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Valorization of galactose into levulinic acid via acid catalysis

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Abstract−We applied methanesulfonic acid (MSA) as a green catalyst to produce levulinic acid (LA) from monomeric sugars. To optimize reaction factors and assess the effect of reciprocal interactions, a statistical experimental design was applied. Optimized result of 40.7% LA yield was obtained under the following conditions: 60 g/L galactose, 0.4 M MSA at 188 °C for 26.7 min. On the other hand, 66.1% LA yield was achieved under 60 g/L fructose and 0.4 M MSA at 188 °C for 36 min conditions. For the effect of combined severity factor on the LA yield from galactose, the LA yield showed a peaked pattern, which was linearly increased until a CSF 3.2 and then diminished with a high CSF. Moreover, it was closely fitted to a non-linear Gaussian peak pattern with a high regression value of 0.989. These results suggest that MSA and galactose, derived from marine red macro-algae, can potentially be applied for the conversion into platform chemicals.

Keywords: Levulinic Acid, Galactose, Methanesulfonic Acid-catalyzed Hydrothermal Conversion

INTRODUCTION

Various chemicals and materials are produced from fossil resources such as petroleum, but due to limited fossil resources, the replacement of carbon skeleton is required for the sustainable development of the industry [1-3]. New carbon skeleton such as sugar-based building blocks (platform chemicals), which have been recommended by the U.S. DOE, can be derived from various biomass sources (sugars, starches, lignocellulosics, macro- and micro-algae resources) by appropriate thermochemical and biological conversion processes [1,3-5]. These building blocks can subsequently be converted to diverse, novel and valuable chemicals or materials [3,5,6].

Among bio-based platform chemicals, levulinic acid ($C_5H_8O_3$; 4-oxopentanoic acid; LA), which has two reactive carbonyl and carboxyl groups, is a versatile chemical [4,6-9]. Owing to its functionality and reactivity, it can be converted to diverse useful chemicals, fuel additives, and polymeric materials [6-8]. Recently, it has been produced commercially by the petrochemical conversion route. By the way, it is an energy-intensive process and requires expensive feedstocks. As alternatives to the petrochemical route, various acid-catalyzed processes using renewable carbohydrates have been proposed for LA production [4,6,8,10-14]. Marine red macro-algae contain mainly agar or carrageenan as storage carbohydrates. Agar is predominantly composed of agarose (D-galactose and 3,6-anhydro-L-galactopyranose) and agaropectin (D-galactose and L-galactose) [10,15,16]. The potential of galactose for the conversion to platform chemicals has not been investigated.

In this study, to convert galactose to platform chemicals, we introduced methanesulfonic acid (CH_3SO_3H; MSA), the simplest of alkanesulfonic acids, as a catalyst. It is known as an eco-friendly and strong (pK_a=−1.9) green acid catalyst in several reactions such as condensation, solvolysis liquefaction, alkylation, and esterification [13,17,18]. In addition, it is non-oxidizing, less corrosive, low in toxicity, and biodegradable [13,17].

We investigated the possibility of producing the platform chemical LA from monomeric sugars (galactose and fructose) using MSA as a catalyst. To optimize reaction factors and evaluate the effect of reciprocal interactions, an experimental design of RSM was introduced. Finally, the efficiency of MSA as a catalyst was evaluated by combined severity.

MATERIALS AND METHODS

1. Materials

Galactose, fructose, 5-hydroxymethylfurfural (5-HMF), levulinic acid (LA), and formic acid (FA) were purchased from Sigma-Aldrich Co., Ltd. (USA). The methanesulfonic acid (Samchun Pure Chemical Co., Ltd., Korea) was of reagent grade.

2. Batch Experimental Procedure

Initially, a fixed amount of monomeric sugar and MSA was dissolved in distilled water and transferred with sufficient mixing to glass bottles. After sealing, the glass bottles were inserted into a stainless steel reactor. The reactor temperature was controlled and monitored using proportional integral derivation temperature controller. After 5 min preheating time, reaction was started. Upon finishing the reaction, the stainless steel reactor was quickly cooled using tap water. Samples for HPLC analysis were prepared by centrifugation and subsequent filtration [19].

3. Statistical Experimental Design and Analysis

For statistical experimental design, an experimental 5-level 4-factor CCRD (central composite rotatable design) was applied using Design-Expert 9 (Stat-Ease, Inc., USA) [19]. The four reaction parameters were substrate amount (30-150 g/L), catalyst amount (0.1-0.5 M), reaction temperature (130-210 °C), and time (10-50 min) (Table 1). The model was predicted and evaluated by multiple regres-

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Table 1. Reaction factors and their levels in the experimental 5-level 4-factor central composite rotatable design

Reaction factor	Symbol	Coded factor levels				
		−1.68	−1	0	1	1.68
Substrate amount (g/L)	X_1	30	60	90	120	150
Catalyst amount (M)	X_2	0.1	0.2	0.3	0.4	0.5
Reaction temperature (°C)	X_3	130	150	170	190	210
Reaction time (min)	X_4	10	20	30	40	50

sion and analysis of variance (ANOVA) [19].

4. Analysis and Calculation of Yield

Qualitative and quantitative analyses of sugars and products were performed by an analytical HPLC system (Agilent 1100 model; USA) [11]. Product yield and conversion yield were calculated by the following equations: Sugar conversion yield (mol %)=(final mole concentration of sugar)/(initial mole concentration of sugar)×100, and Product yield (mol%)=(mole concentration of product)/(mole concentration of initial sugar)×100. The results are presented as the average±SD [11].

RESULTS AND DISCUSSION

We investigated the possibility of converting monomeric sugars (galactose and fructose) to levulinic acid, which is a diverse versatile chemical, using MSA as a catalyst. To produce LA from monomeric sugars, the optimization of reaction factors was investigated using response surface methodology design and analysis. In addition, the efficiency of MSA-catalyzed hydrothermal process was assessed using CSF.

1. Optimization of Reaction Factors for Levulinic Acid Production

1-1. Evaluation and Analysis of Model

To optimize reaction factors and to assess the reciprocal interactions via the MSA-catalyzed hydrothermal conversion, a 5-level 4-

Table 2. Experimental reaction design and data in 5-level 4-factor central composite rotatable design

Substrate amount (g/L), X_1	Catalyst amount (M), X_2	Temperature (°C), X_3	Time (min), X_4	Fructose		Galactose	
				Conversion (mol%)	LA yield (mol%)	Conversion (mol%)	LA yield (mol%)
1	−1	1	−1	99.6	58.2	97.9	34.7
0	0	0	0	99.2	61.4	72.5	28.7
1	−1	−1	−1	98.7	47.0	41.9	2.9
1	−1	−1	1	99.1	55.1	43.2	6.7
−1	−1	1	−1	99.5	62.6	97.1	37.9
1	1	1	−1	99.7	59.8	99.6	35.0
−1	−1	−1	−1	98.9	51.6	16.0	3.1
−1	1	−1	−1	99.1	61.3	25.9	8.0
−1	−1	1	1	99.8	62.5	99.5	39.3
0	0	0	−1.68	99.2	60.7	43.2	14.2
0	−1.68	0	0	99.3	54.3	40.4	12.0
0	0	0	0	99.5	60.3	72.5	28.8
1	1	1	1	100	60.3	99.6	35.6
1	−1	1	1	100	58.1	99.6	36.2
−1	−1	−1	1	98.1	59.6	23.1	6.5
−1	1	1	1	100	66.1	99.6	40.3
1.68	0	0	0	99.6	56.8	79.4	28.2
0	1.68	0	0	99.6	63.7	91.9	35.7
0	0	0	1.68	99.5	61.0	88.7	35.7
−1	1	1	−1	99.7	65.4	99.5	39.4
0	0	1.68	0	99.9	59.9	99.5	30.2
0	0	−1.68	0	89.9	29.6	62.0	0.7
0	0	0	0	99.3	61.1	75.3	28.8
1	1	−1	−1	99.1	55.5	43.8	7.9
0	0	0	0	99.3	60.7	74.4	29.4
−1	1	−1	1	99.2	63.9	34.1	13.5
0	0	0	0	99.5	61.5	73.5	29.8
1	1	−1	1	99.2	58.7	48.1	13.9
0	0	0	0	99.4	60.7	73.8	29.5
−1.68	0	0	0	97.3	64.7	70.9	30.8

Table 3. Predicted model for LA yield resulting from experimental reaction design

Sugar	Final equation in terms of actual factors	Model	R^2
Fructose	Sqrt(LA yield (%))$=-18.191-0.011\ X_1+8.896\ X_2+0.267\ X_3+0.073\ X_4$ $-0.005\ X_1X_2+0.00001\ X_1X_3+0.00001\ X_1X_4-0.035\ X_2X_3-0.041\ X_2X_4$ $-0.00045\ X_3X_4+0.00004\ X_1^2+0.357\ X_2^2-0.001\ X_3^2+0.00035\ X_4^2$	Quadratic	0.827
Galactose	Sqrt(LA yield (%))$=-68.592+0.024\ X_1+38.782\ X_2+0.651\ X_3+0.288\ X_4$ $-0.004\ X_1X_2-0.00013\ X_1X_3+0.00003\ X_1X_4-0.133\ X_2X_3-0.002\ X_2X_4$ $-0.001\ X_3X_4-0.00002\ X_1^2-19.472\ X_2^2-0.001\ X_3^2-0.002\ X_4^2$	Quadratic	0.964

X_1 (Substrate amount, g/L), X_2 (Catalyst amount, M), X_3 (Reaction temperature, °C), and X_4 (Reaction time, min) are the actual values of the independent factors

factor CCRD was applied. The experimental reaction designs and their results (Table 2) for LA production from fructose and galactose are presented. In the case of fructose, LA yields ranged from 29.6-66.1%. The highest value (66.1%) was obtained under the condition of 60 g/L fructose, 0.4 M MSA at 190 °C for 40 min. Also, fructose conversions were mostly nearly 99%. However, in the case of galactose, LA yields ranged from 0.7-40.3% ranges. The highest 40.3% yield was obtained under the condition of 60 g/L galactose, 0.4 M MSA at 190 °C for 40 min as similar to fructose. In addition, galactose conversion is ranged from 16.0-99.6%.

The predicted models of LA yield from fructose and galactose were demonstrated by predicting a quadratic model with Design Expert in Table 3. In all cases of fructose and galactose, the predicted models were well fitted with high R^2 of 0.827 and 0.964, respectively. These high values demonstrated that the models had similar predicted values and observed values [10].

Tables 1S and 2S present the ANOVA results of predicted models of fructose and galactose. In the case of the fructose, three linear coefficients (X_1, X_2, X_3) and one quadratic coefficient (X_3^2) were significant (Table 1S). The coefficient of determination (R^2) was 0.827. The "Adeq Precision" ratio of 10.399 indicated an adequate signal (over 4 is desirable) [11]. The model *F*-value of 5.11 indicated the model's significance. In galactose, three linear coefficients terms (X_2, X_3, X_4) and two quadratic coefficients terms (X_2^2 and X_3^2) were significant (Table 2S). The model *F*-value of 28.40 indicated model's significance. The R^2 was 0.964. The "Adeq Precision" ratio of 20.888 indicated an adequate signal. In all cases of fructose and galactose, high coefficients of determination (R^2) and model *F*-values indicated that all model equations are useful for predicting the LA yield.

The parity plots of LA yields from fructose and galactose are presented in Fig. 1. There was a close relationship between observed values and predicted values in all cases of fructose and galactose with high coefficients of determination.

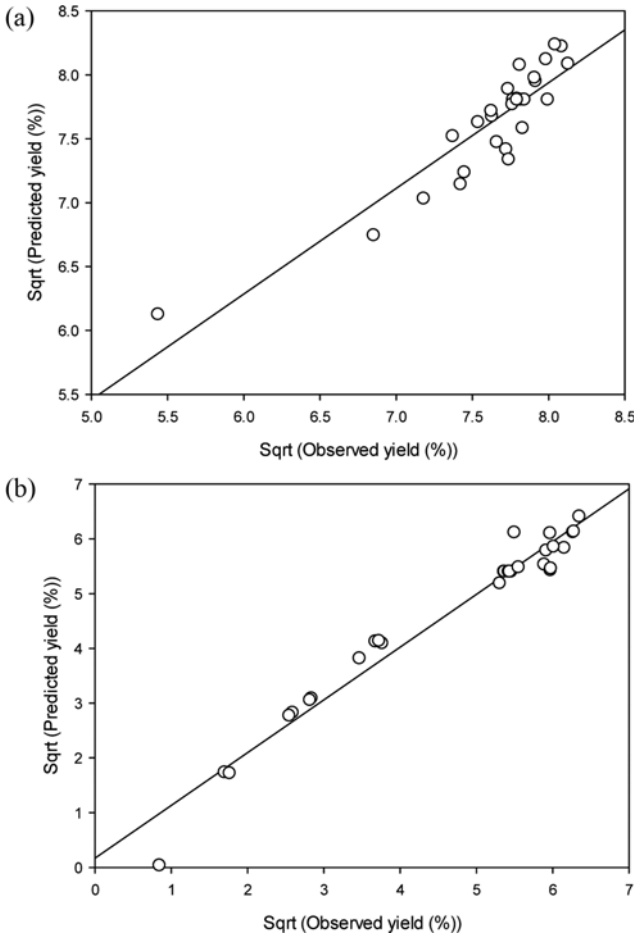

Fig. 1. Parity plots of levulinic acid from fructose and galactose models. (a) Fructose, (b) galactose.

Fig. 2 presents the effects of reaction factors on the models for LA yield from fructose and galactose. In the case of fructose, the factors X_2, X_3, X_4, X_1^2, and X_4^2 positively influenced. In particular, X_3 (temperature) had the greatest positive effect on LA production from fructose. Similarly, in the case of galactose, the reaction factors of X_2, X_3, and X_4 positively affected on LA yield. Moreover, X_3 had a greater positive effect than others on LA yield. This result indicated that the production of LA from fructose and galactose was accelerated at a higher temperature compared with other reaction factors [19,21]. Comparably, three reaction factors (temperature, catalyst amount, and reaction time) had a positive effect on LA production via hydrothermal conversion with sulfuric acid-catalyzed hydrolysis using the red macro-algae *G. verrucosa* [10]. Moreover, in comparison with other factors, catalyst amount had a greater effect.

1-2. Effect of Reciprocal Interaction of Reaction Factors

To assess the effect of reciprocal interaction of reaction factors on LA production from fructose and galactose via MSA-catalyzed hydrothermal conversion, 3D response surface plots were obtained under reaction conditions at a constant level. Fig. 3 presents the effects of reciprocal interactions of reaction temperature and time,

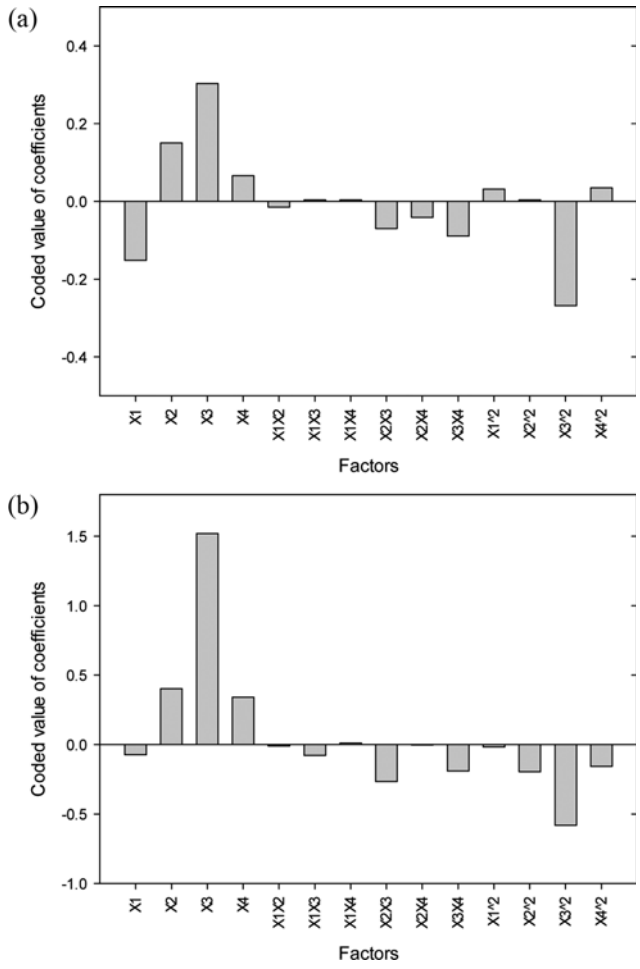

Fig. 2. Effects of reaction factors on levulinic acid yields. X_1 (Substrate amount, g/L), X_2 (Catalyst amount, M), X_3 (Reaction temperature, °C), and X_4 (Reaction time, min). (a) Fructose, (b) galactose.

substrate and catalyst amounts on LA production from fructose. Fig. 3(a) shows the effect of substrate and catalyst amounts at 170 °C for 30 min. At a constant catalyst amount condition, LA yield was slightly diminished by increasing substrate amount. In the condition of substrate amount, LA yield was linearly enhanced with increasing catalyst amount. Accordingly, LA yield was predicted to be the highest with a low substrate amount and high catalyst amount. Fig. 3(b) presents the effect of reaction temperature and substrate amount with 0.3 M MSA for 30 min. In the condition of a constant reaction temperature, LA yield was slightly diminished by increasing substrate amount. However, in the condition of constant substrate amount, LA yield was sharply increased by increasing temperature. The effect of substrate amount was smaller than reaction temperature on LA yield. Accordingly, LA yield was predicted to be the highest with a lower substrate and higher temperature. Fig. 3(c) presents the effect of substrate amount and time at 170 °C with 0.3 M MSA condition. With a constant condition of reaction time, LA yield was slightly increased by decreasing substrate amount. Moreover, at a constant substrate condition, LA yield was slightly enhanced with increasing time. Accordingly, LA yield was predicted to be the highest with a longer reaction time and lower substrate amount. Fig. 3(d) indicates the effect of temperature and catalyst amount with 90 g/L fructose for 30 min condition. In constant catalyst amount condition, LA yield was dramatically enhanced with increasing temperature. In a constant temperature, LA yield linearly rose with increasing catalyst amount. Accordingly, a higher LA yield was predicted with a higher catalyst amount and higher temperature. Fig. 3(e) shows the effect of reaction time and catalyst amount at 170 °C with 90 g/L fructose condition. With a constant time, LA yield was a little enhanced by increasing catalyst amount. Also, LA yield was somewhat enhanced by passing the time. Accordingly, a higher LA yield was predicted with a longer time and higher catalyst amount. Fig. 3(f) presents the effect of reaction time and temperature with 90 g/L fructose and 0.3 M MSA condition. With a constant time condition, LA yield was sharply enhanced by temperature rising. However, by passing the reaction time, LA yield was a little enhanced. Accordingly, higher LA yield was predicted with a higher temperature and longer time. Moreover, reaction temperature had greater influence than that of time on LA production. Overall, these results indicate that the conversion of fructose to LA by MSA-catalyzed hydrothermal reaction was stimulated under the condition of higher temperature, lower substrate amount, higher catalyst amount, and longer time. However, in comparison with other factors, substrate amount had a smaller effect. Of the four factors, reaction temperature had the greatest effect, as shown in Fig. 2(a).

The influences of reciprocal interactions of temperature, substrate amount, catalyst amount, and time on LA production from galactose are presented in Fig. 4. The reciprocal influences of reaction factors on LA production from galactose are similarly presented as the case of fructose (as shown in Fig. 3). However, in the case of galactose, the reciprocal interactions of the factors are greater than fructose. Fig. 4(a) presents the effect of substrate and catalyst amounts at 170 °C for 30 min condition. In the constant substrate condition, LA yield was sharply enhanced by increasing catalyst amount. Moreover, LA yield was somewhat diminished with increasing substrate amount. High LA yield was achieved with a high catalyst (0.4 M MSA) amount and low substrate amount (60 g/L). Fig. 4(b) presents the influence of reaction temperature and substrate amount under 0.3 M MSA for 30 min condition. In the constant substrate condition, LA yield sharply rose with increasing temperature. At high temperature condition, linear improvement of LA yield was obtained by decreasing substrate amount. At a low temperature condition, the yield was similarly maintained within the ranges of substrate. Accordingly, the highest LA yields were achieved with a higher temperature (190 °C) and lower substrate amount (60 g/L). Overall, the effect of temperature was greater than that of substrate amount. According to several works, LA production has been stimulated by a higher heat energy condition [10,13,19,21]. Fig. 4(c) presents the influence of substrate amount and time at 170 °C with 0.3 M MSA condition. With a constant time condition, LA yield was a little diminished by high substrate amount. Moreover, LA yield linearly rose over time with a constant substrate condition. Accordingly, a higher LA yield was achieved with a lower substrate and longer time. Fig. 4(d) presents the influence of temperature and catalyst amount with 90 g/L galactose for 30 min condition. LA yields were sharply increased by increasing both tem-

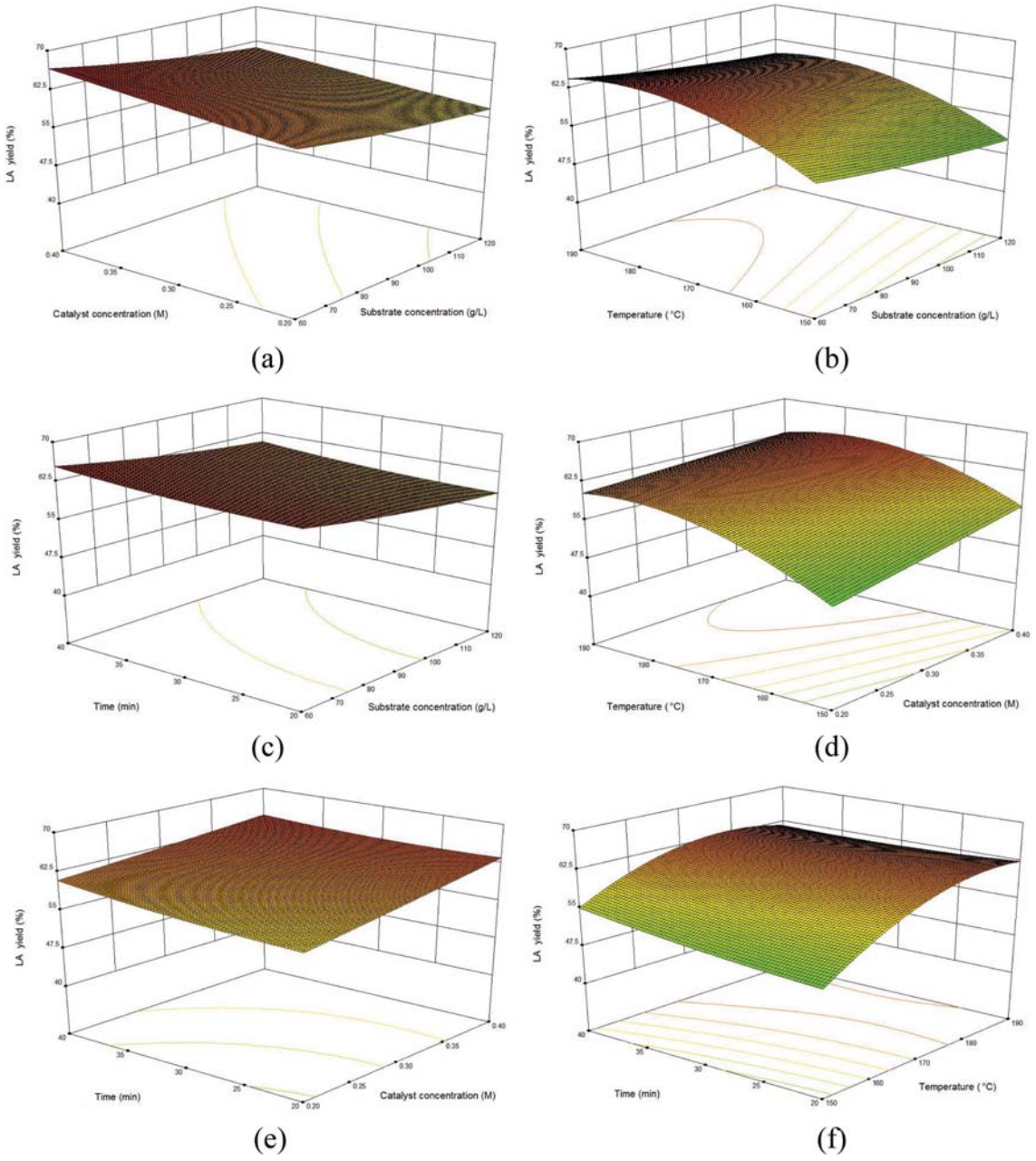

Fig. 3. Effects of reaction temperature, substrate amount, catalyst amount, reaction time, and their reciprocal interactions on levulinic acid production from fructose under constant reaction condition.

perature and catalyst. This result indicated that conditions of both higher temperature and higher catalyst amount could have a synergistic effect on LA production from galactose [10]. Moreover, the effect of temperature on LA yield was greater than that of catalyst amount. Fig. 4(e) presents the effect of catalyst amount and time at 170 °C with 90 g/L galactose condition. The linear improvement of LA yield occurred with increasing both catalyst amount and time. Therefore, the conditions of higher catalyst amount and longer time could increase LA production. Fig. 4(f) presents the influence of temperature and time with 90 g/L galactose and 0.3 M MSA condition. With a constant reaction time condition, LA yield was drastically improved by reaction temperature rise. An increase in reaction time also slightly improved LA yield. Accordingly, high LA yield was obtained under both condition of higher temperature and longer time. Also, the effect of temperature was greater than that of time on LA yield [10,13,19,21]. Overall, the reaction condition for the production of LA from galactose with MSA was optimized under the condition of a higher temperature, higher catalyst amount, lower substrate amount, and longer reaction time. In comparison with other factors, reaction temperature had the greatest effect on LA production, as shown in Fig. 2(b). In similar studies using red macro-algae *G. verrucosa* [10] and *K. alvarezii* [21], the reaction condition of a higher temperature and catalyst concentration, and longer time improved LA production during sulfuric acid-

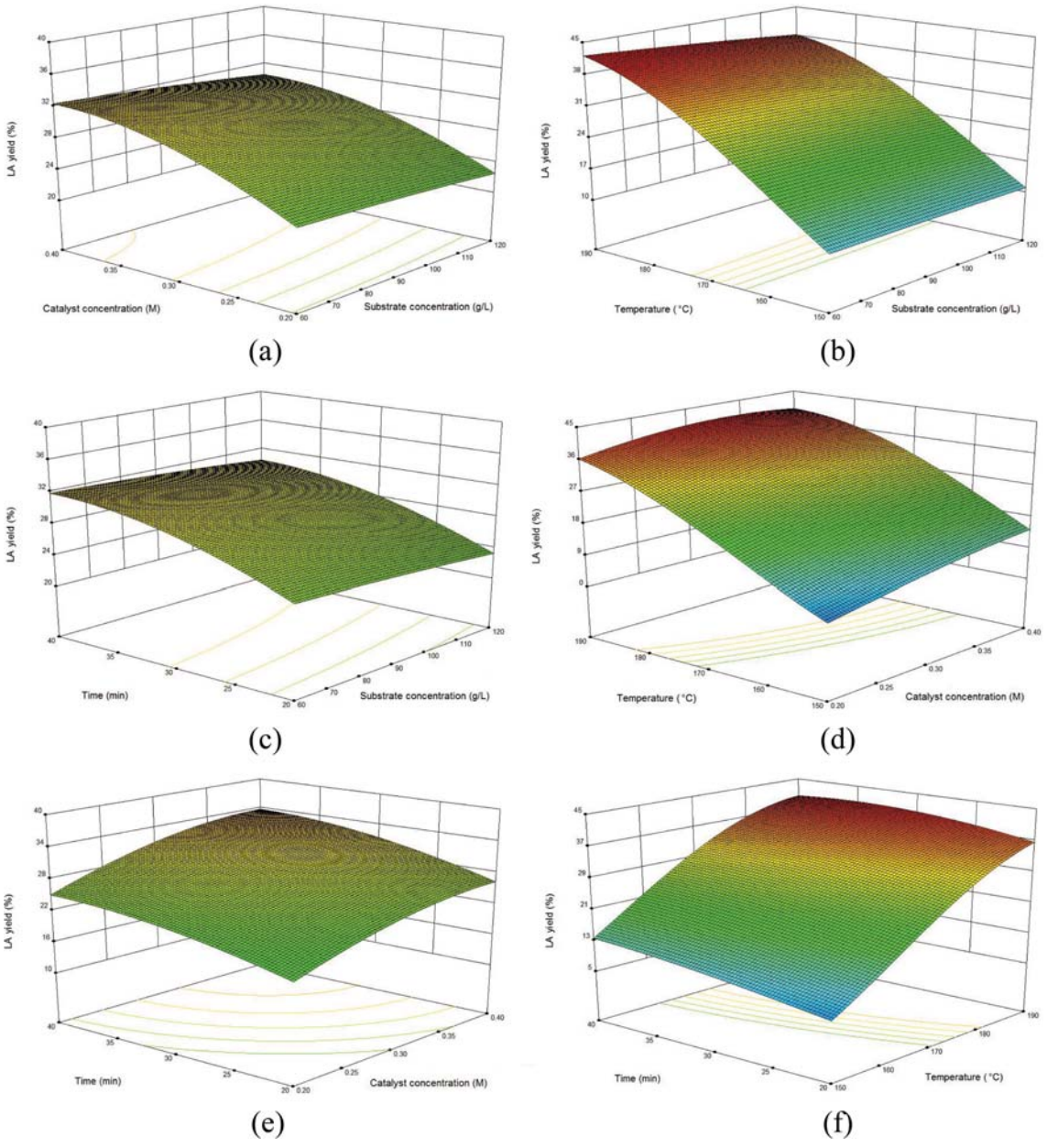

Fig. 4. Effects of reaction temperature, substrate amount, catalyst amount, reaction time, and their reciprocal interactions on levulinic acid production from galactose under constant reaction condition.

catalyzed hydrothermal process. In particular, reaction temperature and H_2SO_4 amount had a greater effect on LA yield [10].

1-3. Optimization of LA Production

To optimize LA yield, the MSA-catalyzed conversion of monomeric sugars (fructose and galactose) was investigated using an experimental CCRD with 30-150 g/L substrate amount, 0.1-0.5 M MSA catalyst amount, 130-210 °C temperature, and 10-50 min time conditions. Following the optimization of LA yield from fructose, an LA yield of 66.1% was predicted under the condition of 60 g/L fructose and 0.4 M MSA at 188 °C for 36 min. Fructose conversion of 100% was also predicted. Following repeated experiments under optimized condition, 99.5% fructose conversion and 63.5% LA yield were achieved. This result was in close agreement with the prediction. In galactose, following the optimization of LA yield, an LA yield of 40.7% was predicted under 60 g/L galactose and 0.4 M MSA at 188 °C for 26.7 min condition. Furthermore, a galactose conversion of 97.1% was predicted. Following repeated experiments under optimized conditions, a 99.3% galactose conversion and a 39.3% LA yield were achieved. These values were in good agreement with prediction.

Fig. 5 shows the time-course of fructose and galactose conversion, and LA, FA and 5-HMF yields under optimum condition (60 g/L fructose/galactose and 0.4 M MSA at 188 °C). In the case of fructose (Fig. 5(a)), fructose conversion yield was maintained above 99% from 0 min, which was reached 5 min after heating start. On the other hand, 5-HMF yield was 2.32% at 0 min and decreased to

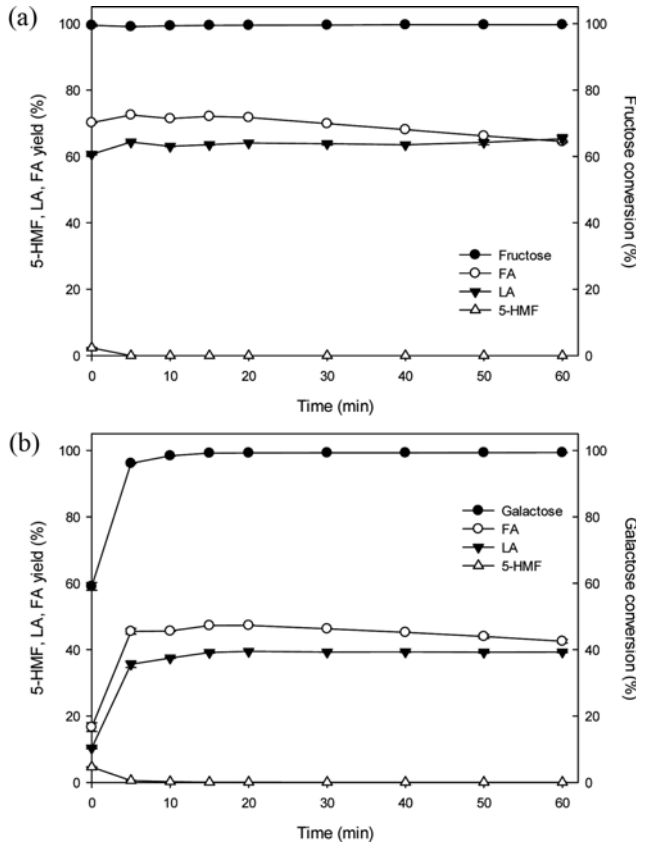

Fig. 5. Production of levulinic acid from fructose (a) or galactose (b) under optimized condition (60 g/L fructose/galactose and 0.4 M MSA at 188 °C).

nearly zero over time. The result indicated that the hydration of 5-HMF, which is formed from fructose by dehydration, into LA, and also the condensation to humin-like substances rapidly occurred under this condition [22,23]. Simultaneously, LA and FA yields were 60.67% and 70.19% at 0 min, respectively. After 0 min, LA yield was slightly increased to 65.32% until 60 min. Then, the FA yield was slightly decreased to 64.5% after 30 min. This decrease in FA yield indicated the occurrence of degradation (such as decarboxylation) into hydrogen and carbon dioxide in the aqueous condition [24].

In the case of galactose (Fig. 5(b)), galactose conversion yield was sharply increased for 5 min and was maintained above 99% after 15 min. However, 5-HMF yield was 4.64% at 0 min and decreased to nearly zero over time. This phenomenon is similar to that in the case of fructose. Simultaneously, LA and FA yields were drastically increased for 5 min and steadily maintained for 60 min. The highest LA yield was 39.46±0.04% at 20 min, whereas the highest FA yield was 47.34±0.07% at 20 min. In comparison between fructose and galactose, fructose could be more easily converted to LA than galactose.

1-4. Mass Balance of LA Production from Galactose

Fig. 6 presents the mass balance diagram of LA, FA, and 5-HMF under the conditions of 60 g/L galactose and 0.4 M MSA at 188 °C for 20 min. From this condition, 99.3% galactose was converted to 15.27 g/L (39.46 mol%) LA and 7.26 g/L (47.34 mol%) FA. However, 5-HMF formed nearly zero (0.03 g/L) under this condition.

Various studies of the conversion mechanisms of fructose or glucose to 5-HMF and LA have been reported. Fructose can be easily dehydrated to 5-HMF and subsequently rehydrated to LA and FA [5,7,25]. On the other hand, glucose is first isomerized to fructofuranose. Then, it is converted to 5-HMF by keto-enol tautomerization and dehydration [26,29]. LA could be produced by the subsequent rehydration of 5-HMF under extended exposure condition of higher temperature and catalyst amount [25,28]. Although, the conversion of galactose is similar to that of glucose, an intermediate, which has a different spatial configuration compared with that of fructofuranose form, is formed during the isomerization of galactose [28]. The formation of this intermediate is difficult due to the steric hindrance caused by the coupling of neighboring C3 and C4 hydroxyl groups [28]. This can result in lower 5-HMF and LA in the galactose conversion process compared with the fructose or glucose conversion process [28]. However, a comparison with other catalysts and biomasses is difficult because of the difference in the composition of the biomass and property of the catalyst [30]. There are limited studies on the conversion to 5-HMF and LA from galactose. Hu et al. [28] reported that the galactose conversion to LA was lower than that from glucose and fructose (fructose>glucose>galactose) using Amberlyst 70 as a catalyst at 175 °C. These lower yields may be attributed to a difference in the

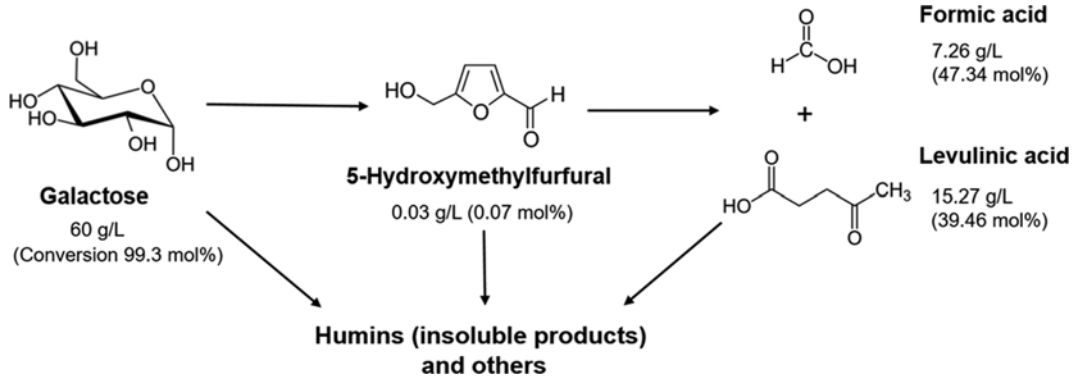

Fig. 6. Mass balance of formation of levulinic and formic acids from galactose under the condition of 60 g/L galactose and 0.4 M MSA at 188 °C for 20 min.

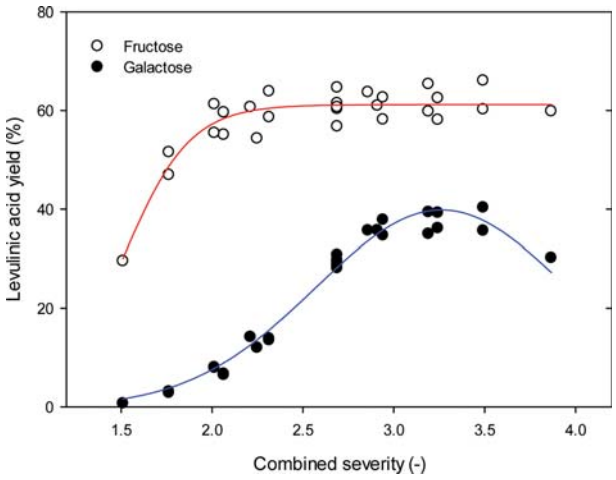

Fig. 7. Effect of combined severity on levulinic acid production from fructose or galactose by MSA-catalyzed hydrothermal conversion. Combined severity CSF=log [t exp(T−T_{ref})/14.75]−pH, where T(t) is temperature (°C), T_{ref} is reference temperature (100 °C), t is the reaction time (min), and 14.75 is the fitted value of the arbitrary constant. The pH values of reactant were measured before the reaction [10,20].

structure (spatial configuration of the C4 hydroxyl group) of glucose and galactose [28]. Furthermore, in H_2SO_4-catalyzed hydrothermal hydrolysis of *G. verrucosa*, 18.64% LA yield was reported under the condition of 2.85% H_2SO_4 at 180.9 °C for 50 min [10].

2. Influences of Combined Severity

The CSF has been used to compare and evaluate the influence of strength and activity on the pretreatment and conversion of lignocellulosic biomass and marine macro-algae [10,20]. It is formulated by the strength of temperature, time, and acidity of the catalytic solution [10,20]. Fig. 7 presents the influences of CSF on LA production from fructose and galactose by MSA-catalyzed hydrothermal conversion. In fructose, LA yield was linearly improved with increasing CSF values until 2.0 CSF. Above a CSF of 2.0, LA yield was maintained at around 60%. It was closely fitted to a non-linear regression model (sigmoidal; f=a/(1+exp(−(x−x_0)/b)); a=61.20 (p<0.0001), b=0.181 (p<0.0001), x_0=1.517 (p<0.0001)) with a high regression value (R^2=0.924). In galactose, LA yield demonstrated a peaked form with CSF values. LA yield was linearly improved until CSF 3.2, and diminished by further increasing CSF. The decrease in LA yield above a CSF of 3.2 indicated the occurrence of unwanted reactions such as condensation and decomposition under harsh reaction conditions [10,19]. The relationship between LA yield and CSF was well fitted into a Gaussian peak model (f=a*exp(−0.5*((x−x_0)/b)^2); a=39.845 (p<0.0001), b=0.692 (p<0.0001), x_0=3.263 (p<0.0001)) with a high regression value (R^2=0.989). As shown in Fig. 6, the conversion of fructose was easier than that of galactose to LA. Even under conditions with low CSF values (below 2), the LA yield from fructose was higher than that from galactose. Moreover, LA production from galactose requires more complex procedures such as the isomerization of galactose [25,28]. The required additional steps in galactose conversion could limit the formation of LA. Overall, an optimized CSF is needed to have a positive effect on LA production in the MSA-catalyzed conversion of galactose.

3. Comparison of LA Production from Galactose

Table 4 presents the results of comparable studies on LA production from various substrate using methanesulfonic acid [13,18,31-33]. Kim et al. [31] reported that 48.95% LA yield was achieved under the condition of 0.25 M glucose, 0.35 M MSA, 181.3 °C for 44.4 min. In similar works, Rackemann et al. [13] achieved 63.13 mol% LA yield under using 0.1 M glucose and 0.5 M MSA, 180 °C for 15 min. Mthembu [18] reported 34.9% LA yield under the condition of 0.5 M MSA, 180 °C for 45 min. Comparably, Kim et al. [32] reported the LA production from chitosan using MSA. It was achieved to 28.2% LA yield under 2% (w/w) chitosan, 0.2 M MSA, 200 °C for 30 min. *Gracilaria verrucosa*, which is a red macroalgae, is mainly composed to agar (galactose and 3,6-anhydro-galactopyranose). Park et al. [33] achieved 36.92% LA yield based carbohydrate content of *G. verrucosa* under 10% biomass, 0.5 M MSA, 180 °C for 20 min. In H_2SO_4-catalyzed hydrothermal hydrolysis of *G. verrucosa*, 18.64% LA yield was reported under the condition of 2.85% H_2SO_4 at 180.9 °C for 50 min [10]. Comparably, in this study, a 65.3 mol% LA yield was achieved at 188 °C using 60 g/L fructose and 0.4 M methanesulfonic acid for 60 min during MSA-catalyzed hydrothermal reaction. In addition, in the conversion of galactose, 39.46 mol% LA yield was obtained at 188 °C using 60 g/L galactose and 0.4 M methanesulfonic acid for 20 min. Nevertheless, it is hard to compare the LA yield from various biomass due to the difference of reaction condition, substrate types (polymer or monomer) and others [32,33]. In our study, during the conversion of fructose and galactose, fructose could be easily converted to LA than galactose. Similarly, Hu et al. [28] reported that the lower galactose conversion to LA than that of glucose and fructose (fructose> glucose>galactose) under 175 °C and Amberlyst 70 catalyst condition.

Table 4. Comparison of LA production from galactose and others

Substrate	Concentration	Reaction conditions	LA	References
Glucose	0.25 M	181.3 °C, 0.35 M methanesulfonic acid, 44.4 min	48.95 mol%	[31]
Glucose	0.1 M	180 °C, 0.5 M methanesulfonic acid, 15 min	63.13 mol%	[13]
Glucose	42 g/L	180 °C, 0.5 M methanesulfonic acid, 45 min	34.90%	[18]
Chitosan	2% (w/w)	200 °C, 0.2 M methanesulfonic acid, 30 min	28.21 wt%	[32]
G. verrucosa	10% (w/w)	180 °C, 0.5 M methanesulfonic acid, 20 min	36.92%	[33]
G. verrucosa	62.5 g//L	180.9 °C, 2.85% sulfuric acid, 50 min	18.64%	[10]
Galactose	60 g/L	188 °C, 0.4 M methanesulfonic acid, 20 min	39.46 mol%	This work
Fructose	60 g/L	188 °C, 0.4 M methanesulfonic acid, 60 min	65.32 mol%	This work

CONCLUSIONS

For the optimization of LA yield, four reaction factors were optimized using response surface methodology with CCRD, in which monomeric sugars were converted by MSA-catalyzed hydrothermal conversion. In four reaction factors, temperature had the highest significant effect on LA production from monomeric sugars. By verification experiments, LA yields of 63.5% and 39.3% were achieved by converting fructose and galactose, respectively, under optimal conditions. In the relationship between LA yield and CSF, the conversion of galactose into LA showed a non-linear Gaussian peak regression pattern. These results suggest the possibility that MSA and galactose, which is derived from marine macro-algae, is available to convert into valuable chemicals and materials.

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SUPPORTING INFORMATION

Additional information as noted in the text. This information is available via the Internet at http://www.springer.com/chemistry/journal/11814.

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Supporting Information

Valorization of galactose into levulinic acid via acid catalysis

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Table 1S. ANOVA results for the response surface quadratic model for LA production from fructose using MSA

Source	Sum of squares	df	Mean square	*F*-value	*P*-value (Prob>*F*)[a,b]
Model	5.900	14	0.421	5.108	0.0017
X_1, substrate concentration	0.552	1	0.552	6.686	0.0207
X_2, catalyst concentration	0.544	1	0.544	6.593	0.0214
X_3, temperature	2.207	1	2.207	26.747	0.0001
X_4, time	0.105	1	0.105	1.271	0.2773
X_1X_2	0.003	1	0.003	0.042	0.8403
X_1X_3	0.000	1	0.000	0.002	0.9613
X_1X_4	0.000	1	0.000	0.003	0.9567
X_2X_3	0.078	1	0.078	0.947	0.3459
X_2X_4	0.027	1	0.027	0.322	0.5786
X_3X_4	0.128	1	0.128	1.552	0.2320
X_1^2	0.028	1	0.028	0.336	0.5706
X_2^2	0.000	1	0.000	0.004	0.9490
X_3^2	1.981	1	1.981	24.018	0.0002
X_4^2	0.033	1	0.033	0.398	0.5377
Residual	1.237	15	0.082		
Lack of fit	1.233	10	0.123	149.812	0.0000
Pure error	0.004	5	0.001		
Cor total	7.137	29			

[a]Prob>*F*=level of significance

[b]Values of "Prob>*F*" less than 0.05 indicate model terms are significant

Table 2S. ANOVA results for the response surface quadratic model for LA production from galactose using MSA

Source	Sum of squares	df	Mean square	*F*-value	*P*-value (Prob>*F*)[a,b]
Model	74.045	14	5.289	28.400	0.0000
X_1, substrate concentration	0.128	1	0.128	0.688	0.4199
X_2, catalyst concentration	3.886	1	3.886	20.866	0.0004
X_3, temperature	55.454	1	55.454	297.772	0.0000
X_4, time	2.806	1	2.806	15.069	0.0015
X_1X_2	0.002	1	0.002	0.011	0.9188
X_1X_3	0.101	1	0.101	0.540	0.4738
X_1X_4	0.002	1	0.002	0.009	0.9253
X_2X_3	1.139	1	1.139	6.114	0.0259
X_2X_4	0.000	1	0.000	0.000	0.9842
X_3X_4	0.585	1	0.585	3.142	0.0966
X_1^2	0.008	1	0.008	0.043	0.8392
X_2^2	1.040	1	1.040	5.584	0.0320
X_3^2	9.277	1	9.277	49.813	0.0000
X_4^2	0.673	1	0.673	3.613	0.0767
Residual	2.793	15	0.186		
Lack of fit	2.785	10	0.279	172.984	0.0000
Pure error	0.008	5	0.002		
Cor total	76.839	29			

[a]Prob>*F*=level of significance

[b]Values of "Prob>*F*" less than 0.05 indicate model terms are significant