

Salen-iron Complexes: Synthesis, Characterization and Their Reactivity with Lactide

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Abstract Schiff-base metal complexes as efficient catalysts are widely used in ring-opening polymerization of cyclic esters. The salen Fe complexes were formed with their excellent biocompatibility and less toxicity. A series of salen Fe complexes were designed in this work in order to study the activity and control of polymerization of lactide. The salen Fe complexes' activities changed with the ligands' configuration and substituent groups.

Keywords Salen Fe; Ring-opening polymerization; Lactide

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INTRODUCTION

The emergence of new materials had brought human radical changes, and its significance is not merely restricted in the industrial revolution period, but also extending to the modern industrial society. Human progress and social development put forward new requirements for modern materials, which should be environmentally benign, biodegradable and biocompatible^[1, 2]. Poly(lactic acid) (PLA) is a member of these plastics which arouses wide interest. Its tremendous utilization is taking place as packing materials^[3, 4], bio-pharmaceutical^[5], tissue engineer^[6] and drug delivery^[7] and so on.

Most recently, developing new catalytic systems capable of replacing precious metals with first row, earth-abundant congeners^[8], which make the catalyst more biocompatible and less toxic in application, is an urgent task^[9]. The PLA is commonly produced by ring-opening polymerization (ROP) of lactide (LA)^[10], while a dimer of lactide acid could be obtained from renewable resource^[5, 11]. The ROP progress is usually catalyzed or initiated by metal alkoxide complexes based on tin^[12], zinc^[13, 14], aluminum^[15, 16], or rare-earth metals^[17]. Among these complexes, catalysts based on iron are particularly attractive because of the universal low toxicity and excellent biocompatibility. There are only few reports about iron catalysts for lactide polymerization so far^[18, 19]. Thus, a series of iron(III) complexes were designed as shown in Scheme 1.

EXPERIMENTAL

General

All experiments were carried out in a glovebox or in noble gas atmosphere using standard Schlenk techniques^[20]. Raw materials were purchased from Aldrich Inc. and used without further purification. The solvents mentioned in the experiments such as propylene oxide (PO) and ethyl acetate were distilled for further procedure. Lactide (Purac) was purified by recrystallization from ethyl acetate and then dried under vacuum at room temperature (RT) before use.

Synthesis of Ligands and Complexes

Complex (Scheme 1): The ligand **1** (2.7 mmol) and anhydrous FeCl₃ (0.40 g, 2.50 mmol) were added to the mixed solvent of MeOH (15 mL), CH₃CN (20 mL) and Et₃N (0.2 mL) with magnetic stirring. After the reactants were stirred for 1 h at room temperature, dark purple powder solid was obtained by vacuum filtration. The complex was then washed with CH₃CN and purified by recrystallization in CH₃CN/CH₂Cl₂. The ligands used in experiments were synthesized utilizing the same method as reported in the literature^[21]. The rest complexes were obtained according to the same procedure. Complexes **1a–4a** were characterized using matrix-assisted laser desorption/ionization time of flight (MALDI-TOF). **1a**: *m/z*: 336.1 [M]; **2a**: *m/z*: 364.1 [M]; **3a**: *m/z*: 574.3 [M], 609.3 [M-Cl]; **4a**: *m/z*: 588.3 [M] (Fig. 1).

General Procedure for Lactide Polymerization

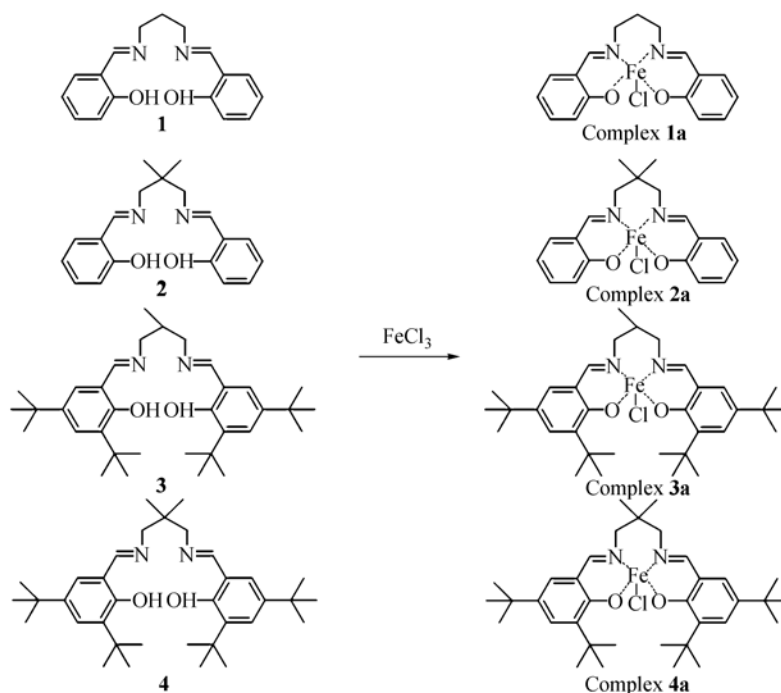
The polymerization was carried out in the 25 mL steel autoclave, which was preprocessed at 120 °C for 12 h, then cooled down to room temperature in a glovebox prior to use. In a general polymerization experiment, the lactide monomer,

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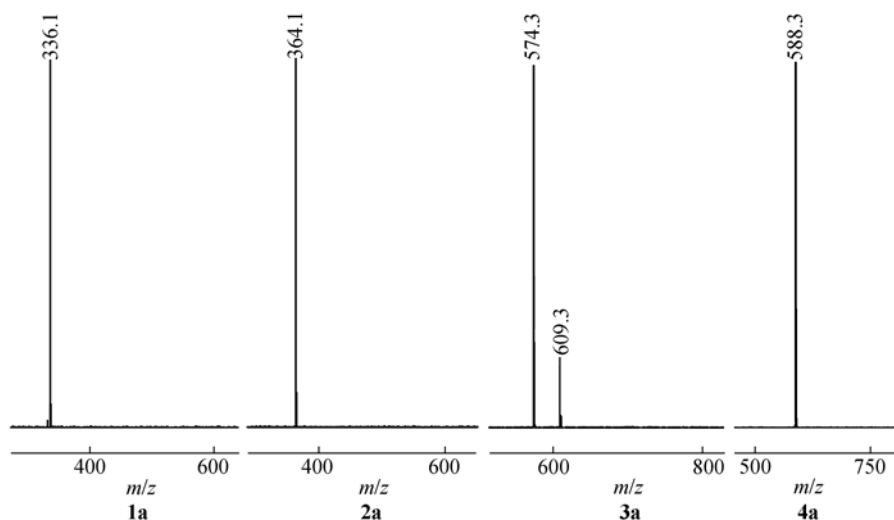
E-mail xpang@ciac.jl.cn (X.P.)

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Scheme 1 Synthetic route for the salen Fe complexes

Fig. 1 Mass spectrum of complexes **1a–4a** (MALDI-TOF-MS)

iron complexes **1a–4a** and propylene oxide were added into an autoclave with stoichiometry. The autoclave was sealed before placed in an oil bath at the desired temperature. When the reaction reached certain reaction time, trace of the mixture was taken out for $^1\text{H-NMR}$ test; the polymer was isolated by precipitation with acidified ethanol and then dissolved in CH_2Cl_2 , then precipitated with acidified ethanol for three times. Finally the polymer was dried under vacuum at $40\text{ }^\circ\text{C}$ for 24 h.

RESULTS AND DISCUSSION

Salen Fe(III) complexes were considered to be efficient catalysts in many fields, but they were barely used in LA polymerization. A series of experiments and analysis were

performed to demonstrate the structure of the complexes and the activities in polymerization of LA.

The single crystal of the complex **3a** was obtained by recrystallization from methanol/acetonitrile. X-ray diffraction analysis illustrated the molecular structure of the complexes. Crystal structural refinements details and the selected bond lengths and angles are listed in Tables 1–3.

Figure 2 depicts the molecular structure of complex **3a**. According to the X-ray diffraction crystal data, $a = 17.8464(4)\text{ \AA}$, $b = 9.6832(2)\text{ \AA}$, $c = 19.7742(5)\text{ \AA}$; $\alpha = 90^\circ$, $\beta = 91.5120(10)^\circ$, $\gamma = 90^\circ$; the crystal is monoclinic. Fe as a center metal atom contains five coordinate bonds and the complex **3a** exhibits an asymmetric structure through the bond lengths of Fe1–O1 , Fe1–O2 , Fe1–N2 , Fe1–N1 and bond angles of $\text{O1–Fe1–N2-121.44(9)^\circ}$, $\text{O2–Fe1–N1-167.85(9)^\circ}$.

Table 1 Sample and crystal data for **3a**

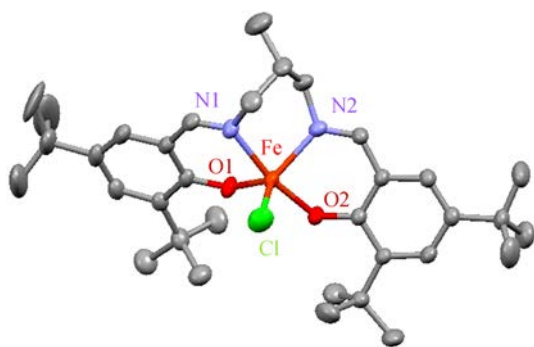
Chemical formula	C ₃₄ H ₅₀ ClFeN ₂ O ₂
Formula weight	610.06 g·mol ⁻¹
Temperature	273(2) K
Wavelength	0.71073 Å
Crystal size	0.260 mm × 0.260 mm × 0.280 mm
Crystal habit	Black block
Crystal system	Monoclinic
Space group	P 1 21/n 1
Unit cell dimensions	$a = 17.8464(4)$ Å $b = 9.6832(2)$ Å $c = 19.7742(5)$ Å $\alpha = 90^\circ$ $\beta = 91.5120(10)^\circ$ $\gamma = 90^\circ$
Volume	3415.99(14) Å ³
Z	4
Density (calculated)	1.186 g·cm ⁻³
Absorption coefficient	0.550 mm ⁻¹
$F(000)$	1308
$R[I > 2 \sigma(I)]$	0.0458
wR (all data)	0.1248
GOOF	1.004

Table 2 Bond lengths (Å) for complex **3a**

Fe1—O1	1.8522(18)	Fe1—O2	1.9035(18)
Fe1—N2	2.086(2)	Fe1—N1	2.115(2)
Fe1—Cl1	2.2459(9)	N1—C15	1.276(3)
N1—C16	1.462(3)	N2—C20	1.289(3)
N2—C19	1.473(3)	O1—C1	1.327(3)

Table 3 Bond angles (°) for complex **3a**

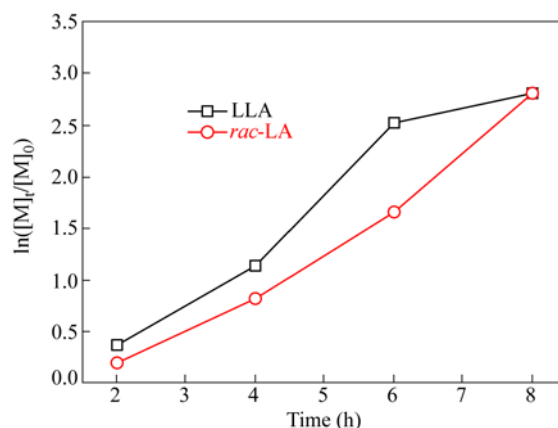
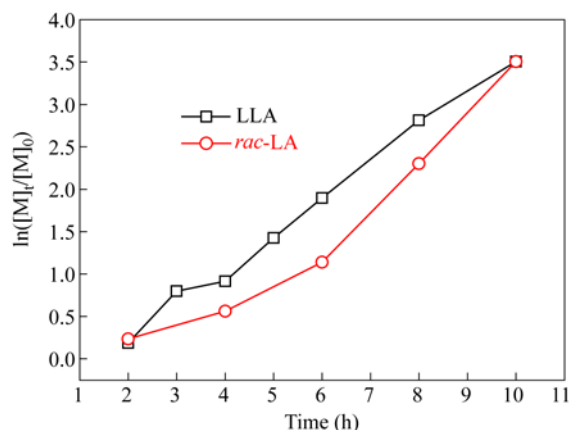
O1—Fe1—O2	96.60(8)	O1—Fe1—N2	121.44(9)
O2—Fe1—N2	85.89(8)	O1—Fe1—N1	86.54(8)
O2—Fe1—N1	167.85(9)	N2—Fe1—N1	82.48(8)
O1—Fe1—Cl1	114.72(7)	O2—Fe1—Cl1	98.29(7)
N2—Fe1—Cl1	122.77(7)	N1—Fe1—Cl1	90.97(7)
C15—N1—C16	120.6(2)	C15—N1—Fe1	125.04(18)
C16—N1—Fe1	114.30(17)	C20—N2—C19	117.1(2)
C20—N2—Fe1	122.83(18)	C19—N2—Fe1	120.09(18)

**Fig. 2** Molecular structure of **3a**
Hydrogen atoms and carbon atoms are omitted for concise. CCDC number: 1571584

The parameter τ was used to evaluate the complexes' configuration whether approximates square pyramidal or trigonal bipyramidal^[22]. When τ equals 0, the complex is the perfect square pyramidal, while perfect trigonal bipyramidal corresponds to τ of 1. As calculated τ value equals 0.77, it performs approximately as trigonal bipyramidal.

In order to illustrate the activity of Salen Fe(III) complexes in polymerization, kinetic studies of lactide polymerization were carried out at different monomer to complex ratios. The monomer conversion was monitored as a function of polymerization time by ¹H-NMR. The kinetic plots calculated from conversion versus time are shown in Figs. 3–6.

The polymerization results demonstrate that all complexes are efficient catalysts in ROP. Complexes **1a** and **2a** have almost the same rate in the polymerization of LA and *rac*-LA according to Figs. 3 and 4, which can also be concluded from the GPC analysis (Table 4, entries 1 and 2)—both of the complexes showed high activity in polymerization but with wide PDI. Complexes **3a** and **4a** were less active than complexes **1a** and **2a** (Figs. 5 and 6); however, they showed a narrow PDI than complexes **1a** and **2a** (Table 4, entries 3 and 4). Comparison of the kinetic plots revealed that the backbone of the ligands affects the activity of the complexes. Substituent effect on salicylaldehyde was considered as the main contribution. Compared to complex **1a**, complex **2a** had

**Fig. 3** Kinetic plots for the ROP of *rac*-LA and LLA by applying **1a** as catalyst in PO with [LA]₀ = 1.4 mol·L⁻¹, $T = 25^\circ\text{C}$ **Fig. 4** Kinetic plots for the ROP of *rac*-LA and LLA by applying **2a** as catalyst in PO with [LA]₀ = 1.4 mol·L⁻¹, $T = 25^\circ\text{C}$

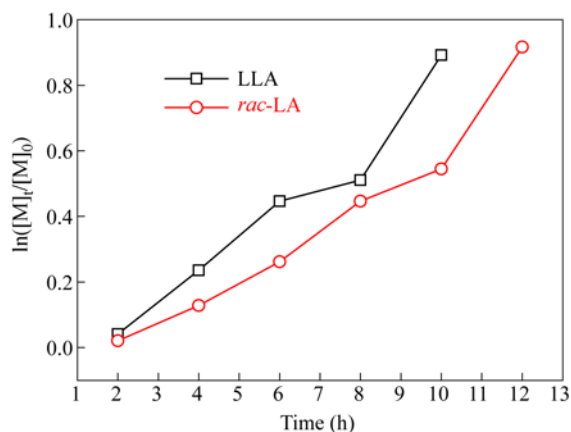


Fig. 5 Kinetic plots for the ROP of *rac*-LA and LLA by applying **3a** as catalyst in PO with $[LA]_0 = 1.4 \text{ mol}\cdot\text{L}^{-1}$, $T = 25 \text{ }^\circ\text{C}$

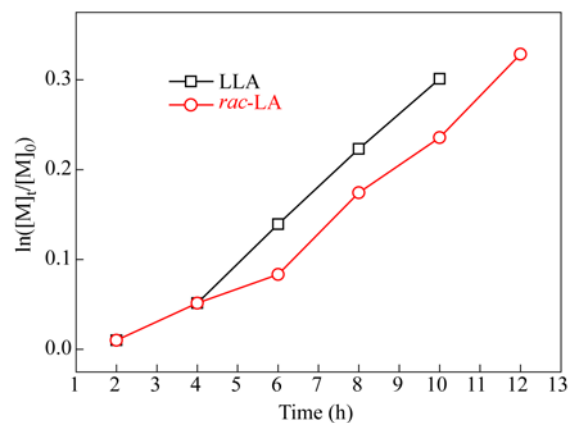


Fig. 6 Kinetic plots for the ROP of *rac*-LA and LLA by applying **4a** as catalyst in PO with $[LA]_0 = 1.4 \text{ mol}\cdot\text{L}^{-1}$, $T = 25 \text{ }^\circ\text{C}$

Table 4 Polymerization data of LLA with complexes **1a–4a** in PO ^a

Entry	Complex	Monomer	[M]/[I]	Time (h)	Con ^b (%)	M_n	PDI ^c	P_m ^d
1	1	LLA	100	8	98	15828	1.78	–
2	2	LLA	100	10	98	8798	2.16	–
3	3	LLA	100	24	92	14582	1.33	–
4	4	LLA	100	12	61	13538	1.11	–
5	1	<i>rac</i> -LA	100	10	99	16126	1.33	0.77
6	2	<i>rac</i> -LA	100	8	98	15686	1.87	0.68
7	3	<i>rac</i> -LA	100	12	56	7555	1.45	0.73
8	4	<i>rac</i> -LA	100	12	54	7969	1.06	0.72

^a All polymerizations were carried out in a 25 mL autoclave at 25 °C, $[LA]_0 = 1.4 \text{ mol}\cdot\text{L}^{-1}$, 2 mL PO; ^b Measured by ¹H-NMR; ^c Obtained by GPC analysis and calibrated against the polystyrene standards. The true value of M_n (calcd) could be calculated according to the formula $M_n = 0.58 M_n \times \text{GPC}^{[23]}$; ^d Measured by homonuclear decoupled ¹H-NMR. P_m is the probability of meso linkage between monomer units.

an amine bridge of 2,2-dimethyl-propane diamine, and the polymerization rate increased sluggishly. And the appearance goes the same when changing the amine bridge on complexes **3a** and **4a**. Then, the substituent on salicylaldehyde broke the deadlock; it exhibited a great increasing on polymerization rate, which makes possible to control the polymerization rate in LA polymerization.

CONCLUSIONS

In conclusion, four Salen Fe-Cl complexes were synthesized successfully. All the complexes can catalyze the ROP of LA in PO solution. The activities of complexes had been studied through the kinetic of polymerization. The different performance of these complexes was attributed to the different bridging part and the substituent of salicylaldehyde. The polymerization rate varied as the backbone of the complexes changed. Kinetic analysis revealed that the substituent effect on salicylaldehyde could affect the catalyst activity acutely while the substituent on amine bridge mildly influenced the catalysts activity.

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