

Supporting Information

Novel Epoxide-Promoted Polymerization of Lactide Mediated by Zinc Guanidine Complex: Potential Strategy for Tin-Free PLA Industry

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1. Experimental Procedures

1.1 General Information

Chemicals

All manipulations were carried out with standard Schlenk techniques under argon protection. All solvents and reagents, unless otherwise specified, were purchased from commercial suppliers, and used without additional processing. Toluene and tetrahydrofuran were refluxed in sodium and distilled under argon. Racemic lactide (*rac*-LA) and L-lactide (*L*-LA) were recrystallized from toluene once prior to use. Cyclohexene oxide (CHO), 1,2-butene oxide (BO), propylene oxide (PO), epichlorohydrin (ECH), and glycidyl methacrylate (GMA) were refluxed over CaH₂ and distilled under argon.

Characterizations

NMR: All ¹H NMR and ¹³C NMR spectra were recorded on a JEOL-400YH spectrometer at a frequency of 400 MHz.

GPC: The molecular weight (*M_n*) and polydispersity (Đ) of the polymer was determined by gel permeation chromatography (GPC) on a Waters 2414 binary system with a refractive index detector, calibrated with polystyrene standards. The column temperature was maintained at 40 °C during the test using THF as the eluent at a flow rate of 1.0 mL/min.

MALDI-TOF-MS: MALDI-TOF-MS were acquired in linear mode in a *m/z* range 1000-10000 using a Bruker microflex LRF-MALDI TOF MS with 2,5-dihydroxybenzoic acid (DHB) as matrix. Samples were dissolved in THF (2-5 mg/mL).

DSC: Differential Scanning Calorimetry (DSC) analysis was performed on NETZSCH DSC 200F3. The experiments were performed by heating the samples from -20 to 200 °C (heating and cooling scans were repeated, at least in triplicate, to ensure reproducibility). Also, the measurements were carried out at a heating rate of 10 °C/min, in nitrogen atmosphere. The degree of crystallinity (*X_c*) is calculated firstly by obtaining the values for melting enthalpy (ΔH_m) and cold crystallization (ΔH_c) as determined and automatically calculated from the DSC thermogram. The reference enthalpy ΔH_m^0 at 100% crystallinity is given as: $\Delta H_m^0 = 93$ J/g (PLA)¹. *X_c* is given by the following equation:

$$X_c = \frac{\Delta H_m - \Delta H_c}{\Delta H_m^0} \times 100$$

ICP-OES: ICP-OES (Inductively coupled plasma-optical emission spectrometry) was pretreated as follows and tested on an Agilent 5110: A polymer sample (134.5 mg) was digested with acid and made up to 25 mL. These 25 mL solutions were subsequently analyzed for Zn content using ICP-OES. Calibration curve was built from 0.5, 1.0, 2.0, 5.0 and 10.0 mg/L. Samples were then measured and correlated relative to the calibration curve.

1.2 Procedural Information

Complex synthesis

Guanidine-based ligand and zinc catalyst used were synthesized with reference to the relevant literature.² The acetonitrile (15 mL) solution of 2-chloro-1,3-dimethylimidazoline (2.53 g, 15 mmol) was added to the acetonitrile (15 mL) solution of 1, 2-cyclohexenediamine (0.85 g, 7.5 mmol) and triethylamine (2.08 mL) at 0 °C. The mixture was stirred by reflux in an oil bath at 83 °C for 12 h. After cooling to room temperature, NaOH (60 mmol) was added, and the solvent along with triethylamine were evaporated under vacuum. Then KOH (30 mL, 50 wt%) solution was added to deprotonate, extracted with acetonitrile (3×30 mL), the organic phase was dehydrated with anhydrous Na₂SO₄, and distilled under reduced pressure to obtain a yellow oil. Yield: 83%.

Zn(CF₃SO₃)₂ (0.1454 g, 0.4 mmol) and the ligand (0.3065 g, 1 mmol) were stirred in 4 mL and 6 mL of THF, respectively. In an oil bath at 55 °C, the ligand solution was added dropwise to the Zn(CF₃SO₃)₂ solution to obtain a white precipitate, which was then filtered, washed three times with THF and diethyl ether. Subsequently, the powder was dried in vacuum to obtain a white powdery solid. Yield: 96%.

Ligand: ¹H NMR (CDCl₃, 400 MHz): δ = 3.22-3.19 (m, 2H), 3.14-3.11 (m, 8H), 2.85-2.84 (m, 4H), 2.65-2.63 (s, 12H), 1.68-1.64 (m, 2H), 1.59-1.57 (m, 2H), 1.37-1.29 (m, 2H), 1.21-1.16 (m, 2H) ppm. ¹³C NMR (CDCl₃, 101 MHz): δ = 157.7, 60.9, 49.1, 36.2, 33.6, 31.1, 24.7 ppm. Complex: ¹H NMR (CDCl₃, 400 MHz): δ = 3.75-3.95 (m, 4H), 3.52 (m, 16H), 3.14 (m, 24H), 2.07-2.10 (m, 4H), 1.65-1.81 (m, 4H), 1.39-1.41 (m, 4H), 1.25-1.37 (m, 4H) ppm. ¹³C NMR (CDCl₃, 101 MHz): δ = 158.0, 68.1, 47.9/49.4, 34.7/35.0, 31.6, 23.0 ppm.

General procedure for polymerization of lactide (*rac*-LA and *L*-LA)

Taking a typical polymerization of CHO/[*rac*-LA]/[Zn] = 1000/5000/1 as an example: The polymerization is carried out in a 20.0 mL pre-dried tube. Appropriate amounts of zinc complex (5 μmol), CHO (5 mmol) and *rac*-LA (25 mmol) were added in the glove box; the mixture was then placed in an oil bath with a pre-set temperature and reacted for a predetermined time. After cooling to room temperature with water and taking out a small amount of the reaction mixture for ¹H NMR analysis, the remaining mixture was dissolved with a small amount of dichloromethane and precipitated with a large amount of ethanol. The resulting polymer was collected, washed several times with ethanol and dried overnight under vacuum at 45 °C.

2. Supplementary Figures and Tables

2.1 Characterization of Zinc Complex

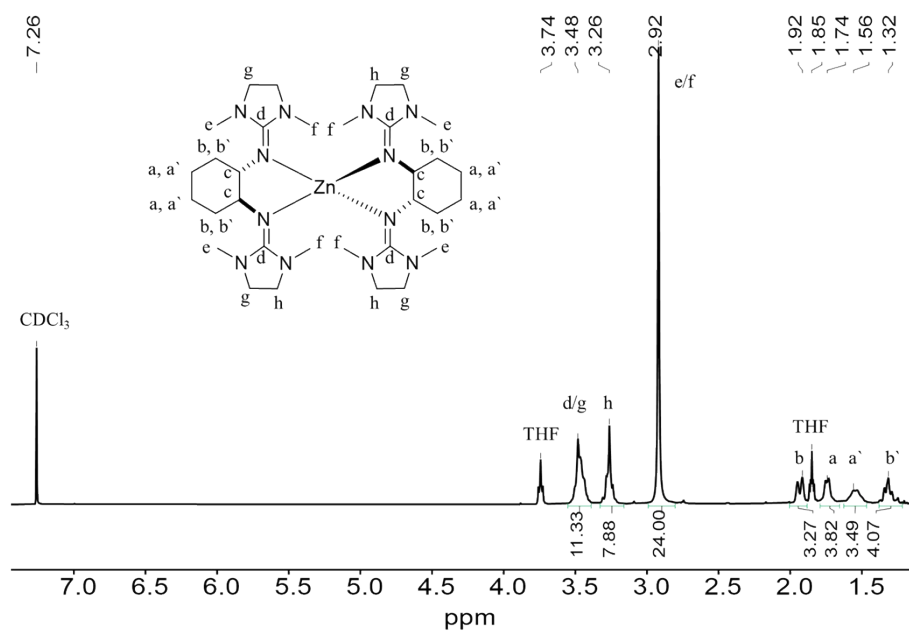


Figure S1. ¹H-NMR spectrum of the zinc complex (CDCl₃, 400 MHz).

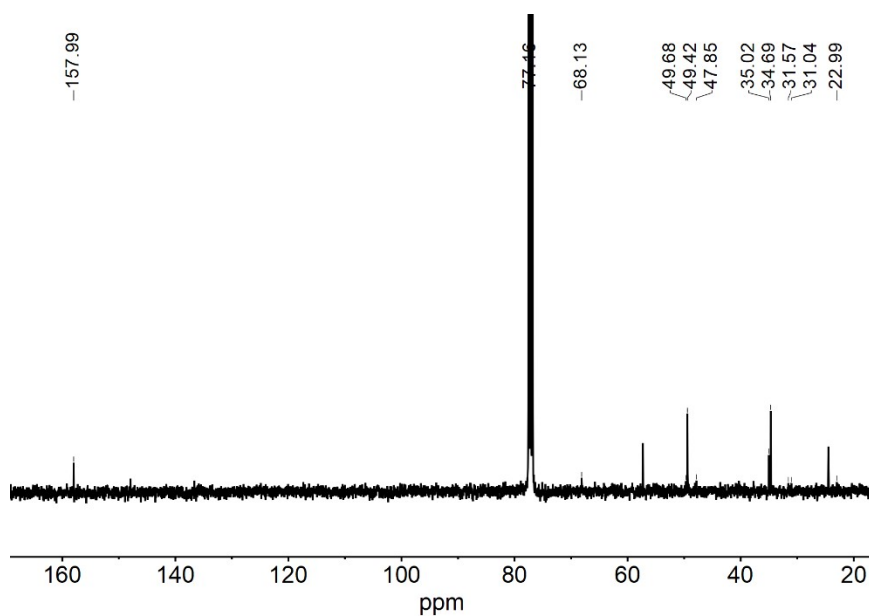


Figure S2. ¹³C-NMR spectrum of the zinc complex (CDCl₃, 101 MHz).

2.2 NMR Characterization

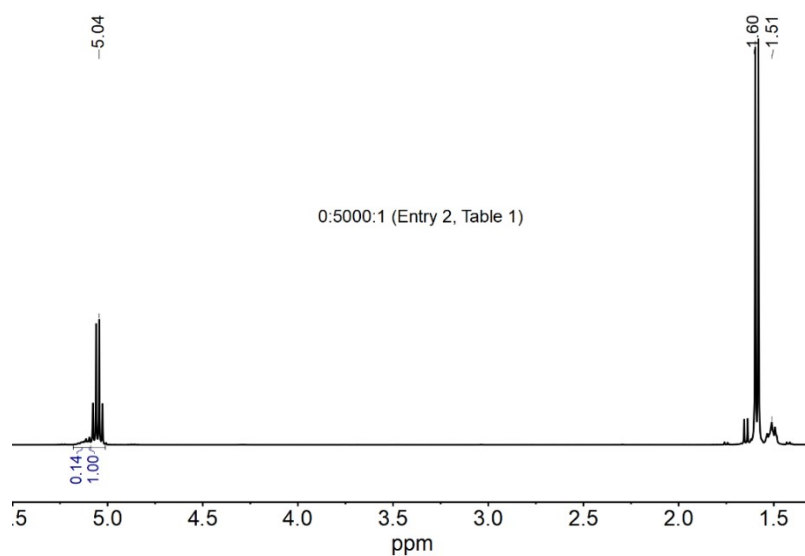


Figure S3. Example of ¹H NMR spectrum of *rac*-LA polymerization. CHO/[*rac*-LA]/[Zn] = 0:5000:1, conversion=14% (Entry 2, Table 1).

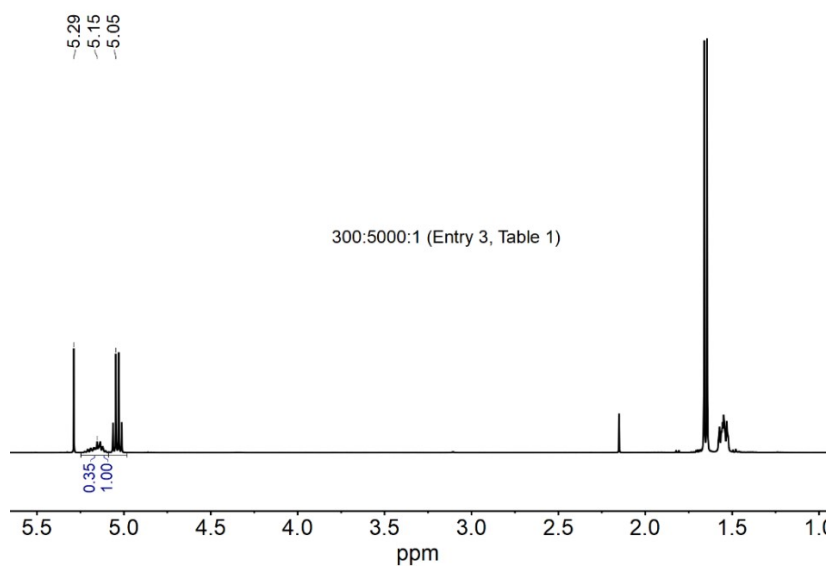


Figure S4. Example of ¹H NMR spectrum of *rac*-LA polymerization. CHO/[*rac*-LA]/[Zn] = 300:5000:1, conversion=35% (Entry 3, Table 1).

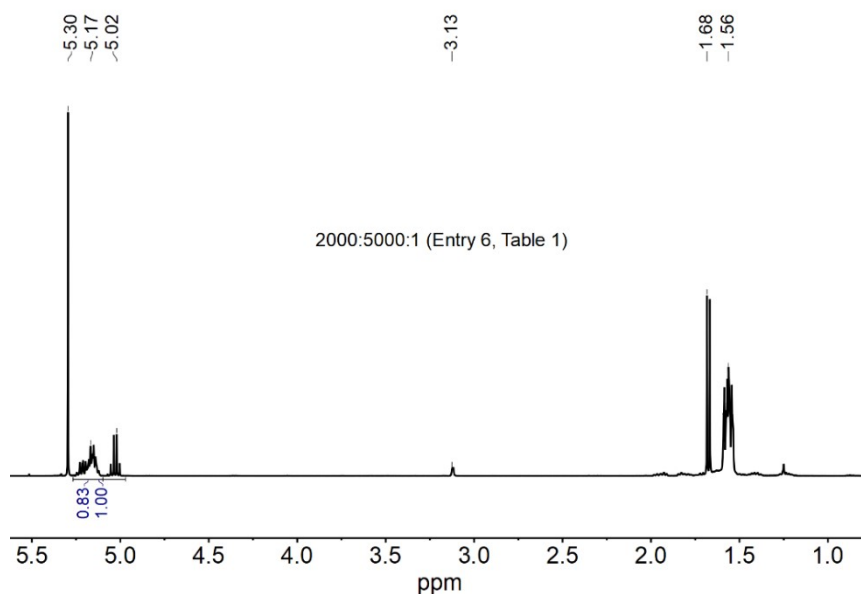


Figure S5. Example of ^1H NMR spectrum of *rac*-LA polymerization. $\text{CHO}/[\textit{rac}\text{-LA}]/[\text{Zn}] = 2000:5000:1$, conversion=83% (Entry 6, Table 1).

The parameter P_m is the tetrad probability to give *meso* enchainment between monomer units and is determined from the methine region of the homonuclear decoupled ^1H NMR spectrum: $[\text{mmm}] = P_m^2 + (1 - P_m)P_m/2$, $[\text{mmr}] = [\text{rmm}] = (1 - P_m)P_m/2$, $[\text{rmr}] = (1 - P_m)^2/2$, and $[\text{mrm}] = [(1 - P_m)^2 + P_m(1 - P_m)]/2$.

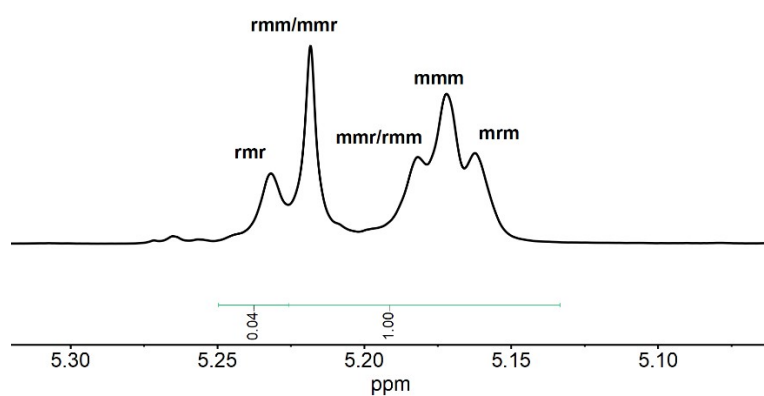


Figure S6. Homonuclear decoupled ^1H NMR spectrum of the methine part of poly(*rac*-LA), $P_m = 0.72$. (Entry 2, Table 1).

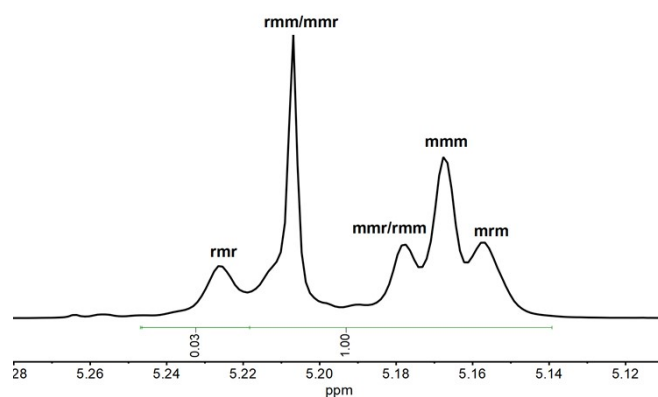


Figure S7. Homuncular decoupled ^1H NMR spectrum of the methine part of poly(*rac*-LA), $P_m = 0.76$. (Entry 3, Table 1).

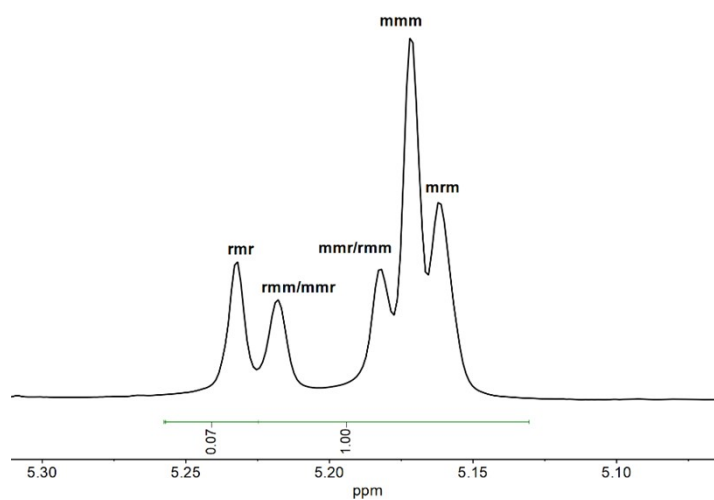


Figure S8. Homuncular decoupled ^1H NMR spectrum of the methine part of poly(*rac*-LA), $P_m = 0.63$. (Entry 6, Table 1).

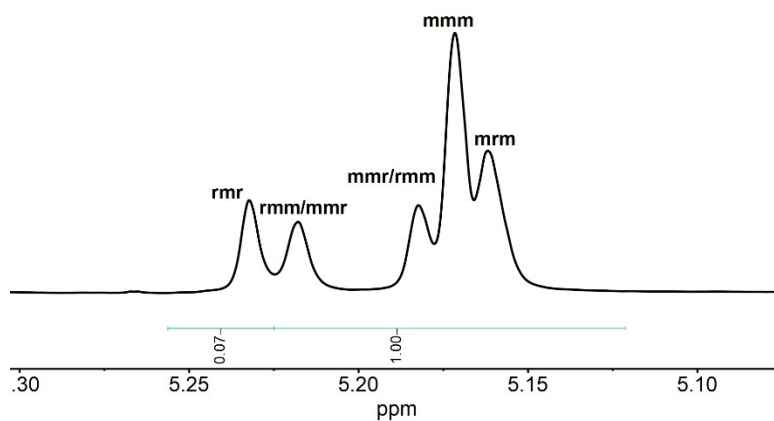


Figure S9. Homuncular decoupled ^1H NMR spectrum of the methine part of poly(*rac*-LA), $P_m = 0.63$. (Entry 3, Table 2).

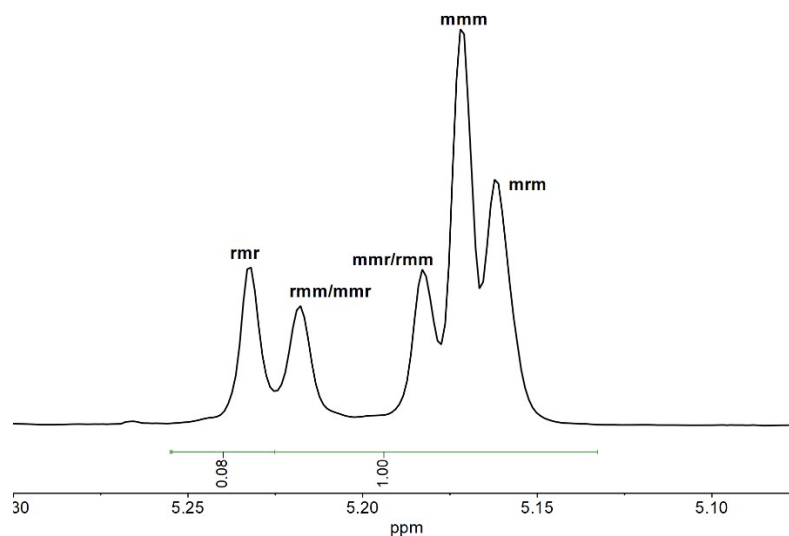


Figure S10. Homuncular decoupled ^1H NMR spectrum of the methine part of poly(*rac*-LA), $P_m = 0.60$. (Entry 4, Table 2).



Figure S11. The images show, from left to right, the crude product when the reaction was stopped, the untreated product, and the purified product.

2.3 Polymerization Results

Table S1. ROP of *rac*-LA initiated by the complex/epoxide catalytic system^a

Entry	Co-initiator	Cat.	Co-initiator:LA:cat.	t/min	Conv. ^b / %	M_n^c	D^c
1	PO	Zn	1000:5000:1	20	85	111.4	1.33
2	BO	Zn	1000:5000:1	20	54	60.6	1.41
3	ECH	Zn	1000:5000:1	20	92	28.8	1.43
4	GMA	Zn	1000:5000:1	20	94	16.0	1.32
5 ^d	-	Zn	0:5000:1	20	0	-	-
6 ^e	-	Sn(Oct) ₂	0:5000:1	20	27	52.7	1.29

^a Conditions: 150 °C, 5 μmol [Zn]. ^b According to ^1H NMR. ^c $\text{kg}\cdot\text{mol}^{-1}$, determined by GPC in THF vs. polystyrene standards using a correcting factor of 0.58.³ ^d Using BnOH as the co-catalyst, the reaction was carried out according to monomer: catalyst: BnOH = 5000:1:2. ^e Using Sn(Oct)₂ as catalyst.

2.4 GPC Traces for Polymer Degradation

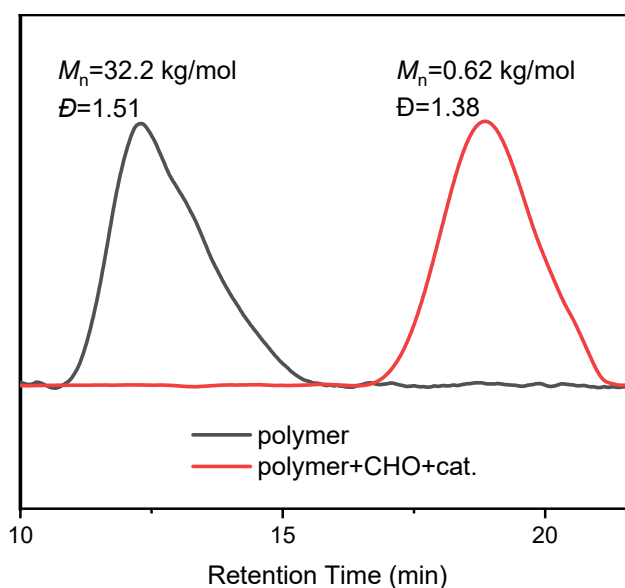


Figure S12. GPC traces: Obtained poly(*rac*-LA) (entry 2, Table 2) vs. the product of the polymer after 1 h reaction in the presence of CHO and catalyst (conditions: Polymer/[cat.] = 100/1, 0.2 mL CHO, 180 °C)

2.5 Thermal Analysis

Table S2. Thermal analysis of selected PLAs^a

	CHO:LA:cat.	t/min	M_n /(kg/mol) ^b	P_m ^c	T_g /°C	T_m /°C	ΔH_m /J/g	X_c /%
<i>rac</i> -LA	2000:5000:1	20	60.8	0.63	50.8	-	-	-
	1000:10000:1	20	50.1	ND ^d	45.8	-	-	-
	5000:50000:1	60	36.7	0.63	50.4	-	-	-
	5000:50000:1 ^e	60	6.3	0.60	49.4	-	-	-
<i>L</i> -LA	1000:5000:1-20 min	20	22.1 ^f	ND	60.2	176.8	52.7	87.0
	1000:5000:1-7.5 min	7.5	23.7 ^f	ND	60.7	175.6	40.8	75.9

^a DSC experimental conditions are reported in Supporting Information. ^b Experimental M_n values determined by GPC in THF vs. polystyrene standards using a correcting factor of 0.58.³ ^c P_m is the probability of forming a new *m*-triad. ^d Not determined. ^e 180 °C. ^f M_n values of PLLA was determined by GPC in CHCl₃ vs. polystyrene standards with a correcting factor of 0.58.³

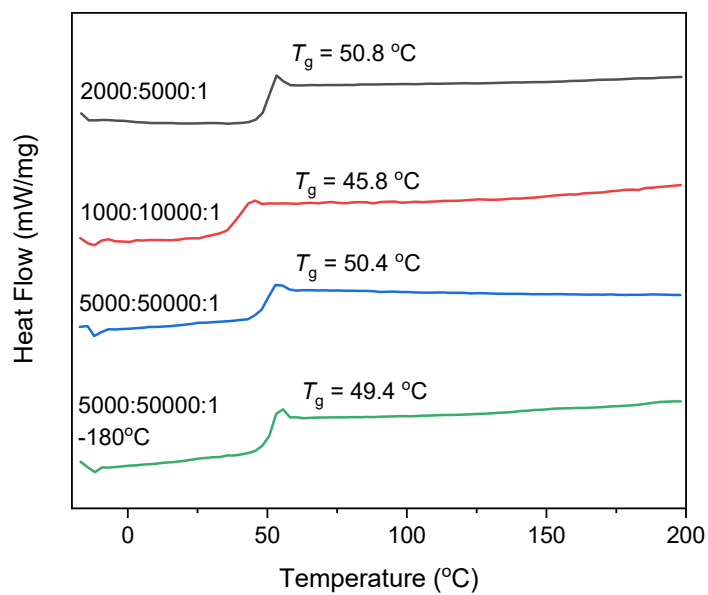


Figure S13. Typical second heating DSC runs of poly(*rac*-LA) obtained at different molar ratios and temperatures (entries 6, 10 and 11, Table 1; entry 4, Table 2).

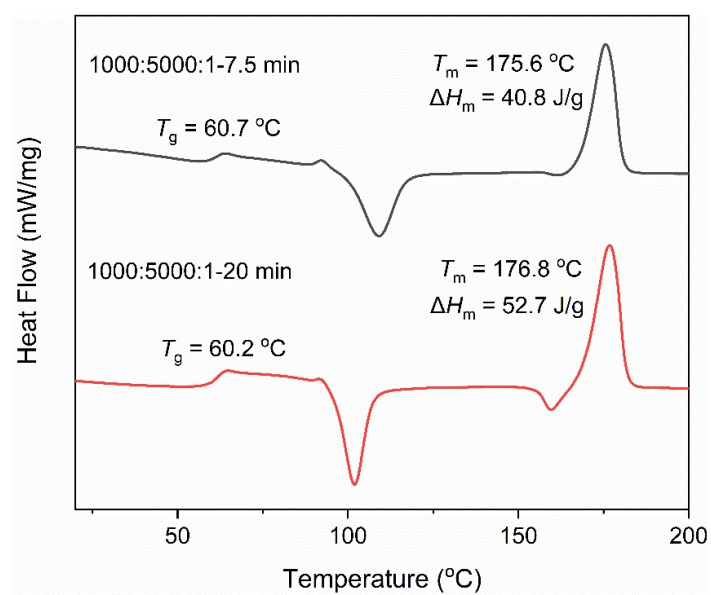


Figure S14. Typical second heating DSC runs of poly(*L*-LA). Samples are from Table S2.

2.6 Kinetic Study

Table S3. Kinetic study of ROP of *rac*-LA and *L*-LA catalyzed by CHO/[Zn] system.^a

monomer	t/min	Temp./°C	Conv. ^b /%	M_n /(kg/mol) ^c	\bar{D} ^c
<i>L</i> -LA	6	150	16	-	-
	7	150	73	27.2	1.37
	7.5	150	77	23.7	1.51
	8	150	86	32.5	1.57
<i>rac</i> -LA	10	150	61	20.5	1.59
	12	150	66	25.3	1.34
	16	150	83	27.1	1.40
	18	150	86	30.2	1.53
	3	180	61	28.1	1.37
	4	180	67	33.9	1.38
	4.5	180	69	46.6	1.42
	7.5	180	82	32.5	1.37

^a Condition: CHO/[LA]/[Zn] = 1000/5000/1. ^b According to ¹H NMR. ^c Experimental M_n values determined by GPC in THF vs. polystyrene standards using a correcting factor of 0.58.³

2.7 MALDI-TOF-MS Spectra

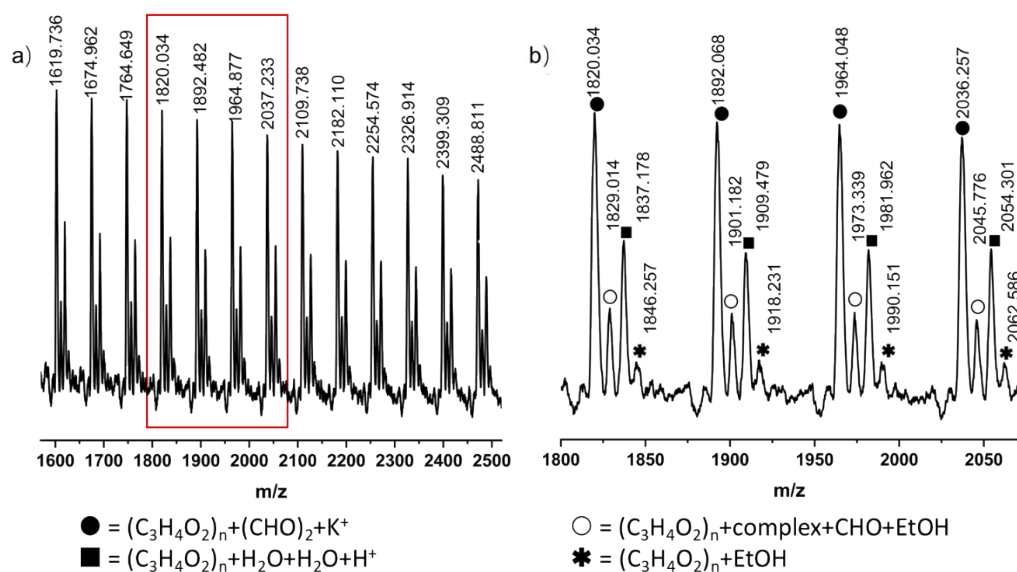


Figure S15. MALDI-TOF-MS spectrum of PLA as obtained in entry 4, Table 2. a) Region from 1600 to 2500 m/z. b) Enlargement of Figure S14, region from 1800 to 2070 m/z; with symbols ○, ●, ○, and ← indicate the species on the bottom.

The observation of ethanol as end group can be traced back to its use for polymer precipitation; the presence of water as end group originates from the impurity of LA.^{2,4,5} The presence of EtOH in Figure 3a may be due to its role as a precipitant and its coordination with the complex during the precipitation process.

2.8 The Role of CHO

To investigate the role of CHO, the following experiments were conducted: The polymerization was carried out in a 20.0 mL pre-dried tube. CHO (100 or 1000 equivalents) was pre-stirred with the catalyst at 150 °C for 5 min, then 5000 equivalents of LA monomer was added and the reaction was stopped by water cooling after 20 min. A minute quantity was extracted for the purpose of ¹H NMR examination. The collected data and ¹H NMR spectra are presented in Table S4 and Figure S16.

Table S4. Polymerization after stepwise addition of CHO, catalyst and monomer.^a

Entry	CHO:cat.:LA	t/min	Conv. ^{b/} %
1	100:1+5000	5+20	46
2	1000:1+5000	5+20	84
3 ^c	300:1:5000	20	35
4 ^c	1000:1:5000	20	88

^a Conditions: 5 μmol [Zn], 150 °C. ^b According to ¹H NMR. ^c CHO, catalyst and monomer were added together for the reaction, data from entries 3 and 5 in Table 1 in the main text.

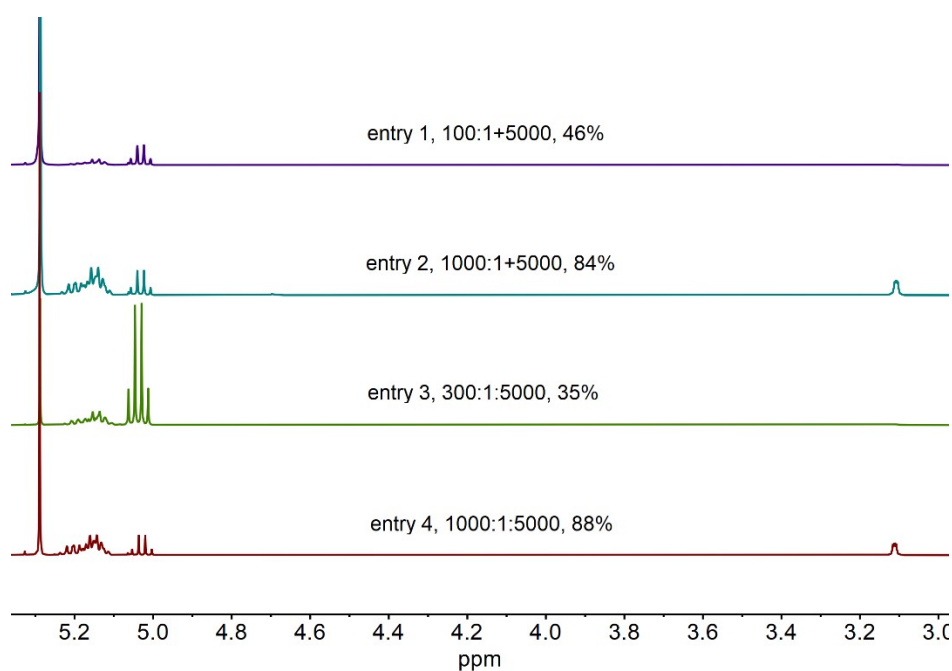


Figure S16. ¹H NMR spectra of *rac*-LA polymerization, including stepwise and one-step reactions (entries 1-4, Table S4).

2.9 ICP-OES Data

Table S5. Zn residue content^a

PLA sample	Zn content
Unpurified polymer (entry 11, Table 1)	15.5 mg/kg (15.5 ppm)
Precipitated polymer	6.7 mg/kg (6.7 ppm)

^a Zn content as derived from inductively coupled plasma-optical emission spectrometry in 25 mL sample solution, calculated Zn content in original polymer samples, and their weight content.

3. References

- (1) Fischer, E. W.; Sterzel, H. J.; Wegner, G. Investigation of the structure of solution grown crystals of lactide copolymers by means of chemical reactions. *Kolloid Z. Z. Polym.* **1973**, *251*, 980-990.
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- (5) Impemba, S.; Della Monica, F.; Grassi, A.; Capacchione, C.; Milione, S., Cyclic polyester formation with an [OSSO]-type iron(III) catalyst. *ChemSusChem* **2020**, *13*, 141-145.