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Highly Selective Production of Propionic Acid from Lactic Acid Catalyzed by Nal

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Propionic acid (PA), a valuable chemical widely used in the food and feed industry, is currently produced from the petrochemical industry. Selective production of PA from bio-based lactic acid (LA) is difficult due to the high activation energy of the hydroxyl group at the α position of the carboxyl group. Herein, a metal-free catalytic system for the highly selective transformation of bio-based LA to PA, which was used as the solvent to simplify the separation step, is reported using NaI as the catalyst. Under optimal reaction conditions, a >99% yield of PA can be obtained from LA. A heat-induced radical-activated hydrogen mechanism was proposed based on the kinetic study and intermediate capture. The metal-free system can be reused five times without any loss in activity, and the PA product is easily separated. In addition, a two-step method using cellulose as raw material to produce PA was conducted. This strategy offers a green and efficient approach to synthesize PA from biomass resources.

Introduction

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Propionic acid (PA) is an important raw material and preservative, and has been widely used in many fields such as the chemical, medical, feed, and food industries¹. Global production of PA is estimated at ~450,000 tonnes per year with 2.7% annual growth². Currently, PA is usually produced from petrochemical resources by chemical methods through hydrocarboxylation of ethylene³, hydrogenation of acrylic acid⁴, and oxidation of propanol⁵. With the increasing depletion of fossil resources and energy shortages, it is urgent to develop a sustainable method to produce PA from renewable biomass resources. Lactic acid (LA) similar to PA in structure, has great potential to be used for PA production. LA can be produced by fermentation of corn, cellulose, sugar and sorbitol⁶ and is widely used for biodegradable poly-LA synthesis, which requires a high optical purity of LA. In addition, LA can be efficiently obtained with chemical methods using raw biomass materials such as cellulose⁷, hemicellulose⁸, glucose⁹, glycerol¹⁰. However, the key drawback of chemical methods is low optical purity of LA, which greatly limits its application. Fortunately, this low-opticalpurity LA could serve as an ideal feedstock to prepare PA.

PA production from LA lies in the selective hydrogenolysis of the α -hydroxyl group. Some previous works¹¹ used homogeneous noble metals or solid acid catalysts in the reaction temperature range of 250-400 °C. Among these works,

the maximum yield of PA reported is 50.5%, obtained by using a PtH(PEt₃)₃ catalyst^{11e} (Table 1, entry 1). Recently, Korstanje¹² used a non-noble metal (molybdenum) complex as a catalyst and obtained a 41% yield of sodium propionate at 200-270 °C (Table 1, entry 2). Subsequently, Jin¹³ reported a catalytic system with Co powder as the catalyst and Zn powder as the reducing agent to convert LA to PA in liquid-solid reaction mode, and the maximum yield of PA reached 58.8% (Table 1, entry 3). In addition, some iron oxide and MoO₂ catalysts were developed by Tang¹⁴ for this conversion, and the best result was obtained (96.8% conversion and 60.8% PA yield) by using MoO₂ at 390 °C (Table 1, entry 4). To date, as far as we know, this is the highest reported PA yield that can be directly obtained from LA.

Table 1. Production of PA from LA under different reaction conditions						
Entry	Catalysts	T(°C)	Time (h)	Conv. (%)	Yield (%)	Ref.
1	PtH(Pet₃)₃	250	0.25	97.8	50.5	11e
2	$MoO_2(acac)_2$	200-270	1.0	85.0	41.0	12
3	Co and Zn	250	2.0	~88	58.7	13
4 ^a	MoO ₂	390	/	96.8	60.8	14
5	Nal	220	6.0	100.0	> 99	This report

a: (React in an up-down tubular quartz reactor).



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The low selectivity for removing the α -hydroxy group of LA by direct catalytic hydrogenation is probably due to the fact that theoretically¹³, the reaction enthalpy of α -hydroxyl hydrogenation (Δ Hr = -118 kJ/mol) is higher than that of carboxyl hydrogenation (Δ Hr = -85 kJ/mol) (Scheme 1). Thus, a different methodology must be used to further improve the selectivity.

Hydroiodic acid is a strong reducing agent and iodide is a good nucleophilic and leaving group, which makes it good at reducing hydroxyl groups. As early as 1860¹⁵, HI was used to remove the hydroxyl group of LA to prepare PA. Recently, our work¹⁶ also reported that PA could be prepared from LA in hydroiodic acid over noble metals, which could catalyze the insitu regeneration of HI from I₂ under H₂. In the latest research, an HI/I⁻ mediated metal-free catalytic system was developed for the selective reduction of hydroxyl groups by H₂. In 2017, Vlachos and Xu¹⁷ reported that tetrahydrofuran-2,5-diformic acid could yield 89% adipic acid using approximately 4 equivalents HI acid under the synergistic effect of PA solvent/HI/H₂ without a metal catalyst. They proposed that H₂ was activated by HI. Subsequently, our group found that using 4 equivalents of NaI in 2-methyltetrahydrofuran (MTHF) as a solvent, 5-hydroxymethylfurfural could be directly reduced to 5-methylfurfural with an 80% yield in the NaI/H₂SO₄/H₂O/H₂ system without metal catalysts¹⁸. The mechanism study speculated that the main reduction process was the free radical reaction. Therefore, it is hopeful to develop an efficient metalfree method to produce PA from LA with HI acid.

Herein, we further improved the system and developed a metal-free system to convert LA to PA catalyzed by Nal. The product PA was used as the solvent to both provide acidity and simplify the product separation step. Under the optimum reaction conditions, a >99% yield of PA was obtained from LA at 220 °C for 6 h without adding extra strong acid. Compared with the previous system, the amount of I⁻ added is greatly reduced to 8 mol% equivalent. A NaI separation and recycling methodology based on the extraction of PA with cyclohexane was proposed, which makes the production process green and sustainable. Furthermore, based on reported work regarding LA production from cellulose^{7b}, a two-step process was developed to produce PA from cellulose, which provides a simple and economically feasible method to obtain PA from sustainable biomass resources. To the best of our knowledge, this is the first time that this metal-free system has been reported to produce PA from biomass with excellent selectivity and yield. The whole process is well in line with the design of a green chemistry future¹⁹.

Results and Discussion

Development of the metal-free system

First, LA was reacted with excess hydroiodic acid. LA was converted completely and yielded 62.3% PA at 180 °C for 1 h (Table 2, entry 1). The reaction solution became brownish-red after the reaction, and the presence of I₂ was confirmed by the potassium iodide-starch method. The formation of I₂ as a side product and the high concentration of HI make this reaction impractical. Therefore, the system was further improved according to the metal-free catalytic systems¹⁷⁻¹⁸ with lowconcentration of HI mentioned above. First, a system with 0.36 mmol H₂SO₄, 4 mmol NaI as the catalyst, and MTHF as the solvent was applied. However, only a 12.3% yield of PA was obtained with 48.2% LA conversion at 180 °C for 1 h (Table 2, entry 2), which was probably due to the instability of the solvent, as a small amount of the iodinated product of MTHF was detected after the reaction. When the solvent was changed to acetonitrile (Table 2, entry 3), 80.6% of LA was converted, but only an 11.6% yield of PA was obtained. This low selectivity could result from the low acidity of the system. Then acetic acid was used as the solvent (Table 2, entry 4), in which LA was completely converted, and a 70.5% yield of acetoxypropionic acid (AOPA) and 17.0% yield of PA were obtained. AOPA might be the intermediate of the reaction. Increasing the temperature to 200 °C and 220 °C (Table 2, entry 5&6), LA converted completely in both conditions and yielded 64.4% AOPA and 26.2% PA at 200 °C while 3.3% AOPA and 84.3% PA were obtained at 220 °C. Although the yield of PA is slightly higher than that obtained without using H₂SO₄, the reaction system is more corrosive due to the addition of a strong acid. After prolonged the reaction at 180 °C from 1 h to 10 h (Table 2, entry 7), all of LA was consumed to yield 54.1% PA and 28.3% AOPA. It was not a satisfactory result. Surprisingly, when only 2 mmol Nal was used without additional strong acid in the acetic acid solvent system (Table 2, entry 8), the reaction also yielded 9.8% PA and 30.7% AOPA with 43.8% LA conversion. According to previous studies¹⁶⁻¹⁸, a proton is necessary to catalyze iodide substitution of the hydroxyl group. In this reaction, the proton must come from the acetic acid. The good carbon balance under these conditions encouraged us to optimize the reaction without using extra strong acid.

First, the reaction temperature was increased to 240 °C (Table 2, entries 9-11). The yield of PA slightly increased to 23.8% at 200 °C (Table 2, entry 9) and climbed to 72.5% at 220 °C (Table 2, entry 10). Encouragingly, 96.2% PA could be obtained at 240 °C in 1 h (Table 2, entry 11). Thus, high selectivity to PA from LA was realized at a relatively low reaction temperature in our system compared with the previous literature.

To better understand the reaction system, LA conversion with 2 mmol NaI at 220 °C for 1 h was selected as the reaction conditions for the following study. First, under the standard reaction condition (Table 2, entry 10), no I_2 was detected after the reaction, which confirmed that I^- is the catalyst and H_2 is the reducing reagent. When H_2 was replaced by He (Table 2, entry 12), a 49.6% yield of PA was still obtained, but a large amount of iodine was found after the reaction, which rendered the solution brown-black. Thus, without H_2 , HI (generated by NaI in

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acidic conditions) functioned as the reducing reagent for LA reduction, which generated I_2 and led to a lower yield.

Table 2. Conversion of LA under different reaction conditions							
Entry	т (°С)	Solvent	Catalyst	Conversion (%)	Yield of AOPA (%)	Yield of PA (%)	
1	180	57wt% HI	/	100.0	-	62.3	
2 ª	180	MTHF	$Nal+H_2SO_4$	48.2	-	12.3	
3ª	180	MeCN	Nal+H ₂ SO ₄	80.6	-	11.6	
4 ^a	180	HAc	Nal+H ₂ SO ₄	100.0	70.5	17.0	
5	200	HAc	$Nal+H_2SO_4$	100.0	64.4	26.2	
6	220	HAc	$Nal+H_2SO_4$	100.0	3.3	84.3	
7 ^b	180	HAc	$Nal+H_2SO_4$	100.0	54.1	28.3	
8	180	HAc	Nal	43.8	30.7	9.8	
9	200	HAc	Nal	74.8	48.6	23.8	
10	220	HAc	Nal	97.8	25.2	72.5	
11	240	HAc	Nal	100.0	2.9	96.2	
12 ^c	220	HAc	Nal	94.2	12.6	49.6	
13	220	HAc	/	89.8	89.7	0.0	
14	220	HAc	NaCl	95.0	88.6	0.1	
15	220	HAc	NaBr	96.0	89.7	3.2	
16	220	HAc	КІ	100.0	31.8	67.2	
17	220	HAc	Lil	93.5	12.7	66.5	
18	220	HAc	Cal ₂	99.2	1.1	61.7	
19	220	HAc	Snl ₂	100.0	81.0	15.0	

Reaction conditions: LA 2 mmol, 2 mmol catalyst, 400 psi H₂, 8 ml solvent, 1 h, 500 rpm. a: added 0.7 g H₂O, 0.36 mmol H₂SO₄, 4 mmol Nal. b: 10 h. c: He was used instead of H₂

Without Nal, only AOPA was obtained in quantitative yield (Table 2, entry 13). Therefore, iodide is critical for the dehydroxylation reaction. The addition of sodium bromide or sodium chloride severely decreased the formation of PA (Table 2, entries 14-15). This is mostly because iodide is a better nucleophile and leaving group than bromide and chloride.

The influence of cations was also investigated. KI, LiI, and Cal₂ were applied respectively. Compared with Nal, a slightly lower yields of PA were produced (Table 2, entries 16-18). When Snl₂ was used, the reaction efficiency dropped dramatically due to the insolubility of Snl₂ in the system. (Table 2, entry 19). Therefore, cation has a limited effect during the reaction.

To further prove that it is indeed a transition-metal-free system, the reaction system was nitrated and analyzed by ICP-

AES after the reaction. The results showed that only Still had ne concentration higher than 1 ppm (3.212 ppm) and all the officer metals had contents lower than 1 ppm (Table S1). Thus, SnCl₂ (2.3% equivalent) was added to the reaction to check its catalytic activity, and it did not promote PA formation (Table S2). Therefore, our system is indeed a metal-free catalytic process. Effect of Nal concentration and H₂ pressure

Effect of Nai concentration and H₂ pressure

The effect of NaI concentration and H_2 pressure was further investigated. First, the NaI concentration was varied in the 0-4.0 mmol range. It was observed that the concentration of NaI had a dramatic influence on the reaction rate (Fig. 1a). The yield of PA gradually increased from 0% to 82.8% at 220 °C for 1 h when the concentration of NaI increased from 0 to 4 mmol. A high concentration of NaI can significantly increase the iodination capacity, which was also reflected in our previous work¹⁶.

Hydrogen pressure also had a great influence on the reaction. The PA yield increased slowly from 50.6% to 77.6% with H_2 pressure increasing from 0 to 500 psi (Fig. 1b), and the total carbon balance first increased and then remained constant. From saturated vapor pressure calculations, the reaction system is gaseous when the gas pressure is less than 166 psi at 220 °C. Thus, a pressure lower than 200 psi may lead to evaporation of the solvent, causing LA to self-polymerize via side reactions.

Kinetic study



Fig. 1 Effect of concentration of sodium iodide (a), pressure of H_2 (b) on LA dehydroxylation reaction. Rection condition is as follows if not stated otherwise: 2 mmol LA, 2 mmol NaI, 400 psi H_2 , 8 mL HAc, 220 °C, 1 h, 500 rpm.

To determine the reaction pathway, the product distribution with different reaction times was studied (Fig. 2). At 0 min (the time when 220 °C was reached, which requires approximately half an hour, was set as 0 min), 74% of the LA was converted to 65.0% AOPA and 7.6% PA, which showed that AOPA formation was fast. With increasing reaction time, the yield of AOPA decreased from 65.0% to 10.7% in 3 h, and the yield of PA increased to 89.2%. Finally, AOPA was completely consumed, and all the LA was converted into PA within 6 h. No other intermediates were detected during the whole process. Thus, AOPA is the intermediate of the reaction, and the conversion of AOPA to PA is the rate-limiting step.



Fig. 2 The kinetic curve of conversion of LA. Rection condition: 2 mmol LA, 2 mmol NaI, 400 psi H_2 , 8 mL HAc, 220 °C, 500 rpm.

Mechanistic study

Based on the above study and literature reports¹⁶⁻¹⁸, we speculate that LA conversion occurs through the following pathway. LA was first esterified with acetic acid (solvent) to form AOPA, which is a fast process. AOPA is relatively stable, which is why we observed a high concentration of AOPA at 0 min. Then the ester group was substituted by I⁻ (under the promotion of protons from the solvent) to form 2-iodopropionic acid (2-IPA), which is unstable and quickly hydrogenated to PA (Scheme 2). It has been reported in the literature²⁰ that organic acid addition can promote the iodide substitution of hydroxyl groups by forming ester bonds with hydroxyl groups.

To confirm this reaction pathway, model reactions with



possible reaction intermediates were conducted. Under standard conditions, with AOPA as the substrate, a 70.9% yield of PA and 0.8% yield of LA were obtained, which was similar to the results for LA (compare Scheme 3, reaction 1 and Table 2, entry 8), indicating that AOPA is an intermediate of the reaction. Since 2-IPA is too unstable to be available, 2-iodopropionate ethyl (2-IPEt) was purchased for the reduction study. Under the same reaction conditions, 2-IPEt was completely converted, a >99% yield of PA was obtained, and no iodine was detected after the reaction (Scheme 3, reaction 3). As a comparison, ethyl levulinate (LAEt) was used in the same reaction, which led to almost the same result compared with that of LA conversion. Comparing the reactions of 2-IPEt and LAEt (Scheme 3, reactions 2 and 3), it can be seen that 2-IPA is indeed a possible intermediate of the reaction and was formed by the AOPA iodination reaction, which is the rate-limiting step of this reaction.

The effective reduction of 2-IPEt with H_2 without producing I_2 requires the activation of H_2 . However, it is difficult for H_2 to dissociate without metal catalysts. Vlachos and Xu proposed¹⁷

that HI could activate H₂ to reduce α -hydroxycarboxylice acids without metal catalysts. Our recent work ¹Peported CRAE751 iodomethylfurfural, generated by iodide substitution of HMF could be homogenized to produce the 5-methyl furfural radical and iodide free radical, which could activate hydrogen to complete the hydrogenation process. In this work, it was confirmed that 2-IPEt could be directly converted to PA with 97.6% yield under H₂ without HI at 220 °C in 1 h (Scheme 3, Reaction 4), which was consistent with the radical reaction pathway.

To further confirm the free-radical process, a scavenger was used to trap potential radical intermediates. After adding four



Scheme 3. Reaction of possible intermediate. Rection condition is as follows if not stated otherwise: 2 mmol substrate, 2 mmol NaI, 400 psi H_2 , 8 mL HAc, 220 °C, 1 h, 500 rpm.

equivalents of 1,1-stilbene to the reaction under standard conditions, the yield of PA dropped sharply to 16.9% from 72.5%. Furthermore, an addition product of the PA radical with 1,1-stilbene was detected by UPLC-QTOF-MS (Scheme 4, Reaction 1; Fig. S1). These observations strongly support the proposed free-radical pathway. The PA radical was most likely generated from 2-IPA. Then, the 2-IPEt reaction was performed with 4 eq. 1,1-stilbene under H₂ (Scheme 4, Reaction 2). As expected, the PA yield dropped dramatically, and PA radicals were also detected. This result further confirmed that free radicals were generated from 2-IPA.

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Scheme 4. Intermediate capture

Another important point we would like to address is why iodide mediated metal-free reduction only happens on some specific substrates, such as 5-hydroxylmethylfurfural, tetrahydrofuran-2,5-diformic acid, or LA. We speculate that this reduction limitation is mainly related to the stability of the C-I bond at different positions. To probe this hypothesis, reaction with 3-iodopropionic acid (3-IPA) was performed (Scheme 3, Reaction 5), and it was found that only 15.0% 3-IPA was converted to PA in 1 h with almost 100% selectivity. Compared with the 2-IPEt reaction under the same reaction conditions (Scheme 3, Reaction 4), the 3-IPA reaction is much slower, which is consistent with their C-I bond energies (α C-I bond 197.8 KJ/mol²¹; β C-I bond 228.0 KJ/mol²²). Therefore, due to the lower C-I bond energy, it was easier for α -iodocarboxylic acid to be reduced under hydrogen, leading to the faster conversion of 2-IPA to PA. Based on this process, it is reasonable to infer that this method applies to general α -hydroxycarboxylic acids. This inference was further confirmed by the reaction with glycolic acid as the substrate. The glycolic acid was completely transformed in 1 h, and the equivalent acetic acid was obtained without I₂ formation (Scheme 5, Reaction 1). After the addition of 1,1-stilbene (Scheme 5, Reaction 2), the presence of free radicals was also observed (Fig. S2). Thus, this method can indeed be applied to the conversion of other αhydroxycarboxylic acids.



Based on the above experimental results, the metal-free hydrogenolysis of LA with Nal/HAc/H₂ is proposed to proceed as follows (Scheme 6). First, in HAc solvent, LA is esterified fast with the solvent to form AOPA. Then, AOPA is substituted with I⁻ to form 2-IPA, which is the rate-limiting step of this reaction. Due to its instability, 2-IPA rapidly split into PA radicals and







To test the reusability of the system, recycling experiments were carried out (Fig. 3). In this homogeneous system, each cycle followed the following procedure: (1) The reaction stopped at 200 °C after 1 h so that the yield of PA for each reaction was controlled in the range of 23.0%-24.1% to increase precision. (2) The reaction continued at 220 °C for 8 h to completely consume LA to avoid its affecting the next reaction cycle. (3) Before the start of each cycle reaction, only the reactant LA was added. After five cycles, the initial reaction efficiency was maintained. The final yield of PA was equal to the sum of that for each reaction. In addition, the reaction solution was colourless, clear, and transparent; thus, there was no formation of iodine. Therefore, the catalyst system is simple and stable, and has great potential for practical use.



Fig. 3 Recycling experiment. Initial reaction condition: 1 mmol LA, 1 mmol Nal, 400 psi H₂, 8 mL HAc, 220 °C, 1 h, 500 rpm. a: 200 °C, 1 h. b: 220 °C, 8 h. 1 mmol LA was added before the start of each "a" condition.

Simplification and expansion of the reaction

Considering that the separation of PA from acetic acid requires further distillation which causes significant additional costs, a simple system with PA as the solvent is proposed here. First, since LA itself is an organic acid, the reaction without solvent was carried out first (Table 3, entry 1). However, the high concentration of LA easily led to self-polymerization, resulting in a low PA yield (52.6%) and turbid final reaction liquid. As a result, we adjusted the strategy to use the product PA as the solvent. To find the best LA concentration, the solvent PA content was fixed at 8 ml, and the LA feed was gradually

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increased. When the amount of LA was increased from 0.2 g to 0.5 g (Table 3, entries 2-3), a quantitative PA yield was obtained. The method used to calculate the yield is described in detail in the ESI. Upon further increasing the amount of LA from 0.75 g to 1.5 g, all the LA was consumed after the reaction, but the yield of PA decreased from 94.3% to 79.2%, and the solution became more turbid (Table 3, entries 4-6). The PA recovery experiment showed that PA is stable and can be recovered well (details shown in Table S3). Therefore, the decrease in yield may be due to the polymerization of reactants rather than the instability of PA. To prevent the self-polymerization of LA, a small amount of water was added to the reaction system. It was found that after adding 0.3 g water while maintaining all other conditions unchanged, yields of 98.1% PA were still obtained from up to 1.25 g of LA (Table 3, entries 7 & 8). Further increasing the LA amount to 1.5 g led to a slightly decreased PA yield (91.9%, Table 3, entry 9). Moreover, further reducing the Nal amount to 8 mol% equivalent still maintained a good PA yield (Table 3 entry 10), which is a substantial advancement compared to previous systems. To verify the accuracy of PA yield under these conditions, the solvent to was changed to acetic acid, which is supposed to provide similar result. Analogously, LA was completely converted, and a 93.3% yield of PA was obtained (Table S4). This slight difference may be caused by the solvent. This result encouraged us to further expand the scale of the reaction.

Entry	LA/g	PA/mL	Nal/mmol	Conversion (%)	Yield of PA (%)
1ª	8.0	0	10.0	100	52.6
2	0.2	8	2.0	100	>99
3	0.5	8	5.0	100	> 99
4	0.75	8	7.5	100	94.3
5	1.0	8	10.0	100	86.5
6	1.5	8	15.0	100	79.2
7 ^b	1.0	8	10.0	100	98.9
8 ^b	1.25	8	12.0	100	98.1
9 ^b	1.5	8	15.0	100	91.9
10 ^b	1.25	8	1.0	100	99.2
11 ^c	12.5	80	10.0	100	98.8

Reaction condition: 400 psi $\rm H_2,$ 8 mL solvent, 220 °C, 10 h, 500 rpm. a: LA as solvent without add HAc. b: add 0.3 g H_2O. c: add 3 g H_2O.

A scaled-up reaction with 12.5 g (125 mmol) LA and 8 mol% Nal was carried out in a 250 mL high-pressure stainless-steel reactor with 80 ml PA as the solvent. PA (98.8% yield) was

obtained at 220 °C in 10 h (Table 3, entry 11), which is promising for practical applications. DOI: 10.1039/D0GC02676J

Another key issue is how to separate homogeneous Nal from propionic acid. After the reaction was completed (Table 3, entry 10), cyclohexane was used to extract and purify PA. Details are shown in the ESI. Since the remaining water layer containing PA and Nal after extraction can still be used, we only focused on the purity of the PA in the cyclohexane. After extraction, the cyclohexane in the organic layer was removed by rotary evaporation, and no residual Nal was detected by UPLC (Fig. S3). Thus, PA can be separated easily from the catalytic system after reaction.

Therefore, this metal-free system for converting LA to PA is efficient and is expected to be used in industrial mass production.

Preparation of PA from cellulose

Based on this metal-free catalytic system and the previous preparation method of LA from cellulose^{7b}, a two-step method to produce PA from cellulose was proposed. Under the optimal reaction conditions, an 85.1% yield of LA was obtained from cellulose in the first step, and a >99% yield of PA was obtained from LA in the second step (Scheme 7). The details of the reaction process are shown in the ESI. Thus, this metal-free system provides a cost-effective method for the production of PA from renewable resources.

Cellulose -	ErCl ₃ + 30 mLH ₂ O	он	1 eq. Nal + 8 mL PA	~
	2 MPa N ₂ , 240°C, 30min	Соон	400 psi H ₂ , 220°C, 6 h	PA COOH
	First step yield 85.1%		Second step yield >99%	
Scheme 7.	. Conversion of cellulose to	o PA with tw	o steps	

Conclusions

A metal-free catalytic method was developed to convert biomass-based lactic acid to propionic acid by using NaI and H₂ without additional strong acid with PA as the solvent. Under the conditions of low catalyst loading (8 mol%), >99% PA can be obtained from LA. A higher hydrogen pressure, temperature and Nal concentration favor this reaction. The reaction pathway was elucidated to be LA \rightarrow AOPA \rightarrow 2-IPA \rightarrow PA by contrast experiments, kinetic studies and intermediate capture. The iodination of AOPA to form 2-IPA is the rate-limiting step of this reaction, and 2-IPA easily splits into iodine radicals and PA radicals due to its low C-I bond energy, which activates hydrogen to complete the reduction process. Moreover, the metal-free system can be recycled five times without any decrease in reactivity, and the product (PA) can be easily separated from the catalyst (Nal) by cyclohexane extraction. Finally, a two-step method for converting cellulose to PA in yields of up to 85.1% was presented, demonstrating that the approach has great potential for the renewable industrial production of propionic acid. Overall, the catalytic process reported here does not require additional strong acids, metal catalysts or other solvents, and PA is easily separated, which

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provides a simple method for the chemical conversion of LA to PA and fits well with green and sustainable chemistry.

Experimental Section

Materials

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The high-pressure stainless-steel reactor, temperature controller and IKA magnetic stirring apparatus was supplied by Kemi company. 90wt% DL-LA (C₃H₆O₃), PA (C₃H₆O₂), ethyl 2iodopropionate, sodium iodide (NaI), TEMPO, lithium iodide (Lil), sodium bromide (NaBr) were purchased from Aladdin; 3iodopropionic acid (3-IPA), 2-acetoxypropionic acid (AOPA) were purchased from TCI; Acetate (CH₃COOH), cyclohexane (C₆H₁₂), acrylic acid (CH₂=CHCOOH), iodine (I₂), 1,1-Diphenylethylene, were purchased from Innochem; hexane, calcium iodide hydrate (Cal₂) were purchased from Alfa Aesar; Potassium Iodide (KI), Iodoacetic acid (I-CH₂COOH), glycolic acid (HO-CH₂COOH) were purchased from Damas-beta; Acetonitrile (CH₃CN) was purchased from MACKLIN; Sulphuric acid was purchased from Xi Long Scientific. Microcrystalline cellulose (particle size of 20 µm) was purchased from Sigma–Aldrich.

Metal-free reaction procedures

These reactions were carried out in an autoclave with a 50 ml glass liner. Typically, reactants, catalysts and solvents were put into the liner and then the liner was placed into the stainlesssteel autoclave. The stainless-steel autoclave was placed on an IKA magnetic stirring apparatus. The autoclave was purged by three cycles of pressurization/venting with H₂ (400 psi) before pressurization with H₂ (400 psi). The mixture was stirred at a given temperature for the desired time. When the reaction was stopped, the reactor was cooled with a water bath. After the reaction solution volume was adjusted with water, the chemicals in the water were analyzed by UPLC.

Analytical procedures

The aqueous phase product was qualitatively analyzed by a Waters ACQUITY UPLC H-Class. UPLC analysis method was as follows: ICSep Coregel 107H (7.8 mm*300 mm); Waters ACQUITY UPLC PDA $e\lambda$ detector and RI Detector; flow rate of 0.6 mL/min; 0.1 g/L sulfuric acid; and 65 °C column temperature; and 10 µL injection volume.

The concentration of metal ions in solution was measured by inductively coupled plasma atomic emission spectroscopy (ICP-AES, VAROEL). Before measurement, 8 ml of the solution was diluted to 25 ml, 5 ml of which was added to 10 ml of concentrated nitric acid and digested at 120 °C for 12 h.

Free radical adduct products were detected by ultraperformance liquid chromatography quadrupole time-of-flight mass spectrometry (UPLC-X500RQTOF), with an ACQUITY UPLC@BEH C18 1.7 μm (2.1 mm × 50 mm) column.

All samples were filtered to remove the solid particles through 0.22 μ m membrane filters prior to analysis.

Quantitative calculation

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The formula for calculating the conversion and evielde is new DOI: 10.1039/D0GC02676J

$$w_{LA} = \left(1 - \frac{C_{LA} \times V}{M_{LA} \times n_{LA}}\right) \times 100\%$$
$$w_i = \frac{C_i \times V}{M_i \times n_{LA}} \times 100\%$$

 w_{LA} : conversion of LA w_i: yield of product C_{LA} or C_i : LA or product concentration (g / mL) V: solvent volume n_{LA} : mole mass of LA (mol) M_{LA} or M_i: LA or product molecular mass

Conflicts of interest

There are no conflicts to declare.

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Keywords: Propionic acid • Lactic acid • Biomass • Nal • **Radical Reaction**

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