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Cascade production of lactic acid from universal types of sugars catalyzed by lanthanum triflate

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Abstract: Lignocellulosic biomass conversion to value-added platform chemicals in the non-toxic, water-tolerant Lewis acid, and water solutions bears the hallmark of green chemistry. Lactic acid derived from biomass is an important chemical building block for biodegradable polymers such as polylactide. Herein, a universal method of converting lignocellulosic sugars to lactic acid using catalytic amount of water-stable Lewis acid La(OTf)3 is demonstrated. The lignocellulosic sugars studied in this work include 1) pyrolytic sugars from pyrolysis oil, and 2) sugars derived from ionic liquid (IL)-pretreated biomass. Under moderate conditions (250 °C, 1 h), levoglucosan (major pyrolytic sugar), glucose and xylose were converted to lactic acid with the carbon-based molar yields of 75%, 74% and 61% respectively. Furthermore, ~49 mol% (based on levoglucosan) and ~74 wt% (relative to pretreated biomass) of lactic acid were obtained from the conversion of pyrolytic sugars and sugar rich fraction after lignin removal from switchgrass, respectively. To the best of our knowledge, this is the first time to convert pyrolytic sugar into lactic acid by chemocatalysis and also lignocellulosic sugars are converted to lactic acid without hydrolysis. This approach could potentially be extended to other lignocellulosic sugars after simple removal of lignin from biomass pretreatment, rendering moderate to high yields of lactic acid.

Introduction

Lactic acid is on the list of the U.S. Department of Energy's top chemical opportunities from carbohydrate.^[1] The market for lactic acid is increasing rapidly due to the expanding use of lactic acid to produce renewable and biodegradable platform solvents and plastics such as methyl lactate and polylactide.^[2,3,5] The current process of lactic acid production is dominated by fermentation.^[6-10] However, the sugar sources suitable for fermentation are typically monomeric sugars, which necessitate an additional hydrolysis step so as to break down cellulose and hemicellulose into monomeric sugars like glucose and xylose. In contrast, catalytic process to produce lactic acid offers high reaction rates and simple separation process of products.^[2] The

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mechanism of sugar conversion into lactic acid was suggested as retro-aldol condensation and 1,2-intramolecular hydride shift.^[4,11] This retro-aldol condensation was typically rendered by alkaline conditions, but faced the problems of low yield and selectivity for lactic acid with side products including formic acid, malonic acid and acetic acid.^[16] Moreover, the formation of lactic acid salt in alkaline condition makes the separation and purification of lactic acid more difficult. It is thus necessary to develop methods that can result in high yield and selectivity of lactic acid in neutral condition. The pioneer work by E. Taarning et al., demonstrated conversion of sugar to methyl lactate in up to 68% yield using Lewis acidic zeotypes, such as Sn-Beta.^[3,12] By introducing alkali salts, the yield of methyl lactate was further enhanced to 75%.^[13] M. E. Davis et al. combined catalysts for retro-aldol condensation and catalysts for 1,2-hydride shift to achieve efficient lactic acid and alkyl lactate production at milder temperature around 100 °C.^[4] Metal ions were suggested to stabilize the reaction intermediate during the retro-aldol condensation and catalyze further dehydration and tautomerization to lactic acid in the neutral environment.

Recently, non-edible cellulose conversion to lactic acid has become the major interests of many researchers because it serves as a platform chemical for the production of variety of chemicals and polymers.^[14-16] B.F. Sels reported 60% yield of total esters from cellulose catalyzed by tin triflate in methanol at 200 °C after 4 h.^[17] Wang *et al.* reported 68% yield of lactic acid from ball-milled cellulose catalyzed by Lead (II) ions in aqueous solution at 190 °C after 4 h.^[14] Following researches by Dong *et al.* reports higher yields of lactic acid (up to 90 %) from cellulose rendered by homo- and heterogeneous lanthanide ions, and Lin et al. utilized a series of heterogeneous catalysts including $ZrO_2^{[18a]}$ and $LaCoO_3^{[18b]}$ for hemicellulose conversion to lactic acid, affording up to 42 mol% and 30 mol% of lactic acid from xylose and xylan respectively.

However, very few reports focused on the direct conversion of cellulosic biomass to lactic acid, considering the complexity of biomass structures (e.g., cellulose, hemicellulose and lignin), and the possibility of catalyst deactivation caused by lignin.^[19] Thus, a fast and direct approach for biomass conversion to lactic acid is highly desired. Herein, we demonstrate two strategies of directly converting lignocellulosic biomass to lactic acid in the presence of La(OTf)₃ after simple lignin removal by pyrolysis or IL pretreatment. La(OTf)₃, a Lewis acid catalyst, has attracted considerable interest because it is stable in both aqueous and organic solvent. Considering that conventional Lewis acids such as AlCl₃, BF₃, SnCl₄ decompose or are readily deactivated in the presence of water, La(OTf)₃ is a relatively user-friendly catalyst.^[10a]

Results and Discussion

Conversion of pyrolytic sugars to lactic acid

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Pyrolysis introduced a fast way of separating sugars, lignin and volatile compounds in biomass (Scheme 1). In this process, fast pyrolysis occurs in a couple of seconds,^[20] and biomass was converted to pyrolysis oil through fast pyrolysis upon rapid quenching. The pyrolysis oil can be fractionated by the difference of their volatilities. Pyrolytic sugars can be extracted from heavy ends by simple water washing. Other fractions of this reaction, including water-insoluble fraction of heavy ends (*e.g.*, pyrolytic lignins) and light ends, can be upgraded to fuels and chemicals typically through hydrodeoxygenation.^[21] Herein, we have demonstrated an efficient way of converting neat pyrolytic sugars to lactic acid in one-pot process by La(OTf)₃ without time-consuming purification of pyrolytic sugars (Scheme 2).



Scheme 1. Lignocellulosic biomass upgrading through fast pyrolysis.

Sugar contents of pyrolytic sugars were analyzed first and the most abundant sugar component was found to be levoglucosan (66% of all the sugars in the water stream, Table 1 and Figure 1). In particular, levoglucosan was accounted for 9.6 wt% in heavy fraction of pyrolysis oil, while the total sugars (e.g., levoglucosan, cellulose, cellobiosan etc.) were measured to be 14.5 wt%. Therefore, we selected levoglucosan as the model compound for initial study to represent as surrogate of pyrolytic sugars.^[22]

Table 1. Sugar co	ontents in the water stream of pyrolysis oil	
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Entries	Sugars	Weight percent in pyrolysis oil (%)
1	Levoglucosan	9.6±1.0
2	Total sugars ^[a]	14.5±0.2

^[a]Total sugars were measured by HPLC as the sum of glucose and xylose after hydrolysis of the water stream of pyrolysis oil. ^[23]



Figure 1. HPLC Trace for the water stream of pyrolysis oil showing levoglucosan is the major compound in the water stream.

Previously, levoglucosan conversion is mainly through biological fermentation to valuable products such as lactic acid^[24-26] and ethanol.^[25,27-29] Catalytic routes have not been reported. In theory, levoglucosan could be directly converted to lactic acid through cascade reaction of first step hydrolysis to glucose, followed by glucose conversion to lactic acid. Lewis acids based on lanthanide were shown to be effective for cellulose conversion to lactic acid, in which cellulose was first hydrolyzed to glucose.^[10] We therefore tested applicability for levoglucosan conversion to lactic acid through similar cascade reaction of levoglucosan to glucose followed by glucose to lactic acid (Scheme 2). In this scheme, levoglucosan was hydrolyzed to glucose, followed by further isomerization to fructose catalyzed by Lewis acid. The cleavage of C₃-C₄ bond through retro-aldol condensation resulted in the formation of lactic acid (Route 1). Our preliminary results showed that levoglucosan was converted to lactic acid with yield of 75 % at 250 °C within 1 h. The resulting products were predominantly lactic acid, with trace amount of impurities and no char formation. It is worth noting that another possible reaction leads to the formation competing of 5hydroxymethylfurfural (HMF, Route 2), considering this reaction was self-catalyzed under elevated temperatures.^[30] However, we observed only low amount of HMF (<10 mol%) produced during the levoglucosan conversion, indicating our catalytic system is highly selective towards lactic acid.



Scheme 2. Proposed mechanism of aldo sugars conversion to lactic acid in the presence of Lewis acid. [M]ⁿ⁺ represents metal cations, and La³⁺ herein. Route **1** represents the retro-aldol condensation catalyzed by Lewis acid, and Route **2** represents the dehydration catalyzed by Brønsted acid.

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In order to validate our proposed mechanisms, we characterized the various products formation (e.g., glucose, fructose, lactic acid and HMF) at different temperatures under otherwise identical conditions. As shown in Figure 2, almost 40% of levoglucosan was converted at 150 °C in 1 h, yielding 16% and 3% yields of glucose and fructose respectively. Meanwhile, no lactic acid formation and trace amount of HMF (0.7%) were observed. This indicated that during the whole process, the retro-aldol condensation of fructose leading to lactic acid is the rate-limiting step, and the formation of HMF appeared to be unavoidable. If higher temperature was applied, higher yields of lactic acid were obtained. When the temperature increased to 250 °C, up to 75% yield of lactic acid was obtained. For levoglucosan, the conversion increased fast as the temperature increased. Total conversion of levoglucosan was achieved at 170 °C within 1 h. The yields of glucose and fructose due to the hydrolysis and following isomerization of levoglucosan were observed to have the trend of increase-and-decrease as the temperature increased, with maximum yields (34% and 7% respectively) at 160 °C. In addition, we compared the yield and selectivity of lactic acid from glucose and fructose at 180 °C. 61% yield and selectivity of lactic acid were obtained when the starting substrate was fructose. On the other hand, only 38% yield and 39% selectivity of lactic acid were obtained when the starting substrate was glucose under the same conditions. This further confirms that fructose is the intermediate of glucose to lactic acid.

The competing reaction during lactic acid production is the formation of HMF due to fructose dehydration (Scheme 1, Route 2). We have observed the formation of HMF during the levoglucosan conversion. As shown in Figure 2, HMF yield was accumulated from 0.7% at 150 °C up to 8.7% at 170 °C, followed by the gradual decrease at elevated temperatures. This is presumably because 1) the formation of HMF is autocatalyzed in the presence of its degradation products $^{\left[30\right] }$ and 2) higher temperature renders oligomerization of HMF to form humins, which will consume HMF and form precipitates at high concentrations.^[31] The humins are complex and recalcitrant carbonaceous materials produced during the acid-catalyzed conversion of biomass, which is undesired. The formation of humins is undesired since they can possibly absorb lactic acid and thus lower the HPLC yield of lactic acid after filtration. The formation of humins was more significant when the loading of La(OTf)₃ relative to levoglucosan was lower than 14 mol%. For example, only 26% yield of lactic acid was obtained when the La(OTf)₃ loading decreased to 2.8 mol%, while a even lower yield (14%) was resulted from 1.4 mol% loading of the catalyst. Higher loading of levoglucosan with fixed loading (e.g., 14 mol%) of La(OTf)₃ also resulted in lower lactic acid yield (30% yield from 5g/L of levoglucosan and 20% yield from 10 g/L levoglucosan). When CO₂ gas was pressurized in the reactor to introduce a weak Brønsted acid (Carbonic acid, H₂CO₃), lower yield of lactic acid was obtained compared with those in N₂ atmosphere. And precipitations were observed in the resulting solution due to the further decomposition and polymerization of HMF at higher temperatures.^[32] The addition of Brønsted acid, even the weak acid, could divert the reaction towards sugar dehydration to HMF and insoluble humins. Control experiments (lactic acid as the reactant) under otherwise identical conditions revealed that there was no degradation of lactic acid under N₂ atmosphere. Future research direction will be to develop efficient catalysis to promote retro-aldol condensation to lactic acid while suppressing the dehydration reaction leading to HMF.



Figure 2. Levoglucosan conversion to lactic acid at different temperatures for 1 h with levoglucosan loading at 1 g/L and La(OTf)₃ at 14 mol%.

Encouraged by the discovery that La(OTf)₃ was an effective catalyst for levoglucosan-to-lactic acid conversion, we investigated the catalyst performance on the real pyrolytic sugars. The water solution of pyrolytic sugars showed to be acidic (pH \approx 3) due to the presence of water-soluble acidic compounds.^[28] Considering the negative effect of Brønsted acid on the production of lactic acid, we neutralized the pyrolytic sugar solutions using NaOH. Under the same conditions as previously described for levoglucosan conversion (250 °C, 1 h, 14 mol% La(OTf)₃ relative to levoglucosan, 20 bar N₂), we observed a moderate yield (49±1% based on levoglucosan) of lactic acid from neat pyrolytic sugar solution. In contrast, no yield of lactic acid was obtained if the pyrolytic sugar solution was not neutralized. In addition, same experiment was conducted under basic condition to examine the effect of pH change on lactic acid production. The pyrolytic sugar solution was further adjusted to pH 9 using NaOH, which resulted in 43% yield of lactic acid. Although the yield is similar as that rendered by using La(OTf)₃ as the catalyst, alkaline environment generates lactic acid sodium salt, which could cause problems in product separation and purification.

Lactic acid production from sugars after IL pretreatment

In lignocellulosic biomass, the presence of lignin (phenols especially) might deactivate Lewis acid catalysis, based on the observation that phenols could form a stable complex with the coordination metal of Lewis acid, and thus block the active site for catalysis.^[33] Therefore, it is necessary to reduce the lignin amount via pretreatment for further sugar conversion to lactic acid. In our well established IL pretreatment process, lignocellulosic biomass was pretreated with different types of IL,

such as $[C_2C_1Im]OAc$,^[34] protic $IL^{[35]}$ or cholinium lysinate [Ch][Lys],^[34,36] the sugar rich fraction was obtained by water wash and freeze-dried.



Scheme 3. Lignocelulosic biomass upgrading through IL pretreatment.

By pretreatment of switchgrass using [Ch][Lys] IL at 140 $^{\circ}$ C for 3 h, lignin content was significantly reduced from 21.8% to 9.2%. Meanwhile, glucan and xylan contents increased from 32.2% and 20.0% to 47.8% and 23.6% respectively. (Table 2)

Table 2. Chemical composition of dominant components in the switchgrass and solid recovery $^{[a]}$

Conditions	Solid Recovery (%)	Glucan (wt%)	Xylan (wt%)	Lignin (wt%)
Untreated SG	-	32.2±0.1	20.0±0.1	21.8±0.2
10% IL, 3h	63.2	47.8±0.7	23.6±1.0	9.2±0.3

^[a]Pretreatment conditions: 10% biomass loading, [Ch][Lys]: H₂O=10:90 wt:wt, 140 °C. Composition analysis followed NREL acidolysis protocols (LAP) LAP-002 and LAP-005.^[37]

Besides C₆ sugars, there are a variety of C₅ sugars, such as xylose, in the lignocellulosic biomass. We believe xylose could be also converted to lactic acid through isomerization and retroaldol condensation (Scheme 3, Route 1). In this scheme, xylose was isomerized to xylulose in the presence of Lewis acids. The C3-C4 bond of xylulose was cleaved in the following retro-aldol condensation, resulting in lactic acid production. Under the same conditions as those of levoglucosan, 61% yield of lactic acid was achieved for xylose conversion in the presence of La(OTf)3 at 250 °C in 1 h. It is noteworthy that C2 chemicals (such as glycolaldehyde) were generated as the side products of retroaldol condensation of xylose. If glycolaldehyde remained unconverted to lactic acid, the maximum yield of lactic acid from xylose should be no more than 60 mol% based on the amount of carbon. It is therefore very likely that glycolaldehyde is converted to lactic acid. Indeed, from glycolaldehyde, we observed the formation of lactic acid at 26% yield. It is believed that alvcoaldehvde could go through self aldol-condensation to C₄ or C₆ sugars, and then through retro-aldol condensation to form lactic acid.^[12] Another possible degradation pathways of xylose have been previously reported is furfural production due to

fructose dehydration rendered by Brønsted acid (Scheme 3, Route 2).^[38] Interestingly, no formic acid and furfural were observed in our process, indicating our approach offers high selectivity towards retro-aldol condensation towards lactic acid production.



Scheme 3. Proposed mechanism of xylose conversion to lactic acid in the presence of Lewis acid. [M]ⁿ⁺ represents metal cations, and La³⁺ herein. Route 1 represents the retro-aldol condensation catalyzed by Lewis acid, and Route 2 represents the dehydration catalyzed by Brønsted acid.

We further investigated xylose to lactic acid conversion profiles at different temperatures (Figure 3), which clearly illustrates that xylulose (isomerization product from xylose) was formed even at low temperatures (120 °C), but the production of lactic acid was not observed. This indicated that retro-aldol condensation leading to lactic acid was the rate-limiting step compared to isomerization, which was similar as we observed for levoglucosan conversion described above. When the temperature increased to 180 °C, xylose and xylulose were completely converted, with continuous increase of lactic acid as a function of temperature.



Figure 3. Comparison of HPLC chromatograms of xylose conversion at different temperatures after 1 h with 1 g/L xylose solution in the presence of 14 mol% La(OTf)₃.

La(OTf)₃ was also applied to the conversion of other representative C_5 and C_6 sugars to lactic acid as indicated in Table 3. C_6 sugars, including levogluocsan, glucose and cellulose as discussed previously, showed similar lactic acids



yield (~75%) at similar reaction conditions (Entries 1, 2 and 3). This indicates that hydrolysis is not the rate-limiting step of lactic acid production. Xylose showed a lower lactic yield due to the formation of glycolaldehyde (Entry 4). If La(OTf)₃ was applied to the conversion of sugar rich fraction after IL pretreatment (mainly glucan and xylan, Entry 5), high yield of lactic acid was obtained at 72% (based on pretreated biomass) at 250 °C for 1 h. This is advantageous compared with biological route towards lactic acid production since biomass after simple lignin removal could be directly used as the resource without the need for expensive enzymatic saccharification step. It is highly desirable from the techno-economic standpoint. As depicted in Scheme 3, sugar rich fraction was obtained by simple filtration after biomass pretreatment using IL to remove lignin. Lactic acid was produced directly from the sugar rich fraction. Herein, we suggested an alternative way of producing lactic acid from lignocellulosic biomass, in addition to general methods of lactic acid production through time-consuming fermentation of edible C₆ sugars.

Table 3. Conversion of carbohydrates to lactic acid.^[a]

Entries	C_5 and C_6 sugars	Lactic acid yield (mol% Carbon)
1	Levoglucosan	75
2	Glucose	74
3	Cellulose	73
4	Xylose	61
5	Sugar-rich biomass	72 ^[b]
6	Pyrolysis oil	49 ^[c]

[a] Reactions were carried at 250 °C for 1 h with 1 g/L xylose solution in the presence of 14 mol% La(OTf)₃. ^[b]Cellulose and hemicellulose rich precipitates after IL pretreatment, yield is calculated by the weight percentage of lactic acid and sugar-rich biomass. ^[c]Water stream after water wash, yield based on levoglucosan.

Conclusions

In this work, we report a universal method of converting lignocellulosic sugars (C5 and C6 sugars) to lactic acid with high yield and selectivity in the presence of La(OTf)₃. C₆ sugars, including levoglucosan, glucose and cellulose, were converted to lactic acid in >70 % yield, while C_5 sugars, such as xylose, was converted to lactic acid in the yield of 61%. Based on this discovery, two efficient methods of converting lignocellulosic biomass to lactic acid were revealed. The first method is the fast pyrolysis combined with retro-aldol condensation of pyrolytic sugars, producing ~49 % of lactic acid (based on levoglucosan). The second method is the IL pretreatment combined with retroaldol condensation of sugar rich fraction, producing lactic acid in yield (relative to sugar rich fraction). ~72% These demonstrations of lactic acid production could be applied to other pretreated biomass after simple lignin removal process

(e.g., acid, base and organosolv, *etc.*) and thus have important implications of bio-refinery for lignocellulosic biomass.

Experimental Section

Materials: Cellulose (Avicel PH-101), xylose, levoglucosan, glucose and _{DL}-lactic acid (85%) were purchased from Sigma Aldrich. La(OTf)₃ was purchased from Alfa Aesar. Cholinium lysinate was synthesized according to the literature, [39] and used after drying under vacuum. Pyrolysis oil, so-called bio-oil, was produced from the fast pyrolysis of red oak using a pyrolysis development unit (PDU) at Iowa State University.^[40] Switchgrass was grown near Guymon (OK, USA) and was harvested in October 2010. Both of these materials were delivered to Idaho National Laboratory (INL; ID, USA) in the form of 3 × 4 × 8 ft. bales and have been stored since delivery under tarps. These materials were used after milling (≤ 2 mm size). Lactic acid was analyzed using Agilent 1200 HPLC with Aminex HPX-87H column (0.6 mL/min, 60 °C, 4 mM $H_2SO_4,\,30$ min). The injection volume was 20 μL with a run time of 30 min. In all of our systems unless specified, we did not observe the unconverted sugars, assuming the sugar conversion is 100%, and the product selectivity equals to the product yield.

Compositional analysis: Acid-insoluble lignin and structural carbohydrates (including glucan, xylan, arabinan, galactan and mannan) before and after pretreatment were determined according to the two-step acid hydrolysis procedure following NREL acidolysis protocols (LAP) LAP-002 and LAP-005,37 and as reported in our previous work.^[41] Briefly, 200 mg of biomass and 2 mL of 72% H₂SO₄ were incubated at 30 °C while shaking at 300 rpm for 1 h. The solution was diluted to 4% H₂SO₄ with 56 mL of DI water and autoclaved for 1 h at 121 °C. The reaction was quenched by placing samples into an ice bath before removing the biomass by filtration. Carbohydrate concentrations were determined from the filtrate using an Agilent HPLC 1200 Series equipped with a Bio-Rad Aminex HPX-87H column and a Refractive Index detector. An aqueous solution of H_2SO_4 (4 mM) was used as the mobile phase (0.6 mL min⁻¹, column temperature 60 °C). The injection volume was 20 µL with a run time of 25 min. Acid insoluble lignin was quantified gravimetrically from the solid after heating overnight at 105 °C (the weight of acid-insoluble lignin + ash) and then at 575 °C for at least 6 h (the weight of ash).

Extraction of pyrolytic sugars from bio-oil: In this work, heavy ends fraction of bio-oil, mostly water-soluble sugars and water-insoluble phenolic oligomers, was used as the initial material. Pyrolytic sugars in the heavy ends fraction were extracted by simple water washing.^[27] Briefly, 5 g of the heavy ends fraction of bio-oil was mixed with 10 mL of DI water. The mixture was centrifuged and the aqueous fraction was separated by decantation. The aqueous fraction was combined as water stream of pyrolysis oil, in which the amount of total sugars was measured using HPLC after hydrolysis with 400 mM H₂SO₄ at 125 °C for 45 min.^[42] The anhydro-sugars and other polymeric/oligomeric sugars in the water stream were acid hydrolyzed to monosaccharides. After hydrolysis, all samples were filtered prior to HPLC analysis.

Lignin removal from switchgrass by ionic liquids: As an example, 20 g of switchgrass was mixed with 80 g of 10 % cholinium lysinate to give a 20 wt% biomass loading. Pretreatment runs were carried out at 140 °C for 3 h in a high-pressure glass tube reactor. Duplicate runs were performed for each IL pretreatment. After pretreatment, the slurry (sugar rich fraction) was washed five times with DI water to remove the residual cholinium lysinate and lyophilized in a FreeZone® Freeze Dry System (Labconco, MO, USA). After drying, the sugar rich fraction was used for production of lactic acid.

Typical procedures for lactic acid production: In a typical experiment, levoglucosan (20 mg, 3.1 mmol) was added in a 60 mL Parr reactor, to which La(OTf)₃ (10 mg, 14 mol%) and distilled water (20 mL) was further added. The reactor was sealed, purged and pressurized to 20 bar with N₂. The mixture was heated to 250 °C within 30 min under stirring. After 1h reaction, the reactor was cooled down to room temperature. The pressure was relieved and the resulting solution was diluted to 25 mL. Approximate 1 mL aliquot was filtered for HPLC analysis. For pyrolytic sugar conversion to lactic acid, the water stream of pyrolysis oil was first neutralized by sodium hydroxide, and La(OTf)₃ was loaded at 14 mol% relative to levoglucosan in the water stream. For sugar rich biomass conversion to lactic acid, the pretreated biomass was directly used as the starting material with La(OTf)₃ loading at 14 wt%. Lactic acid yields were all based on carbon molar yield unless specified, which is calculated using the equation below:

Lactic acid yield (mol% Carbon) = $\frac{mol \ of \ carbon \ in \ lactic \ acid}{mol \ of \ carbon \ in \ sugars} \times 100\%$

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Keywords: lactic acid • retro aldol condensation • pyrolysis oil • biomass pretreatment • lanthanum triflate

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FULL PAPER

A universal method of converting lignocellulosic sugars to lactic acid using catalytic amount of $La(OTf)_3$ is demonstrated. This is the first time pyrolysis oil conversion into lactic acid by chemocatalysis is reported and also the first time lignocellulosic sugars are converted to lactic acid without hydrolysis. This approach could potentially be extended to other lignocellulosic sugars after simple removal of lignin from biomass.



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Cascade production of lactic acid from universal types of sugars catalyzed by lanthanum triflate

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