The Kinetics of Aqueous Lactose Hydrolysis with Sulfuric Acid

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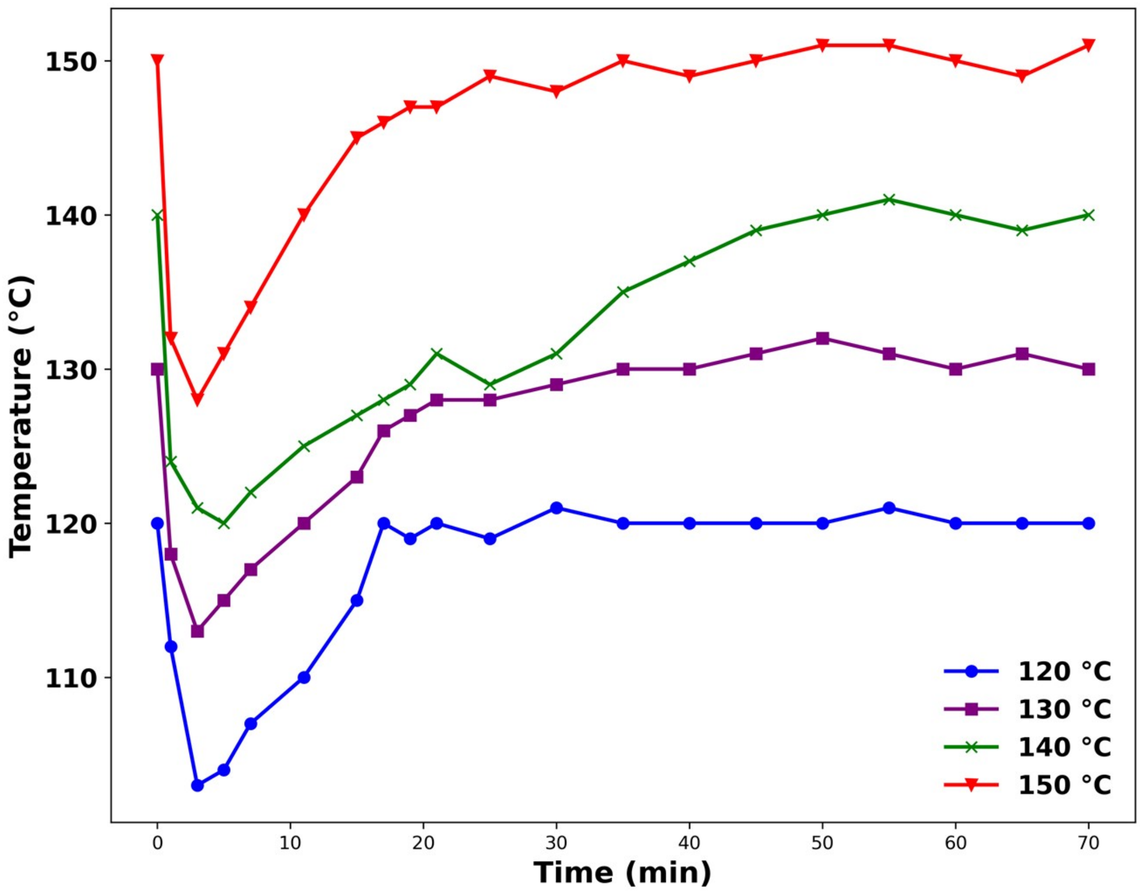

Figure S1. Temperature profile of the reaction system

Table S1. All Possible Combinations of Reaction Networks during Lactose Catalytic Hydrolysis

Number	Reactions	Degree of Freedom (DOF)	Reasonable?
1	R1, R2, R3, R4, R5, R6, R7	7	×
2	R1, R2, R3, R4, R5, R6	6	✓
3	R1, R2, R3, R4, R5, R7	6	✓
4	R1, R2, R3, R4, R6, R7	6	×
5	R1, R2, R3, R5, R6, R7	6	×
6	R1, R2, R4, R5, R6, R7	6	×
7	R1, R3, R4, R5, R6, R7	6	×
8	R1, R2, R3, R4, R5	5	✓
9	R1, R2, R3, R4, R6	5	✓
10	R1, R2, R3, R4, R7	5	✓
11	R1, R2, R3, R5, R6	5	✓
12	R1, R2, R3, R5, R7	5	✓
13	R1, R2, R3, R6, R7	5	×
14	R1, R2, R4, R5, R6	5	✓
15	R1, R2, R4, R5, R7	5	✓
16	R1, R2, R4, R6, R7	5	×
17	R1, R2, R5, R6, R7	5	✓
18	R1, R3, R4, R5, R6	5	✓
19	R1, R3, R4, R5, R7	5	✓
20	R1, R3, R4, R6, R7	5	×
21	R1, R3, R5, R6, R7	5	×
22	R1, R4, R5, R6, R7	5	×
23	R1, R2, R3, R4	4	✓
24	R1, R2, R3, R5	4	✓
25	R1, R2, R3, R6	4	×

26	R1, R2, R3, R7	4	×
27	R1, R2, R4, R5	4	✓
28	R1, R2, R4, R6	4	×
29	R1, R2, R4, R7	4	✓
30	R1, R2, R5, R6	4	✓
31	R1, R2, R5, R7	4	✓
32	R1, R2, R6, R7	4	×
33	R1, R3, R4, R5	4	✓
34	R1, R3, R4, R6	4	✓
35	R1, R3, R4, R7	4	✓
36	R1, R3, R5, R6	4	✓
37	R1, R3, R5, R7	4	×
38	R1, R3, R6, R7	4	×
39	R1, R4, R5, R6	4	×
40	R1, R4, R5, R7	4	×
41	R1, R4, R6, R7	4	×
42	R1, R5, R6, R7	4	×
43	R1, R2, R3	3	×
44	R1, R2, R4	3	×
45	R1, R2, R5	3	✓
46	R1, R2, R6	3	×
47	R1, R2, R7	3	×
48	R1, R3, R4	3	✓
49	R1, R3, R5	3	×
50	R1, R3, R6	3	×
51	R1, R3, R7	3	×
52	R1, R4, R5	3	×
53	R1, R4, R6	3	×

54	R1, R4, R7	3	×
55	R1, R5, R6	3	×
56	R1, R5, R7	3	×
57	R1, R6, R7	3	×

Table S2. Overview of kinetic studies on catalytic hydrolysis of lactose, glucose, and galactose

Reactions	$E_a(kJ/mo$	Kinetic Expression	$ln(A/(min$	Condition	Resource
$LAC \xrightarrow{H^+,H_2O} GAL +$	143.2±0.8	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{lac}$	43.17±0.01	120-150 °C, 5-100 mM H_2SO_4	This study
	118.4	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H_2SO_4][C$	28.75	65-75 °C, 0.5-1 M H_2SO_4	1
	125	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[HCl][C_{lac}$	N.A.	50-70 °C, 0.5-3 M HCl	2
	135.5±3.9	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{lac}$	16.39±0.02	120-160 °C, 0.5-5 mM H_2SO_4	3
	154.4	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{lac}$	56.56	85-95 °C,0.24-0.6 M HNO_3	4
$GAL \xrightarrow{H^+,H_2O} UIC$	165.4±1.2	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{gal}$	42.62±0.01	120-150 °C, 5-100 mM H_2SO_4	This study
	130.7	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{gal}$	32.61	150-190 °C, 0.25-0.75 M H_2SO_4	5
	147.5	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{glu}$	43.26	120-140 °C, 0.2-0.61 M H_2SO_4	6
	170	$\frac{C}{C_0} = exp[-(k\tau)^n]$		180-260 °C	7
$GLU \xrightarrow{H^+,H_2O} UIC$	154.3±0.9	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{glu}$	45.58±0.02	120-150 °C, 5-100 mM H_2SO_4	This study
	130.4	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{glu}$	37.48	100-144 °C, 0.4-2.5 M H_2SO_4	8

	137.5	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{glu}$	33.1	170-190 °C, 40-120 mM H_2SO_4	9
	153±2	$R = (0.018 + 2.6[H^+])e^{[\frac{E_a}{R}(\frac{T-473}{473T}}$		180-220 °C, 5-20 wt.% formic acid	10
	155	$\frac{C}{C_0} = exp[-(k\tau)^n]$		180-260 °C	7
$UIC \xrightarrow{H^+, H_2O} HMF$	140.7±2.3	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{UIC}$	38.83±0.05	120-150 °C, 5-100 mM H_2SO_4	This study
	110±3	$R = (0.109 + 8.6[H^+])e^{[\frac{E_a}{R}(\frac{T-473}{473T}}$		180-220 °C, 5-20 wt.% formic acid	10
	127±2	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{UIC}$	18.3±0.3	74-147°C, pH=0.7-1.6 buffer	11
	138.8	$R = 0.611[H^+]e^{[\frac{E_a}{R}\left(\frac{T-T_R}{TT_R}\right)]}[C_{gal}]$		112-153 °C, 20-80 mM HCl	12
$GLU \xrightarrow{H^+, H_2O} HMF$	136.8	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{glu}$	34.46	140-250 °C, 0.56-1.11 M HCl	13
	152.2±0.7	$R = 0.013e^{[\frac{E_a}{R}\left(\frac{T-413}{413T}\right)]}[H^+]^{1.13}[C_g$		140-200 °C, 0.05-1 M H_2SO_4	14
	156±16	$R = 0.01[H^+][C_{glu}]$		80-180 °C, 5-500 mM H_2SO_4	15
	168±15	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{glu}$	18.5±1.8	150-200 °C, 0.67-6.7 mM HCl	16
$GAL \xrightarrow{H^+, H_2O} HMF$	125.0	$R = Ae^{\left(\frac{-E_a}{RT}\right)}[H^+][C_{gal}$	31.87	150-190 °C, 0.25-0.75 M	5

				H_2SO_4	
	140.2±2.3	$R = 0.006e^{[\frac{E_a}{R}(\frac{T-413}{413T})]}[H^+]^{1.07}[C_g$		140-200 °C, 0.05-1 M H_2SO_4	17
	173	$R = Ae^{(\frac{-E_a}{RT})}[H^+][C_{gal}$	44.46	120-190 °C, 10-500 mM H_2SO_4	18
	164.7±0.6	$R = 0.013e^{[\frac{E_a}{R}(\frac{T-413}{413T})]}[H^+]^{1.13}[C_g$		140-200 °C, 0.05-1 M H_2SO_4	14
$GLU \xrightarrow{H^+,H_2O} Humin$	167±31	$R = 0.004[H^+][C_{glu}]^{1.5}$		80-180 °C, 5-500 mM H_2SO_4	15
	209.5	$R = Ae^{(-\frac{E_a}{RT})}[C_{glu}]^{0.119}$	53.14	170-210 °C, 1-5% H_2SO_4	19
	228±11	$R = Ae^{(-\frac{E_a}{RT})}[H^+][C$	26.1±1.2	150-200 °C, 0.67-6.7 mM HCl	16
	104.8	$R = Ae^{(\frac{-E_a}{RT})}[C_{gal}]$	23.18	100-200 °C	20
$GAL \xrightarrow{H^+,H_2O} Humin$	123.2±4.0	$R = 0.008e^{[\frac{E_a}{R}(\frac{T-413}{413T})]}[H^+]^{0.82}[C_g$		140-200 °C, 0.05-1 M H_2SO_4	17
	181.5±4.5	$R = 0.549[H^+]e^{[\frac{E_a}{R}(\frac{T-T_R}{TT_R})]}[C_{gal}]$		112-153 °C, 20-80 mM HCl	12

Table S3. Tuned operational conditions of pH 1.1 lactose hydrolysis with varying targeted output (lactose conversion, selectivity and yield of monosaccharides, and HMF selectivity), and comparison between simulated and experimental results

No.	Scenario	T (°C)	t (min)	pH	Y_{LAC} (%)		S_{GGS} (%)		Y_{GGS} (%)		S_{HMF} (%)	
					S	E	S	E	S	E	S	E
1	Y_{LAC}≥90%, S_{GGS}≥90%	120	55	1.1	90.0	88.9	97.6	98.1	87.8	87.2	0.06	0.05
2	Y_{LAC}≥95%, S_{GGS}≥90%	120	72	1.1	95.1	96.4	96.6	94.9	91.9	91.5	0.11	0.14
3	Y_{LAC}≥99%, S_{GGS}≥90%	120	110	1.1	99.1	98.5	94.3	92.4	93.5	91.0	0.29	0.31
4	Y_{LAC}≥99%, S_{GGS}≥95%	Impossible										
5	Y_{LAC}≥90%, S_{GGS}≥90%, time ≤30 min	128	23	1.1	90.0	90.8	97.3	95.4	87.6	86.6	0.06	0.09
6	Y_{LAC}≥95%, S_{GGS}≥90%, time ≤30 min	128	30	1.1	95.1	94.7	96.3	97.1	91.6	92.0	0.12	0.14
7	Y_{LAC}≥99%, S_{GGS}≥90%, time ≤30 min	135	22	1.1	99.0	98.5	93.4	92.9	92.5	91.5	0.33	0.27
8	Y_{GGS}≥99%,	Impossible										
9	Y_{GGS}≥95%,	Impossible										
10	Y_{LAC}≥90%, Time ≤30 min	129	24	1.1	93.1	94.2	96.8	95.7	90.1	90.1	0.09	0.10
11	Y_{LAC}≥90%,	133	16	1.1	93.4	92.4	96.6	97.2	90.2	89.8	0.10	0.12

	Time ≤20 min											
12	Y_{LAC}≥90%, Time ≤10 min	140	8	1.1	93.9	91.9	96.2	97.3	90.3	89.4	0.11	0.12
13	[3]	150	26	2.3	92		96		88.3		0.4	
14	[21]	140	16.2	1.1	90		99		89.1		0.5	

Y_{LAC}: lactose conversion; S_{GGS}: selectivity towards monosaccharides (glucose and galactose); Y_{GGS}: yield of glucose and galactose; S_{HMF}: selectivity towards HMF; S: simulated results; E: experimental results.

In this section, we focus on optimizing the operational parameters to achieve the highest possible GGS yield while keeping HMF selectivity to a minimum, ensuring efficient and cost-effective production. Herein, we set up a targeted monosaccharide yield of 90% with minimized HMF selectivity and conducted simulation based on the kinetic model 16. The numerical simulated tuned conditions were adopted in lab-scale batch test, while the optimized conditions from our previous study were also presented in Table 4 for comparison. An initial lactose concentration of 15 wt.% and pH of 1.1, and a temperature range of 120 to 150 °C were used in simulation and experiments.

As shown in Table 4, a GGS yield over 95 % is impossible under the pH conditions and temperature range. However, simulation results successfully minimized HMF formation while achieving the targeted 90% monosaccharide yield. When the optimized parameters from the simulations were applied in lab-scale batch tests, the experimental outcomes closely matched the predicted results, confirming the accuracy of the kinetic model. Both the simulations and experiments demonstrated significantly lower HMF levels compared to the conditions optimized in our previous study, as shown in Table 4. The excellent agreement between the simulated and experimental data validates the robustness of the model in predicting real-world outcomes. This strong correlation suggests that the optimized parameters derived from the simulations can be effectively scaled up for larger production, offering a reliable approach to balance high GGS yield with minimal HMF formation, thereby improving the overall economic and environmental viability of the process.

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