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Supercritical Fluid Rectification of Lignin Pyrolysis Oil Methyl Ether (LOME) and Its Use as a Bio-derived Aprotic Solvent

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Lignin oil methyl ether (LOME) is a bio-derived solvent obtained from lignin by pyrolysis, methylation, and rectification. It performs well as an alternative polar aprotic solvent for organic reactions such as the Menschutkin synthesis of quaternar, amines. Methylation of lignin pyrolysis oil was achieved using dimethylcarbonate under mild reaction conditions. Th resulting methylated oil was subjected to supercritical fluid rectification in supercritical CO_2, yielding LOME (90 wt% of eight identified veratroles and anisoles) which can be directly used as a bio-derived aprotic solvent.

Introduction

Lignocellulose is the most abundant biomass available on Earth for production of biofuels or value-added products that are useful as green polymeric materials, bio-based adhesives and synthetic intermediates.[1, 2] The various methods of breaking down lignin, including pyrolysis, give diversified fractions which require treatment before they can be transformed into value-added products.[3] Pyrolysis oil derived by either conventional or microwave pyrolytic conditions is a promising liquid feedstock and a source of valuable phenolics such as guaiacols, creosols, catechols and cresols.[4, 5]

However, pyrolysis oil contains a diversified mixture of products, so that finding an economic and selective separation of the desired or valuable constituents has been a challenge.[6, 7] Earlier reported methods of extractions such as extraction through alkalis, acids, water precipitation, organic solvents, steam distillations, molecular distillations and organic solvent fractionation combined with basification and acidification process resulted in poor yields, large amounts of salts which are hard to remove later, high base catalyst costs, difficult recovery methods or need for high cost corrosion resistant equipment.[4] Switchable hydrophilicity solvents (SHS) such as *N,N*-dimethylcyclohexylamine have the advantage of facile removals without distillations but due to the acidic nature of the phenols and the basic nature of known SHS, poor selectivity and yields are obtained.[5] Supercritical CO_2 ($scCO_2$) extractions are attractive due to the non-toxic, non-flammable nature of the CO_2. Recently we have reported a supercritical fluid rectification (SFR) process that is highly selective for single ring phenolic compounds.[8]

The high reactivity and acidity of phenols makes them easily converted to desirable products. O-methylation of phenols is an important valorization process but often the transformation is achieved by using toxic and mutagenic reagents such as iodomethane and dimethyl sulfate.[9] The O-methylation of phenolic derivatives in methanol and strong acid catalysts at elevated temperatures has been extensivel, studied but the conversions are poor and the selectivities to aryl methyl ethers are lowered by promotion of C-methylation.[10] Dimethyl carbonate (DMC) is a desirable reagent for O-methylation due to its non-toxic nature and ability to methylate under milder reaction conditions. DMC car. be used as a methylating agent, promoted by mild bases such as potassium carbonate or in the presence of catalytic amounts of ionic liquids such as 1-*n*-butyl-3-methylimidazolium chloride ([BMIM]Cl), to methylate phenols, anilines and carboxylic acids.[10, 11] Here, we report facile and quantitative conversions of phenolic derivatives from lignin pyrolysis oil to their corresponding aromatic methyl ether derivatives and their extraction using SFR to yield up to 90% pure mixture of single-ring veratroles and anisoles, a mixture we call LOME (Lignin Oil Methyl Ether).

While the LOME components (veratroles and anisoles) are individually valuable as fragrants, anticonvulsants, herbicides, weevil anti-feedants,[12] and precursors for perfumes and insecticides,[13-16] we propose that the LOME mixture can be used without further separation as a bio-derived aromatic aprotic solvent. We demonstrate its use as a reaction medium for a common organic reaction, the Menschutkin reaction, with promising high yields and straightforward purification methods. This reaction was chosen because it is a commo

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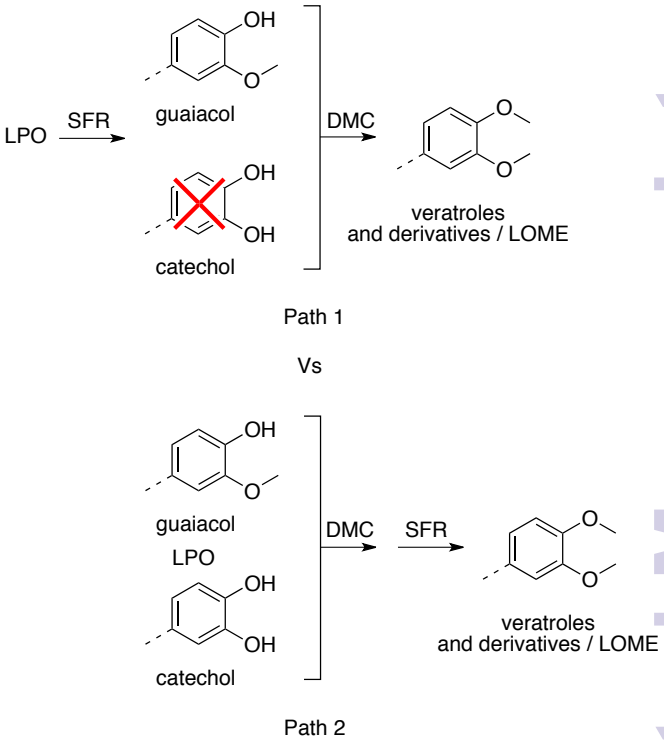
test reaction for evaluating new polar aprotic solvents; the transition state is more polar than the starting materials.[17-21]

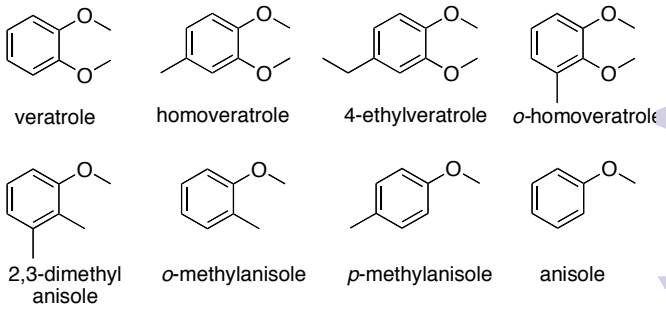
Results and discussion

Microwave pyrolysis of softwood Kraft lignin was performed as described earlier.[5] Even though we used lignin microwave pyrolysis oil in this work, we anticipate that our SFR method should be applicable to all pyrolysis methods such as conventional, fluidized-bed, vortex ablative, vacuum, rotating disk or cone, plasma or solar pyrolysis.[22] All the above processes give different ratios of light and heavy fractions of bio-oil whose composition varies based on the source of biomass and pyrolysis method applied. The heavy bio-oil fraction derived from softwood Kraft lignin was used in this work due to it being a phenol-rich fraction with low water content (14%).[5] The lignin pyrolysis oil (LPO) was stored at -7 °C until used.

Two paths for derivation of methylated products from lignin pyrolysis oil were recognized at this juncture; 1) to perform SFR on lignin pyrolysis oil and methylate the resulting extracts and 2) to methylate lignin pyrolysis oil and then perform SFR to extract the desired/identified products. These two paths should give different results because SFR selectively rejects catechols (Scheme 1). Thus we envisioned that "path 2" would give greater yields of anisoles and veratroles as it combines the yields of methylated products from methylated phenols (such as guaiacols) and catechols whereas most of the catechols are excluded by Path 1 because the extraction precedes the methylation. Nevertheless both paths were studied. The original LPO contained 24 wt% of identified single ring phenolic compounds. Path 1 experiments produced a liquid product containing 51 wt% of the identified veratroles and anisoles (Table 1). Path 2 involved methylation of LPO first, giving a mixture containing 35 wt% of the identified veratroles and anisoles, followed by SFR giving an extract containing up to 90 wt% of those components (Figure 1). Thus path 2 is preferred. Our study of path 2 will now be described in more detail.



Scheme 1. A comparison of the two different paths envisioned to obtain LOME from LPO, contrasting the fate of guaiacols and catechols. Path 1 results in lower yields because the SFR process excludes catechols, while Path 2 converts the catechols to veratroles before the SFR step, and therefore gets better yields.



Scheme 2. Identified LOME products derived from Path 1 and Path 2 consisting of veratrole and anisole derivatives.

Table 1: Concentrations (wt%) of derivatives of veratroles and anisoles of LOME obtained from Path 1 and Path 2. Path 2 has higher concentration (wt%) of LOME compared to Path 1 due to conversions of catechols that are eliminated in Path 1.

Compounds	Concentration of LOME (wt% path 1)	Concentration of LOME (wt% path 2)
homoveratrole	18.2	28.6
veratrole	16.9	22.5
4-ethylveratrole	8.7	10.2
2,3-dimethylanisole	3.8	9.8
o-homoveratrole	0.3	4.5
p-methylanisole	1.6	3.6
o-methylanisole	1.2	2.8
anisole	0.7	2.1
Total	51	84

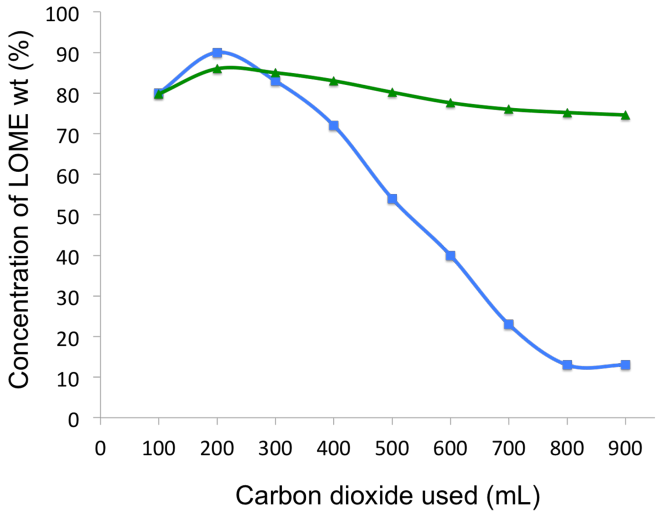


Fig. 1. Incremental and cumulative concentration of the identified LOME obtained by SFR of methylated LPO (Path 2, 7 MPa, 9 mL/min) at 55-95 °C. ■: incremental and ▲: cumulative fractions.

Initially, an artificial mixture of phenols (guaiacol, eugenol, and 4-methylcatechol) representing the major components of lignin pyrolysis oil SFR extract was used to test methylation methods and conditions. The mixtures were subjected to methylation using an excess of DMC (used as both methylating reagent and solvent) in the presence of either catalytic amounts of [BMIM]Cl or stoichiometric K_2CO_3, 16 h at 80 °C. Both the catalyst and the base promoted reactions resulted in quantitative conversions and yielded clean products. The crude products were washed a few times with ice-cold water and then analysed by ^{1}H NMR spectroscopy. The spectrum (Fig. 2) shows that the peaks corresponding to the hydroxy groups of all three phenolic derivatives between 5.0 ppm and 5.8 ppm have disappeared and new methoxy peaks around 3.8 ppm have appeared.

After the methylation had been carried out successfully using an artificial mixture of phenols, a 5.62 g sample of lignin pyrolysis oil was subjected to methylation using [BMIM]Cl conditions that resulted in quantitative conversions to their methylated analogues.[10] Later a few trials with stoichiometric K_2CO_3 were performed. The reactions using the base gave incomplete conversion. While excess base was able to drive the reactions to quantitative conversions,[11] we abandoned that method in favour of the [BMIM]Cl promoted reaction.

The SFR of methylated LPO (methylated by the [BMIM]Cl method) in supercritical CO_2 has the greatest selectivity near the beginning of the extraction process (Figure 1). The selectivity peaks at around 200 mL of CO_2, which corresponds to 22 minutes of extraction at the constant flow rate of 9 mL/min. Thereafter, the selectivity decreases, presumably because the desired anisoles and veratroles are highly soluble in $scCO_2$ and are therefore extracted first, while the unwanted compounds (non-methylated phenols and catechols and heavier multi-ring compounds) are less soluble[23] and therefore extracted more slowly. The use of higher $scCO_2$ pressure for the extraction also gives poorer selectivity, presumably for the same reason.

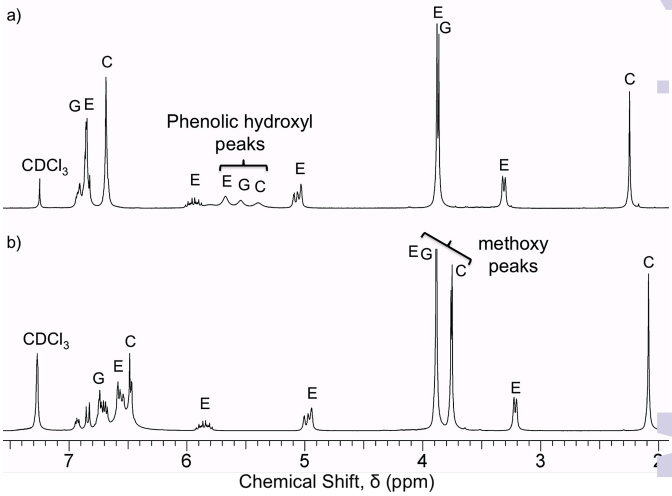


Fig. 2. ^{1}H NMR spectra in $CDCl_3$ of a mixture of phenolic compounds guaiacol (G), eugenol (E) and 4-methyl catechol (C), (a) before and (b) after methylation (using DMC and [BMIM]Cl) to their methoxy analogues.

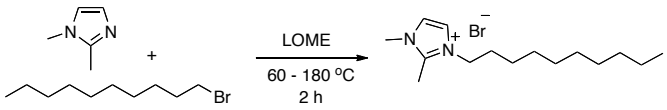
The methylated crude LOME fractions collected after SFR (Path 2) were pooled and passed through a plug of silica and eluted with 2:3 ethyl acetate: hexanes. Repeating this resulted in removing unidentified heavier fractions which constituted 5 wt% of the total crude product. After removal of the ethyl acetate:hexanes, the pure LOME can be used without further purification as an aprotic solvent. Highly viscous oil was left over in the SFR feed chamber and was recycled and stored at 7 °C. This fraction was saved to add it to the front end of the microwave pyrolysis process.

Table 2. LOME constituents, their boiling points and individual uses as precursors and intermediates in various areas.[13-16]

Compounds	Boiling points (°C)	Uses
anisole	154-155	Cosmetics ingredient, precursor to perfumes, pharmaceuticals and insecticides, flavouring agent
o-methylanisole	170-172	in herbicides such as NK-409
p-methylanisole	174-175	synthesis of Cacalol
2,3-dimethylanisole	195-196	pharmaceutical intermediate
o-homoveratrole	202-203	Food additive and drug intermediate
veratrole	206-207	Pharmaceutical intermediate
homoveratrole	220-222	Anticonvulsant
4-ethylveratrole	226-228	Tea and coffee aroma, fragrance

Although the individual components of LOME each have value (Table 2). it is not easy to separate them by fractional distillation due to the similar boiling points of the component (150-230 °C). However, the mixture is a valuable bio-derived

aprotic alternative solvent that could potentially replace hazardous and toxic polar aprotic solvents. The European REACH regulation has targetted DMF, NMP, and DMAc for replacement.[24-26] DMSO is in some cases a viable alternative but has a high melting point and significant corrosivity.[24]



Scheme 3. Menschutkin reaction of 1,2-dimethylimidazole and 1-bromodecane using LOME as an aprotic solvent system.

A series of Menschutkin reactions[21] were conducted at several temperatures with LOME, DMF and DMSO as aprotic solvents (Table 3). All the tested conditions with different solvents resulted in good to excellent yields. Among the three solvents, LOME has the highest boiling point (190-195 °C). Higher temperature reactions gave shorter reaction times, higher yields, and purer products compared to the low temperature reactions (≤ 100 °C). Because LOME has a slightly higher refluxing temperature, it gave the highest yield. Because LOME is very sparingly soluble in water at room temperature and not soluble in ice-cold water, the crude product mixture can be separated by pouring into ice-cold water and decant the LOME layer. This simple work-up is not possible with DMF and DMSO because they are water-miscible. The product then can be recrystallized from ethyl acetate to give pure products. The purity was checked by NMR spectroscopy (supporting information) and 98% of the LOME was recovered and recycled for further use as a solvent. The 2% solvent loss is likely due to slight solubilization of the LOME into the water by the Menschutkin product acting as a hydrotrope. All the reactions were done in triplicates and reported as the average.

Table 3. Menschutkin reaction conditions such as temperature, time along with yields summarized for a series of experiments with LOME, DMF, and DMSO as aprotic solvents.

T, °C	Time for completion of the reaction, h			Yield[a], %		
	LOME	DMF	DMSO	LOME	DMF	DMSO
60	24	26	20	89	88	85
100	16	15	16	90	91	88
140	6	8	6	92	90	89
190	2	N/A	N/A	95	N/A	N/A

[a]Average of three experiments. Standard deviations range from 0.3 to 0.7.

Whether LOME is a greener solvent than DMSO or DMF is a complex question. LOME is bio-derived except for the DMC which can be prepared from methanol and CO_2. LOME and its individual components have much lower water-miscibility than DMSO and DMF, which reduces the problems of separating it from water. DMF is hepatotoxic and embryotoxic.[27] DMSO has a high melting point, corrosivity and is, at high concentrations, a teratogen.[28] Less is known about the components of LOME; none are known to be reproductive toxins or known or suspected of being carcinogens but that may be more to do with a lack of scrutiny than a lack of actual hazard. In terms of acute toxicity, most of the components have comparable LD_{50} (rat) values to DMF except veratrole which has an LD_{50} of 890 mg/kg and several other components have never been tested. Therefore, while LOME has some advantages including sustainability, low water solubility, and excellent performance in the test application, it is not yet possible to claim that LOME is greener than DMSO and DMF; further study is needed.

LOME also represents a more sustainable aromatic solvent. Among aromatic solvents, anisole is the only one recommended by most green solvent guides,[29] but anisole is made industrially from fossil fuels.[15] LOME could serve as a sustainable replacement for anisole and other aromatic solvents such as xylenes or toluene.

LOME has a solvatochromic E_T^N value of 0.34, which indicates a polarity and proticity (E_T^N is a measure of both) greater than those of common aromatic solvents such as anisole and toluene (0.20 and 0.10)[30] but below those of DMF and DMSO (0.39 and 0.44).[30]

Experimental

Materials, equipment and methods

Softwood Kraft lignin (raw material for pyrolysis oil) was obtained from FPInnovations. Lignin was subjected to microwave pyrolysis at Ecole Polytechnique de Montreal, Quebec, Canada as reported earlier.[5] Propylbenzene (internal standard for GC-MS and GC-FID), guaiacol, dimethyl carbonate, [BMIM]Cl, potassium carbonate, 1,2-dimethylimidazole, 1-bromodecane, Reichardt's dye, 4-nitroanisole, guaiacol, eugenol and 4-methylcatechol were purchased from Sigma-Aldrich and used as received. HPLC grade methanol, ethyl acetate, hexanes, isopropanol, DMF and DMSO were purchased from Fisher Chemicals. Chloroform-D was purchased from Cambridge Isotope Laboratories. CO_2 and argon gas cylinders were purchased from Praxair Inc. High pressure CO_2 pump (ISCO model 500D or JASCO PU 980) and a JASCO backpressure regulator (model 880-81) were used for SFR extractions. The details of the SFR equipment were reported earlier.[8] GC analyses were performed using a Clarus 680 from Perkin Elmer. NMR spectra were acquired using a Bruker Avance 500 MHz NMR spectrometer. LOME constituents and Menschutkin reaction products were analysed/followed by ^1H and ^{13}C NMR spectroscopy and their chemical shifts were matched with the reported literature values.

Synthetic and extraction procedures

General method of methylations using dimethyl carbonate and [BMIM]Cl. The methylation reactions were performed by modifying the method reported by Shen et al.[10] In a typical reaction for a pure phenol, one equivalent of phenol and three equivalents of DMC were added under nitrogen and stirred at room temperature until all the phenol was dissolved. [BMIM]Cl (0.1 equivalent) was added in one portion under nitrogen and stirred until it dissolved into the DMC. For the methylation of LPO, for each gram of LPO, 2.5 mL of DMC was used along with 0.25 g of [bmim]Cl. The reaction mixture was heated to 80 °C for 16 h. The contents were then cooled to room temperature and the reaction completion was confirmed by GC-MS and GC-FID. The mixture was allowed to settle and the DMC was decanted and distilled so that it could be used again. The solid methylated residue was washed with ice-cold water to remove the ionic liquid and dried under vacuum. The crude sample was characterized using GC-MS and quantified using GC-FID and then subjected to SFR as is. A batch of 5.62 g pyrolysis oil gives about 4.22 g of methylated residue (before SFR).

General method for supercritical fluid rectification. The SFR of crude LPO (path 1) was performed as reported earlier.[8] For the SFR of methylated LPO (path 2), the SFR line was rinsed a few times with methanol (reagent grade) and purged with CO_2 before the sample was loaded. The preheater coil and the extractor were heated to 35 °C. A 4.22 g sample of methylated LPO was placed into the extractor and CO_2 at a pressure of 7 MPa was passed through the extractor at a flow rate of 9 mL/min of CO_2 and up through the packed rectification column, which had a temperature gradient of 55-95 °C up the column. The extract weighed 1.11 g (26% yield). Higher pressures and flow rates (8 MPa and 10 mL/min of CO_2) as reported in our earlier publication[8] for single ring phenols are not recommended for the methylated LPO because they gave lower selectivity of up to 78 wt% of methylated products. Fractions were collected after every 100 mL of CO_2 and characterized using GC-MS and FID as described elsewhere.[5]

GC-MS and GC-FID analysis. Single ring phenols, veratroles, and anisoles were identified and quantified by GC-MS and GC-FID, respectively. The GC-MS was a PerkinElmer Clarus 680 Gas Chromatograph, a Clarus 600T Mass Spectrometer, capillary column Elite-5MS 30 m x 0.25 mm x 0.25 µm film thickness; injector temperature 280 °C; helium carrier gas with a flow rate of 1.5 mL/min; split ratio 1:33; ion source 250 °C with EI of 70 eV; the MS scan range m/z 50-600. The oven was held at 60 °C for 2 min and then gradually increased in temperature at a rate of 4 °C/min to 250 °C, with a dwell time of 20 min (slightly modified from Song et al.[31] The identification of the individual compounds was performed by comparison with the reported spectra in the NIST MS Library.[32] The samples were dissolved in HPLC grade methanol and passed through a 30 mm, 0.22 µm nylon syringe filter before being injected into the GC-FID. The GC column and conditions were: PerkinElmer Col-Velocity-5 30 m x 0.25 mm x 0.25 µm film thickness; injector temperature 280 °C; detector temperature 280 °C; carrier gas helium; split ratio 1:50. The oven was held at 60 °C for 2 min and then gradually increased in temperature at a rate of 4 °C/min to 250 °C, with a dwell time of 20 min (slightly modified from Song et al.).[31]

General method for Menschutkin reactions. To a 2 mL sample of LOME (made via path 2), 1,2-dimethylimidazole (0.15 g, 1.61 mmol) was added and stirred for a few minutes until dissolved. To this solution, 1-bromodecane (0.37 mL, 1.79 mmol) was added in a single portion. The reaction mixture was heated to 60-190 °C depending on the experiment. The progression of the reaction was monitored by ^{1}H NMR spectroscopy by following the methylene proton signals next to the halogen of 1-bromodecane and by matching the product peaks to the literature reported chemical shifts. The reaction was stopped after completion by cooling of the reaction mixture to room temperature and addition of ice-cold water. After the LOME was removed by decantation, the product was extracted from the water with ethyl acetate. The crude was recrystallized from ethyl acetate and acetone (9:1) twice to remove any excess 1,2-dimethylimidazole impurity. Yields are given in Table 3.

Method for determination of the E_T^N value. After removal of MeOH from LOME under reduced pressure, the LOME was dried under vacuum for 5 h with continual stirring, and flushed with Ar twice during this period. UV visible spectroscopy using an Agilent 8453 spectrometer was used to determine the Dimroth-Reichardt parameters for LOME. Initially, a few mgs of the solid dye was dissolved in *ca.* 1 mL of LOME to generate an intense green solution, and this was used as a stock dye solution. In a representative experiment, a quartz cuvette (McCarthy Precision Cells, type 2) with a path length of 10 mm was filled with dry LOME, and the stock dye solution was added to it dropwise. The spectrum of the LOME was monitored between two successive additions, and the absorption at the highest wavelength recorded. Spectra at absorption values of *ca.* 0.5, 1.0, and 1.5 at the longest absorption wavelength were selected for the purpose of Dimroth-Reichardt parameter calculation. Finally, the sample was discarded, the cuvette was washed and dried, and the experiment was repeated with a fresh volume of dry LOME. Background correction was performed using the spectrum of neat dry LOME in the absence of the dye.

The spectra were plotted in an Excel spreadsheet, and the wavelength corresponding to the maximum absorption at the highest wavelength were determined *via* curve-fitting at three different absorption values. These wavelengths were then averaged to generate the λ_{max} for LOME. The following equations were used to determine the E_T30 (in kcal mole^{-1}) and E_T^N values for LOME:

$$E_T(30) = \frac{28591.5}{\lambda_{max}}$$

$$E_T^N = \frac{E_T(30) - 30.7}{32.4}$$

Conclusions

We present a 3-step process of pyrolysis, methylation, and supercritical fluid rectification for the transformation of softwood Kraft lignin to LOME (Lignin pyrolysis Oil Methyl Ester), a mixture of veratroles and anisoles. LOME is a bio-derived aprotic solvent that could serve as an alternative to toxic or hazardous aprotic solvents that are currently used in applications such as media for organic synthetic reactions. The Menshutkin reaction, which was used as an example application, proceeds in LOME with comparable rates and yields as in DMSO and DMF, solvents that have known issues of mutagenicity, reproductive toxicity, and high water miscibility. Unlike most bioderived solvents, LOME is also an aromatic solvent

Acknowledgements

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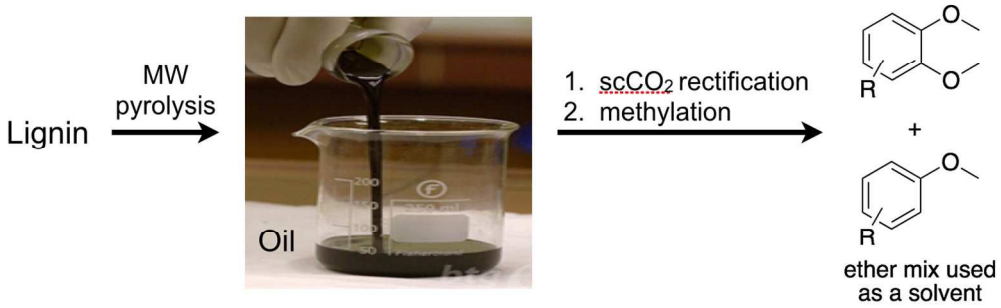
1

Lignin can be converted by pyrolysis, supercritical rectification, and methylation, into an aromatic bio-derived solvent.



546x184mm (72 x 72 DPI)