Acetylated samples were used for all experiments.

The glass transition temperatures (Tg) of all samples were determined by differential scanning calorimetry (DSC) with a TA Q100 instrument under nitrogen (flow rate 50 ml/min) using sealed aluminum crucibles. An appropriate amount of sample (around 8 mg) was put into a pre-weighed pan. The pans were closed by cold-pressing. The samples were heated up to 120 °C (5°C/min), kept here for 30 min, and then quenched to 40 °C. Finally, the samples were heated to 200 °C with a heating rate of 10 °C/min. The glass transition temperatures were determined from the midpoint of the heat flow shift.

After carrying out masking of lignin phenolic OH via oxypropylation and methylation as discussed above, the effect of these derivatizations on the thermal stability and glass transition point of the lignin was examined. Kraft lignin (Indulin) was used for this study as it is one of the most available lignin materials industrially. Samples were characterized by employing different methods. ^{31}P NMR spectroscopy was employed for quantitative determination of hydroxyl groups. Amounts of total phenolic and aliphatic hydroxyl groups in the starting material were determined to be 3.85 mmol/g and 2.4 mmol/g respectively, as shown in FIG. 8. The molecular weight (Mw) was calculated to be about 8000 g/mol by GPC, and the glass transition point (Tg) of the lignin was determined to be 155 °C by DSC.

Kraft lignin was chemically modified directly to methylated and oxypropylated derivatives according to the methods described above. Two methods for lignin methylation were used: i) methylation with methyl iodide was carried out in organic solvent (DMF) in the presence of K_2CO_3 at room temperature; and ii) methylation with dimethyl sulfate was carried out in NaOH solution at 85°C. A summary of the methylation and oxypropylation reaction conditions and results is shown in Table 4, which shows that the values of different hydroxyl groups before and after modifications.

Table 4

Conversion methods	R/L*	Total hydroxyl groups in the samples mmol /g Lignin		
		Phenolic-OH	Aliphatic-OH	New aliphatic-OH
Kraft lignin	00	3.85	2.4	
Methylation with $(CH_3)_2SO_4$	1	2.2	2.34	
	1.5	0.91	2.33	
	2	0.5	2.3	
	2.5	0.03	2.34	
Oxypropylation	0.5	3.35	2.35	0.46
	1	1.92	2.38	1.86
	2	0.41	2.38	3.33
	3	0.05	2.36	3.79

*Molar ration of reagents to phenolic-OH in the lignin

For methylation, four series of samples were synthesized with 1,1.5, 2 and 2.5 molar ratio of dimethyl sulfate to phenolic-OH (R/L) of lignin. ^{31}P NMR spectra of the methylated Kraft lignins are presented in Figure 9 and the data are shown above in Table 4. The comparison of the ^{31}P NMR spectra shows that phenolic hydroxyl groups in lignin were reacted with dimethyl sulfate and converted to their corresponding methylated groups. The phenolic hydroxyl group content decreased, but the aliphatic-OH was completely stable in this reaction. Also the result shows that using of 2.5 mmol dimethyl sulfate per each mmol of phenolic-OH in the lignin can convert very close to 100% of the phenolic OH to the corresponding methylated groups. The ^{31}P NMR spectra of methylated Kraft lignin with dimethyl sulfate shows that the carboxylic acids did not completely undergo transformation to their corresponding methylated groups.

For oxypropylation, four series of samples were synthesized with different mmol propylene oxide per mmol phenolic-OH in the lignin (PO/L ratios). Ratios of 0.5, 1, 2, and 3 were used. Evidence of oxypropylation was checked by ^{31}P NMR and with FTIR. As shown in FIG. 10, two different and distinct broad signals in the aliphatic region of the ^{31}P NMR spectra were recorded between 144.1 to146.5 ppm, and 146.7-149.5 ppm, respectively. Closer examination of the spectra confirms that the NMR signal recorded between 146.7 to 149.5 ppm is attributed to the similar aliphatic–OH groups that were present in the original lignin sample, and the signal in the range of 146.7-149.5 ppm is created by the new aliphatic-OH of oxypropylation. As shown in FIG. 10 and Table 4, the increasing amount of new aliphatic-OH

corresponds to a decrease in phenolic OH in the lignin. Table 4 also shows the evolution of the lignin oxypropylation as a function of mmol reagent per each mmol of phenolic OH in the lignin (R/L ratios). Inspection of the aliphatic-OH and phenolic-OH evolution reveals that oxypropylation of the samples increased with increasing propylene oxide content in the presence of adequate catalyst. Use of 3 mmol propylene oxide per each mmol of phenolic OH in the lignin converted almost all phenolic OH to corresponding, new alkyl groups. As seen in FIG. 11, an increase in the bands at 2971-2870 cm^{-1} of the FTIR spectra was attributed to the stretching of CH_3, CH_2, and CH aliphatic groups and an increase in absorption in the C-O stretching region (1000-1100 cm-1) associated with the ether moieties. This indicated the occurrence of propylene oxide grafting on the lignin.

According to thermal studies carried out, hydrogen bonds of lignin are ruptured at a temperature of about 60-80 °C. Within this range, early stage primary condensation of the lignin begins involving hydroxyl groups and benzyl-alcohol groups of the propane chain. With increasing temperature, a competing reaction of disintegration of alkyl-aryl bonds begins and increases the content of phenolic hydroxyl. This process in lignin continues up to a temperature of about 300 °C. Thermal stability of lignin for polymer use is important. Thermal destruction of lignin structure occurs via a heterolytic mechanism. Phenolic hydroxyl groups play an important role on lignin thermal behavior especially on its condensation reactions.

On the other hand, lignin has a heavily branched structure and is not suitable for preparation of linear polymers. Selective masking of phenolic-OH of the lignin, per the present invention, improves its solubility and thermal stability and can convert it to a valuable material for polymer applications. DSC is the most widely used method to measure the glass transition temperature of an amorphous polymer. See Hatakeyama et al., Thermal Properties of Green Polymers and Biocomposites, *Kluwer Academic Publishers*, 2004, pp 174; and Wada, Y., 1981, Physical properties of polymer in solid state, *Baifukan pub*. Tokyo, the disclosures of which are incorporated herein by reference in their entireties. The prior art had shown that annealing lignin at a temperature of about 30°C above Tg causes the Tg to merge with actual glass transition. See Hatakeyama et al., Thermal decomposition and glass transition of industrial hydrolysis lignin, *J Therm Anal Calorim* (2010) 101:289–295; Hatakeyama et al., Thermal analysis of lignin by differential scanning calorimetry. *Cell Chem Technol.* 1972; 6:521–9; and Marshall et al., Physical aging of glassy polymers: effects of subsidiary relaxation processes. In: Eby RH, editor.

Durability of macromoelcular materials. *ACS Symposium, Series* 95, Washington DC, Am Chem Soc; 1979. p. 245–59; the disclosures of which are incorporated herein by reference in their entireties. The present research, however, indicated that heating above Tg created a significant change in the lignin structure and its molecular weight, and it cannot be a representative of the starting materials. In this work, lignin was heated to 120 °C at a rate of 5 °C/min and isolated for 30 min. The sample was quenched to 30 °C and, after a 5 minute isotherm, the samples were heated at a rate of 10 °C/min to 250 °C. The middle point of heat flow shift was used for Tg determination. The glass transition temperatures (Tg) were determined from the second heating scan. The Tg of Kraft lignin was determined to be around 155 °C, whereas Tg for fully methylated and oxypropylated lignin were found to be around 127 °C. The reason for these lower Tg values is believed to arise from the lowering and breaking of intermolecular hydrogen bound in lignin due to the replacement of phenolic hydroxyl groups and expansion of intermolecular distance. With an increase in methylation, Tg decreased (See FIG. 12). Methylation of 25% of the lignin phenolic hydroxyl decreased Tg about 10 °C. In the fully methylated lignin, the decrease in Tg was about 27 °C.

Molecular weight of Kraft lignin, fully methylated lignin, and fully oxypropylated lignin were determined by gel permeation chromatography (GPC). The results show that the weight average molecular weight (Mw) and the number average molecular weight number (Mn) for Kraft lignin were 8,000 and 2,000 g/mol respectively. The values for fully methylated lignin and fully oxypropylated lignin were essentially identical.

Thermal stability of Kraft lignin and its modified derivatives were examined and compared after heating in N_2 atmosphere at 20 °C above their respective Tg. Effects of derivatization on the thermal behavior are shown in FIG. 13. The data showed that fully methylated lignin was completely stable during heating of the sample at 20 °C above its Tg. On the other hand, the molecular weight of Kraft lignin and fully oxypropylated lignin each increased with heating. Kraft lignin was very sensitive to heating and, after only 20 minutes of heating above Tg, its molecular weight increased from 8,000 to $5x10^4$ g/mol. Heating more than 20 minutes made the Kraft lignin insoluble in usual lignin solvents. Oxypropylated lignin was also sensitive to heating, but its thermal stability was better than the initial Kraft lignin.

The GPC curve of unheated and heated fully methylated lignins is shown in FIG. 14. The molecular weight distribution patterns of thermally treated samples for 20 and 60 min at 20 °C

above its Tg (150°C) were similar to that of the unheated methylated lignin. This illustrated that methylation of the lignin can convert it to a thermally stable form. This is believed to occur, at least in part, because of the removal of phenolic OH in the lignin. Similarly, FIG. 15 shows the GPC curve of unheated and heated, fully oxypropylated lignins. The molecular weight of the samples increased with heating. With an increase in time of heating, the molecular weight showed a greater gain than with the methylated lignin. This illustrated less thermal stability of the oxypropylated lignin compared with the methylated lignin.

The thermal stability of Kraft lignin, fully methylated lignin, and fully propylated were compared, and the results are shown in FIG. 16. As seen therein, the molecular weight of unmodified Kraft lignin and oxypropylated lignin increased with heating.

Many modifications and other embodiments of the inventions set forth herein will come to mind to one skilled in the art to which these inventions pertain having the benefit of the teachings presented in the foregoing descriptions. Therefore, it is to be understood that the inventions are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

CLAIMS:

1. A reactive modified lignin comprising a lignin having about 5% or greater of the reactive functional groups thereon masked with a masking moiety that is less reactive than the functional group.

2. The reactive modified lignin of claim 1, wherein the modified lignin exhibits thermal stability such that heating of the modified lignin at a temperature of about 20 °C above its glass transition temperature (Tg) increases that molecular weight of the modified lignin by no more than about 10%.

3. The reactive modified lignin of claim 1, wherein the modified lignin exhibits thermal stability such that weight loss of the modified lignin is less than 5% when heating to a temperature of greater than 225 °C.

4. The reactive modified lignin of claim 1, wherein the modified lignin exhibits a glass transition temperature (Tg) that increases monotonically with the percentage of reactive functional groups that are masked with the masking moiety.

5. The reactive modified lignin of claim 1, wherein the reactive functional groups are selected from the group consisting of hydroxyl, methoxyl, carbonyl, and carboxyl, and combinations thereof.

6. The reactive modified lignin of claim 1, wherein the masking moiety is selected from the group consisting of optionally substituted alkyl, optionally substituted alkenyl, optionally substituted alkynyl, and combinations thereof.

7. A lignin polymer comprising a chain of reactive modified lignin according to claim 1.

8. The lignin polymer of claim 7 having a molecular weight of about 5,000 Da or greater.

9. A polymer system comprising a reactive modified lignin according to claim 1.

10. The polymer system of claim 10, wherein the reactive modified lignin is covalently bonded within a three-dimensional network polymer.

11. The polymer system of claim 9, wherein the polymer system is a copolymer of the reactive modified lignin and a further monomer.

12. The polymer system of claim 9, wherein the polymer system is a linear polymer.

13. A method of preparing a polymer system comprising reacting a reactive modified lignin according to claim 1 with a second material under conditions such that the modified lignin covalently bonds with the second material.

14. The method of claim 13, wherein the second material is a three-dimensional network polymer.

15. The method of claim 13, wherein the second material is a monomer.

16. A method of forming a reactive modified lignin comprising reacting a starting lignin with a masking moiety under conditions such that about 5% or greater of the reactive functional groups on the starting lignin react with the masking moiety and thereby become masked by the moiety, wherein the masking moiety is less reactive than the functional group.

17. A method of preparing a lignin derivative of increased thermal stability comprising:

at least partially dissolving a lignin in a suitable solvent;

separating a soluble lignin fraction from an insoluble lignin fraction; and

modifying the lignin from the soluble fraction by covalently incorporating a masking moiety into the structure thereof.

ABSTRACT

The present invention relates to reactive modified lignin, methods of preparing such modified lignin, and materials, such as polymer systems, incorporating the modified lignin. More specifically, the lignin can be modified by selectively masking reactive functional groups such that the material has a modulated reactivity and is thus better suited for incorporation into further materials.