

Literature Report 9

Organocatalytic Stereoselective Ring Opening Polymerization of *rac*-Lactide

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Checker : Zi-Biao Zhao

Date : 2019-09-16

Chen, E. Y.-X. *et al. J. Am. Chem. Soc.* **2015**, *137*, 12506.
Williams, C. K. *et al. Angew. Chem. Int. Ed.* **2019**, *58*, 6007.

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CV of Charlotte K. Williams

Education:



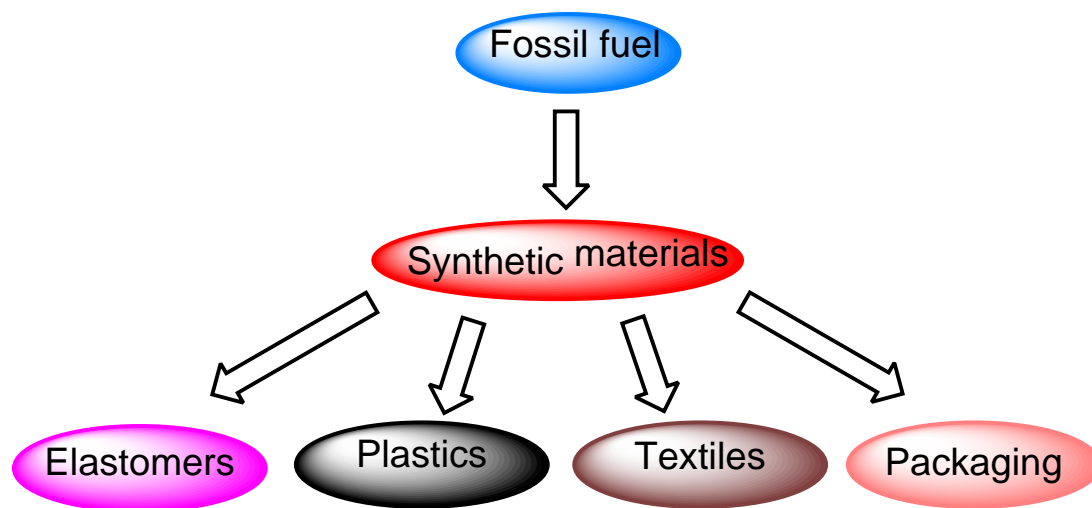
Charlotte K. Williams

- ❑ **2001** B.S. and Ph.D, Imperial College London
- ❑ **2001–2002** Postdoc., University of Minnesota (Prof. Bill Tolman)
- ❑ **2002–2003** Postdoc., Cambridge University (Prof. Andrew Holmes)
- ❑ **2003–2007** Lecturer, Imperial College London
- ❑ **2007–2009** Senior Lecturer, Imperial College London
- ❑ **2009–2012** Reader, Imperial College London
- ❑ **2012–Present** Professor, Imperial College London

Research:

- ★ The study of metal complexes for use as homogeneous catalysts to make polymers, fuels and materials;
- ★ Using renewable resources to make useful products.

Synthetic Materials



Advantages

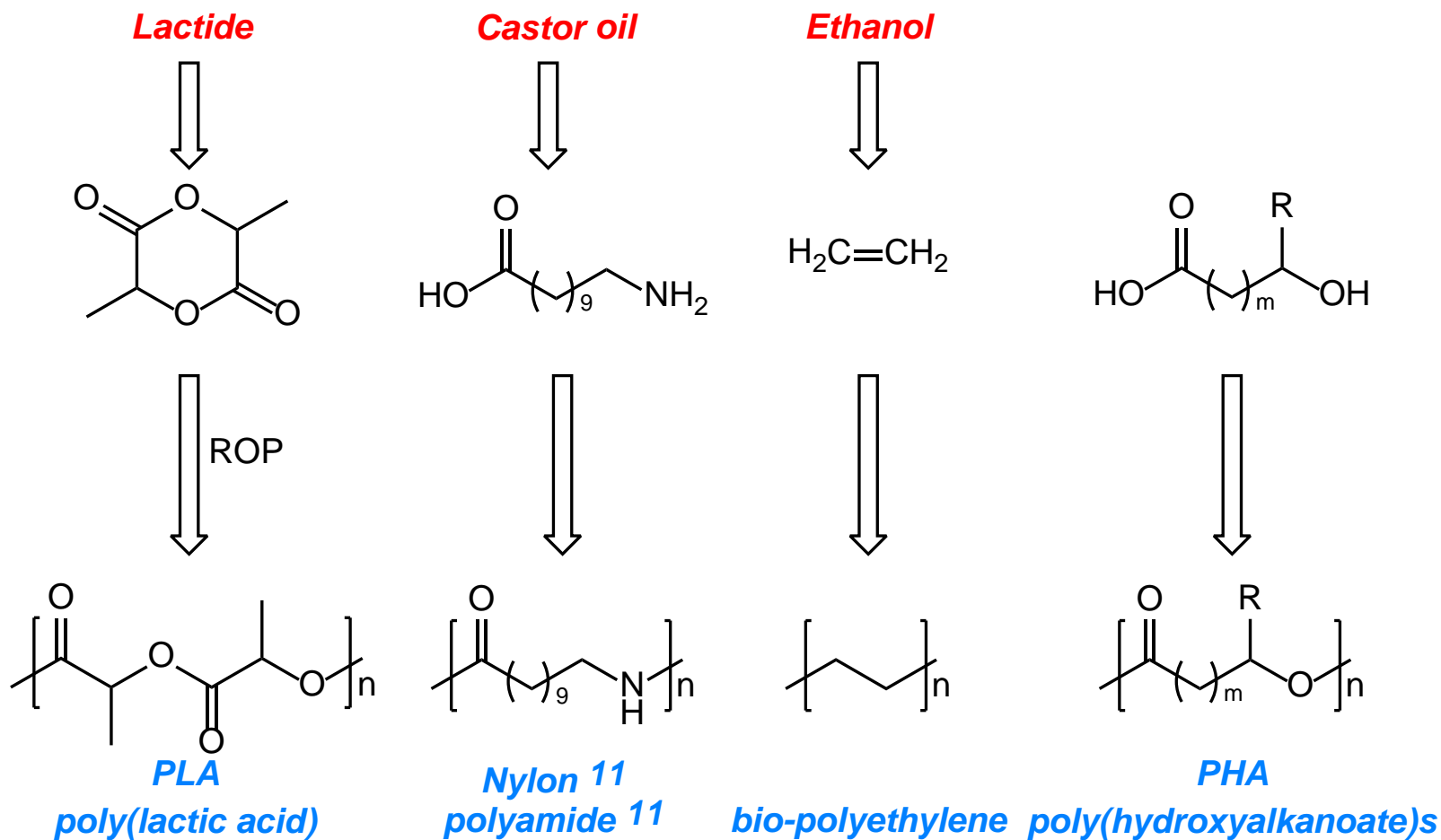
- Durability;
- Elasticity;
- Oxidative stability;
- Hydrolytic stability.

Disadvantages

- Limited resources;
- Aging property;
- Recycling process;
- Inflammability.

Du, G. *et al.* *ACS Sustainable Chem. Eng.* **2018**, 6, 2491.

Renewable and Degradable Polymers



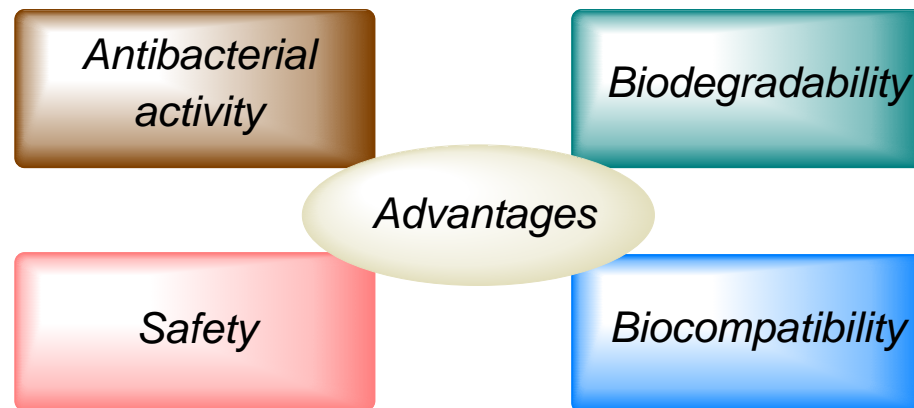
Hartwig, J. F. *et al. Angew. Chem. Int. Ed.* **2016**, 55, 11872.

Poly(lactic acid)

- 聚乳酸（PLA）是一种具有优良生物兼容性和可生物降解性的合成高分子材料。
- 合成PLA的最初原料来源于从小麦、玉米、木薯等植物中提取出的淀粉。淀粉经过酶分解得到葡萄糖，再经过生物合成或化学合成得到乳酸。
- 聚乳酸在土壤和水中，30天内经过微生物、水、酸和碱的作用会分解为 CO_2 和 H_2O 。



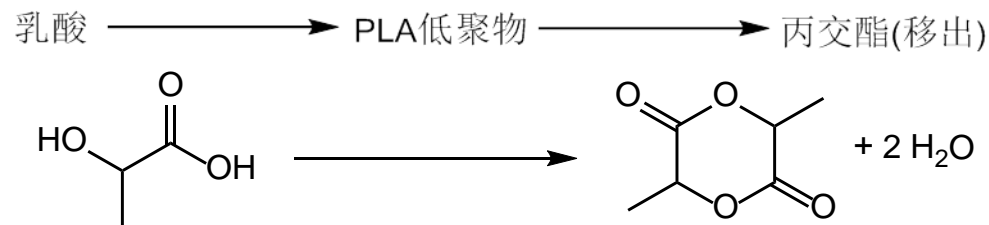
PLA vs Plastics



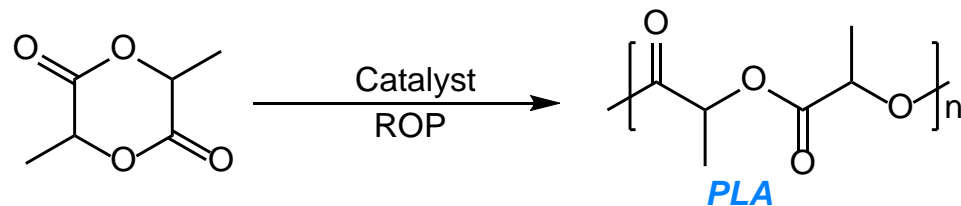
Synthesis of PLA

丙交酯聚合法:

➤ 乳酸原料转化为丙交酯



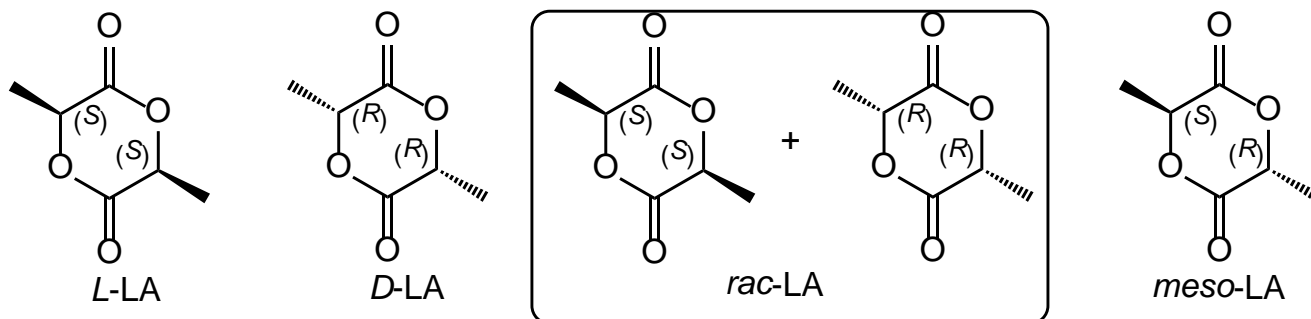
➤ 丙交酯开环聚合得到高分子量PLA产品



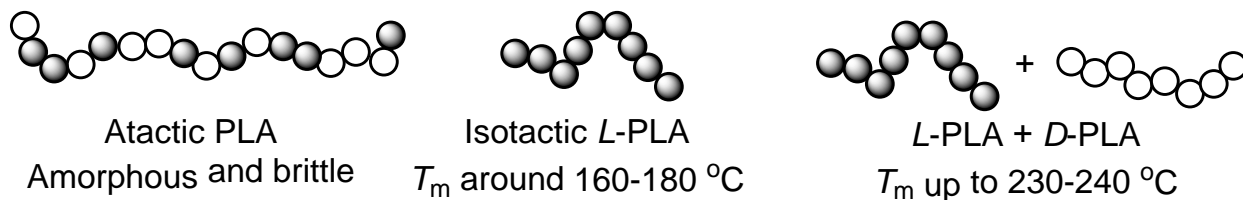
乳酸直接聚合法:

➤ 乳酸溶液聚合、熔融聚合、直接固相聚合。

Ring Opening Polymerization of *rac*-Lactide



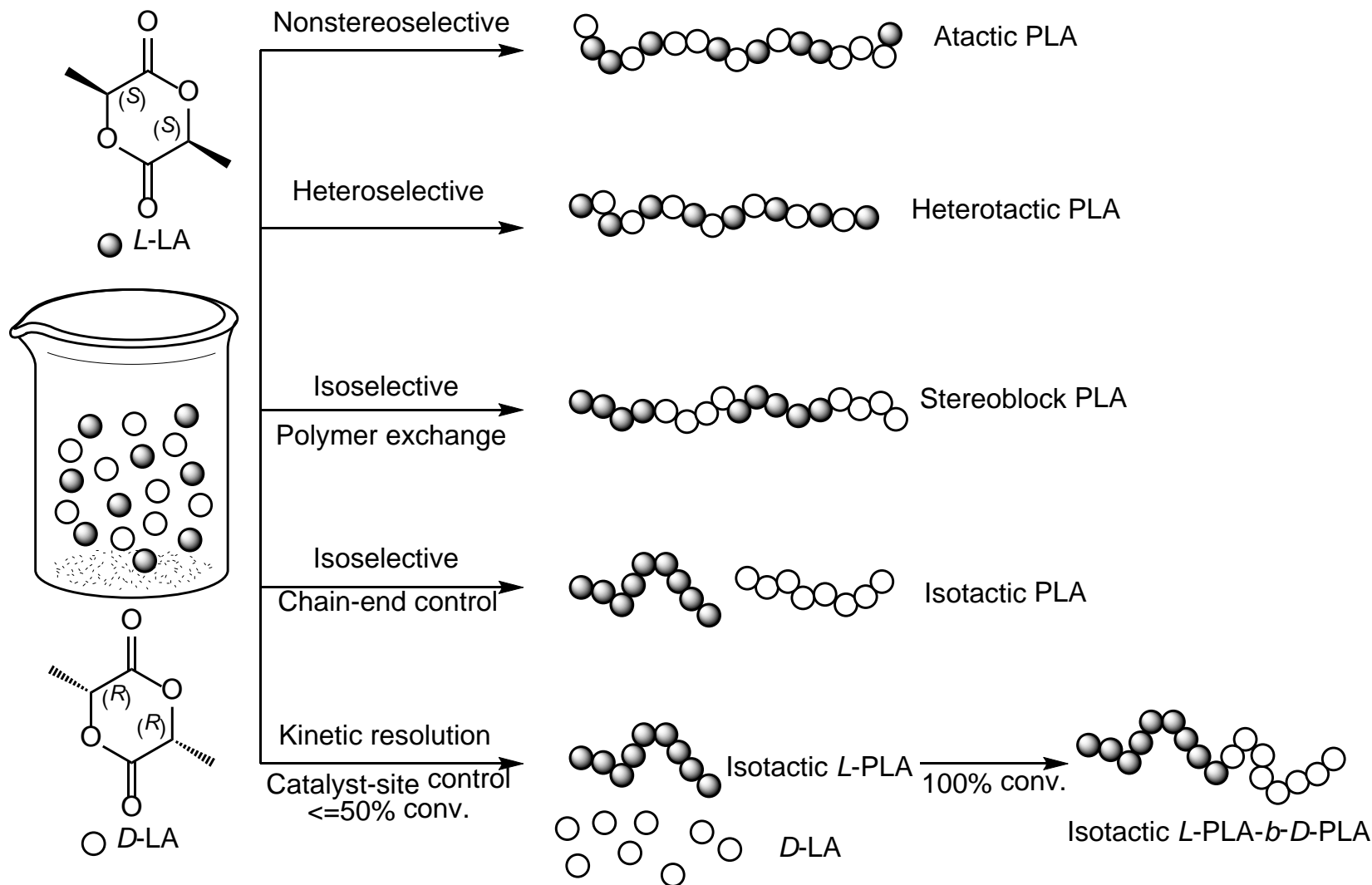
The tacticity (stereomicrostructure) has a drastic effect on the polymer properties such as T_g and T_m .



*The synthesis of high melting stereocomplex PLA directly from inexpensive feedstock *rac*-LA has been an important synthetic target being exploited.*

Wade, C. G. *et al. J. Am. Chem. Soc.* **2007**, 129, 12610.

Ring Opening Polymerization of *rac*-Lactide

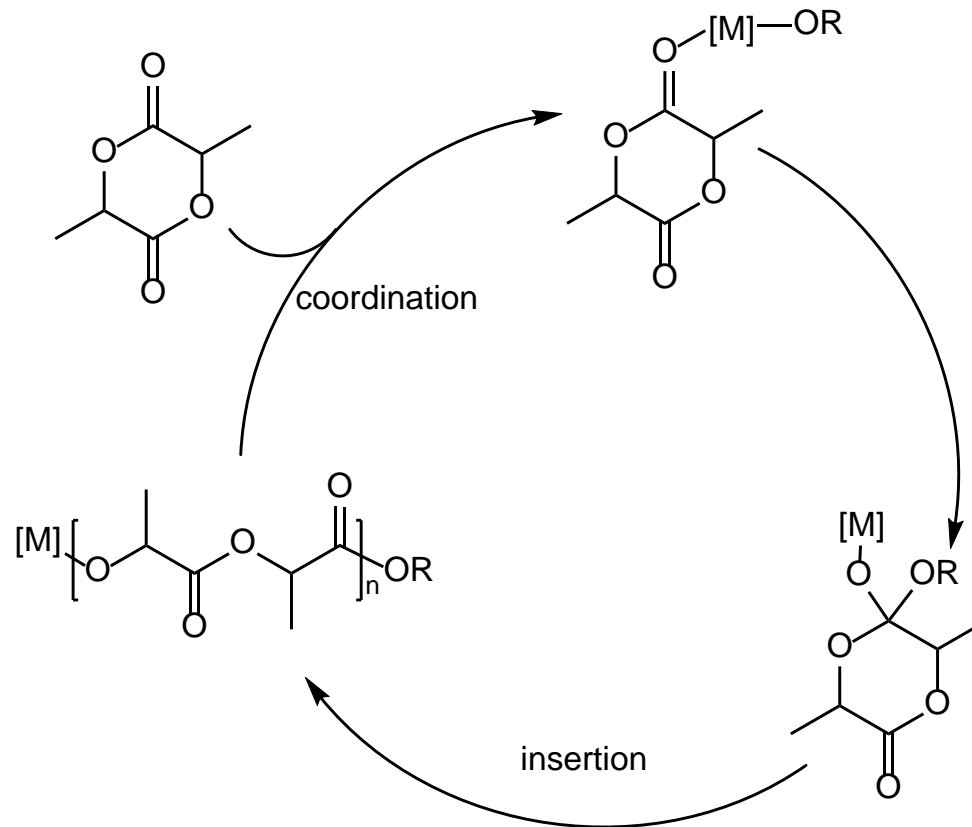


Chen, E. Y.-X. *et al. Macromolecules* **2011**, *44*, 4116.

Mechanism of ROP of *rac*-Lactide

Mechanism

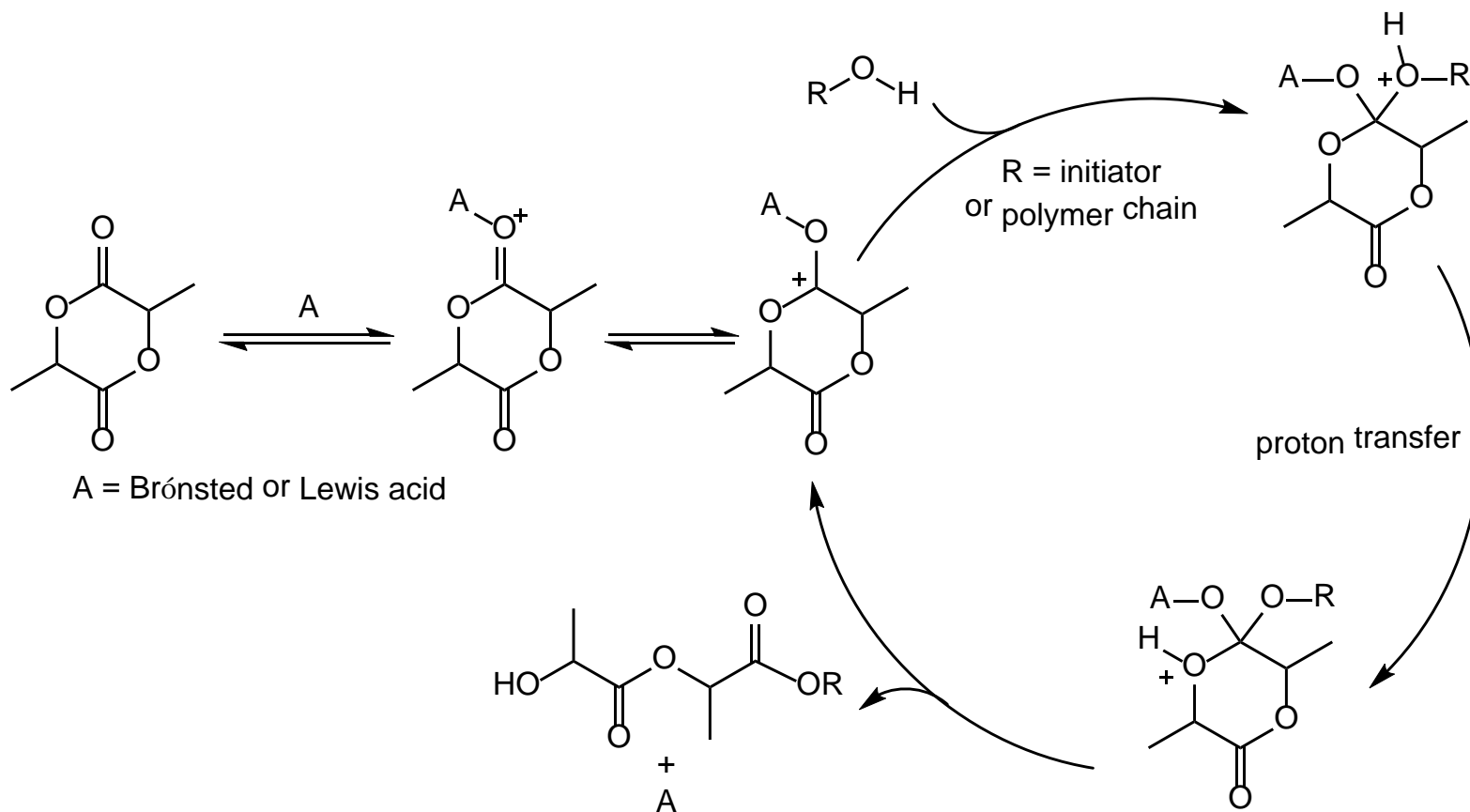
➤ Coordination–Insertion Mechanism



Mechanism of ROP of *rac*-Lactide

Mechanism

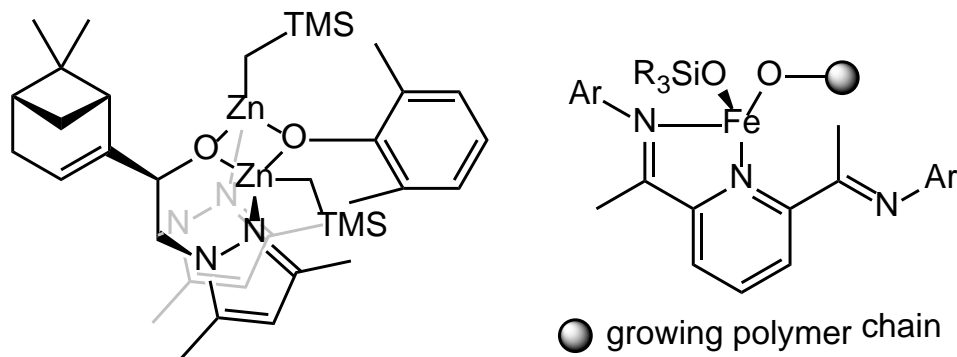
➤ Activated Monomer Mechanism



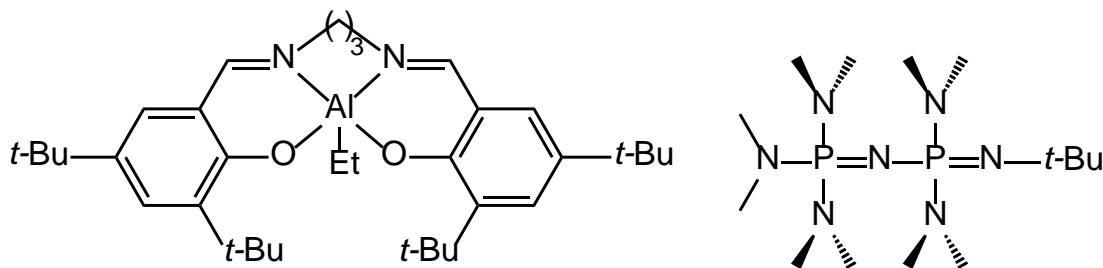
Stereocontrol Mechanism of ROP of *rac*-Lactide

Mechanism

- **ESC (Enantiomorphic site-control):** the chirality of the catalyst defines the stereochemistry of the monomer insertion.



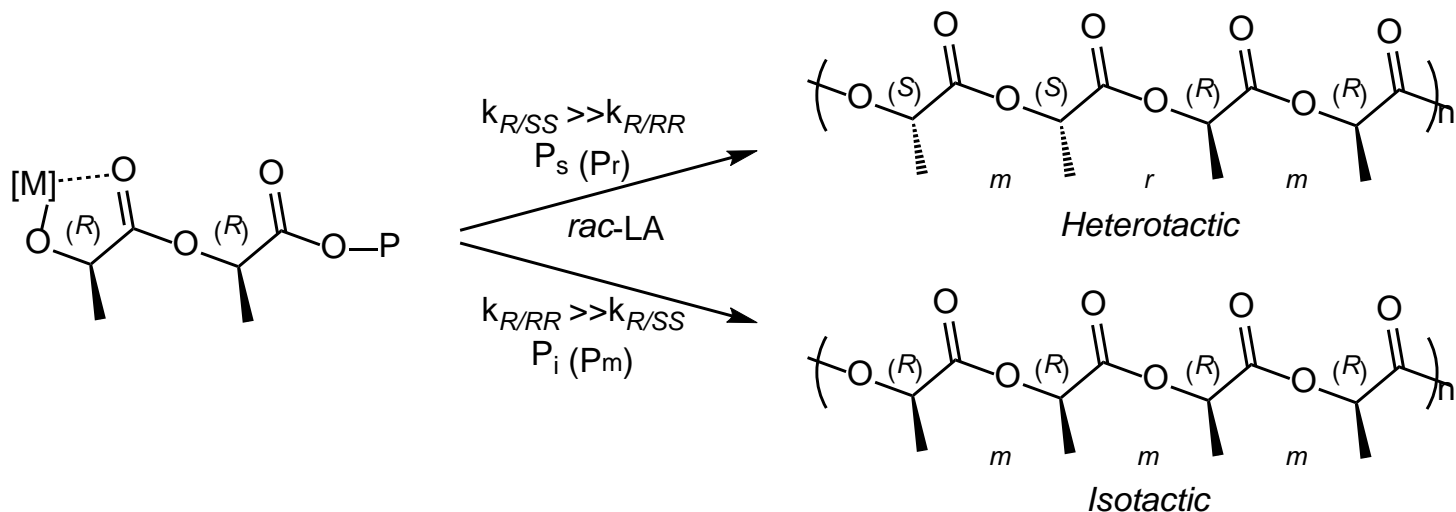
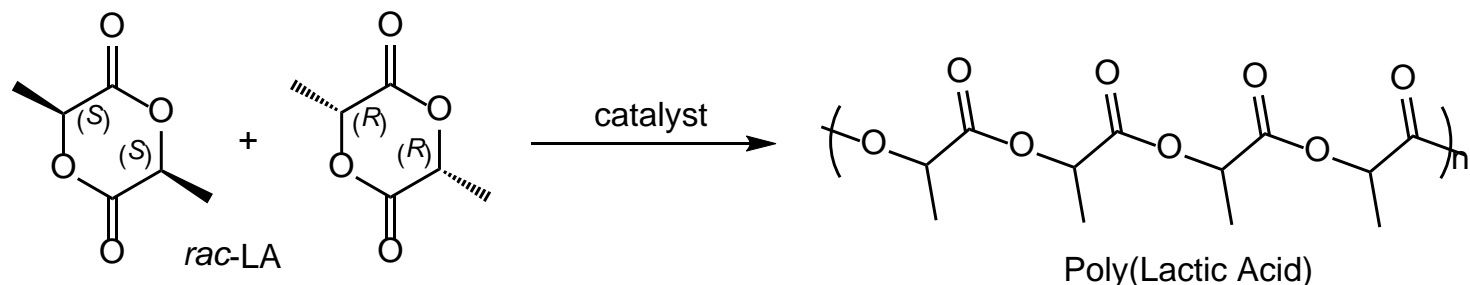
- **CEC (Chain-end control):** the stereochemistry of the last inserted monomer defines the stereochemistry of the subsequent ring-opening step.



Stereoselective ROP of *rac*-Lactide

P_s and P_i (P_r and P_m)

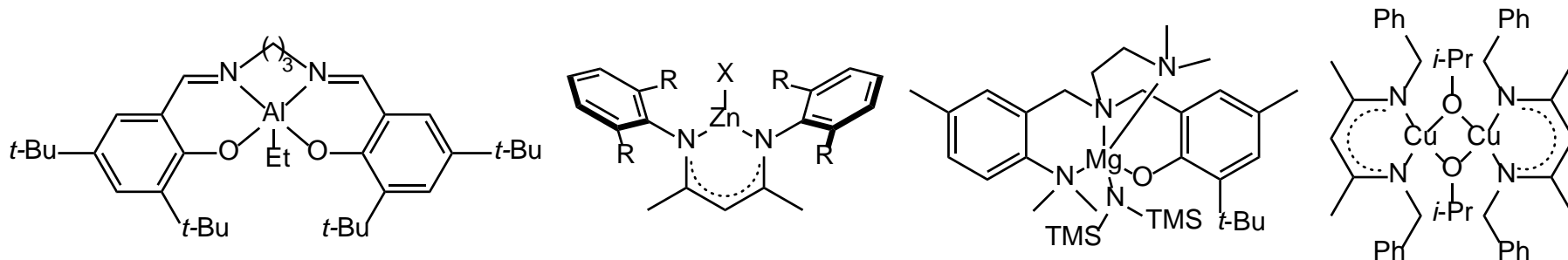
- P_s : The percentage of syndiotactic enchainment between lactide units;
- P_i : The percentage of isotactic enchainment between lactide units.



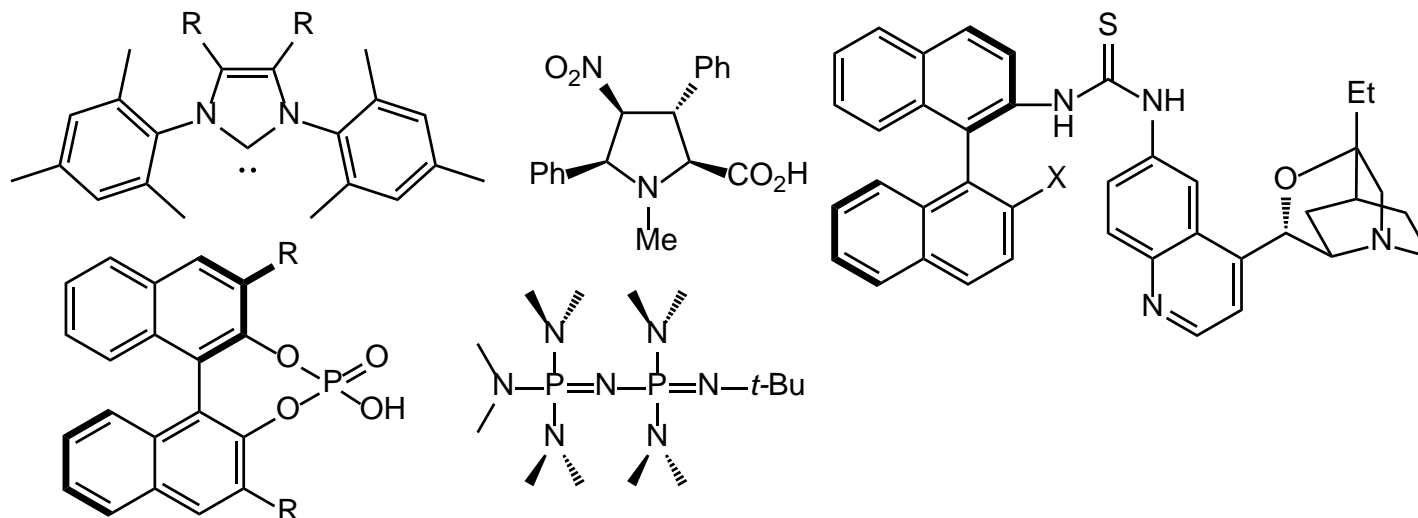
Coates, G. W. *et al.* *J. Am. Chem. Soc.* **2001**, 123, 3229.

Stereoselective ROP of *rac*-Lactide

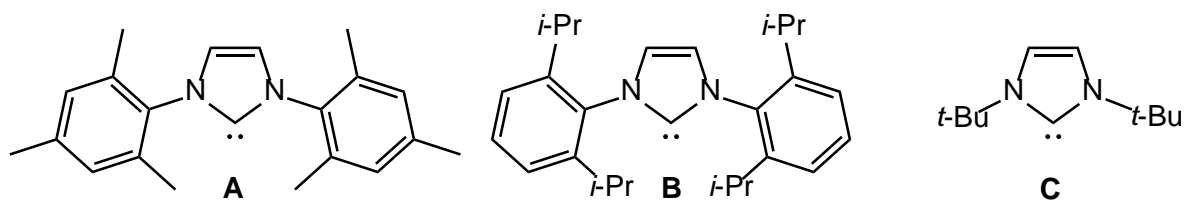
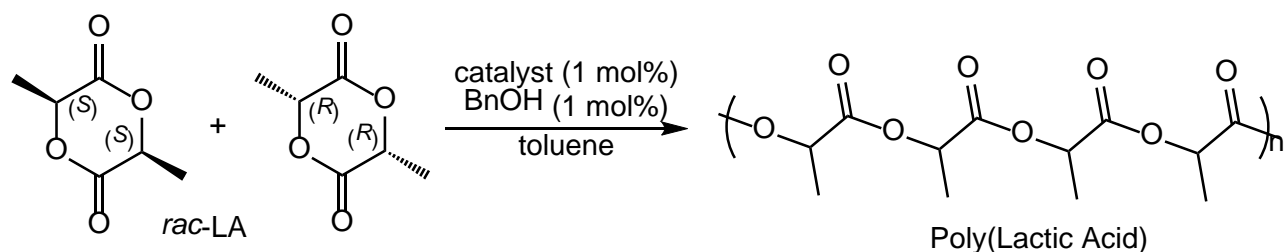
Metal-based catalysts for ROP of *rac*-lactide



Organocatalysts for ROP of *rac*-lactide



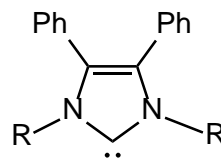
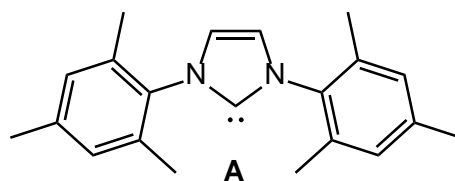
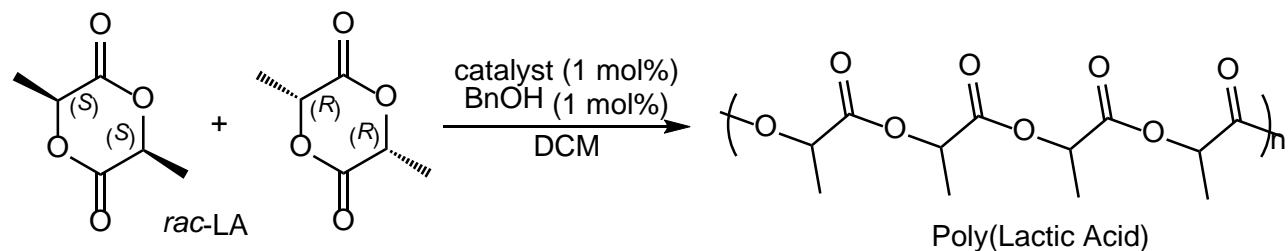
Organocatalytic ROP of *rac*-Lactide



Entry	cat	T (°C)	conv. (%)	M_n	PDI	P_i
1	A	25	98	16.9	1.23	0.59
2	A	-20	71	15.9	1.26	0.75
3	B	25	92	8.4	1.39	0.60
4	C	25	95	7.0	1.36	0.55

Tolman, W. B. *et al. Chem. Commun.* **2004**, 2504.

Organocatalytic ROP of *rac*-Lactide



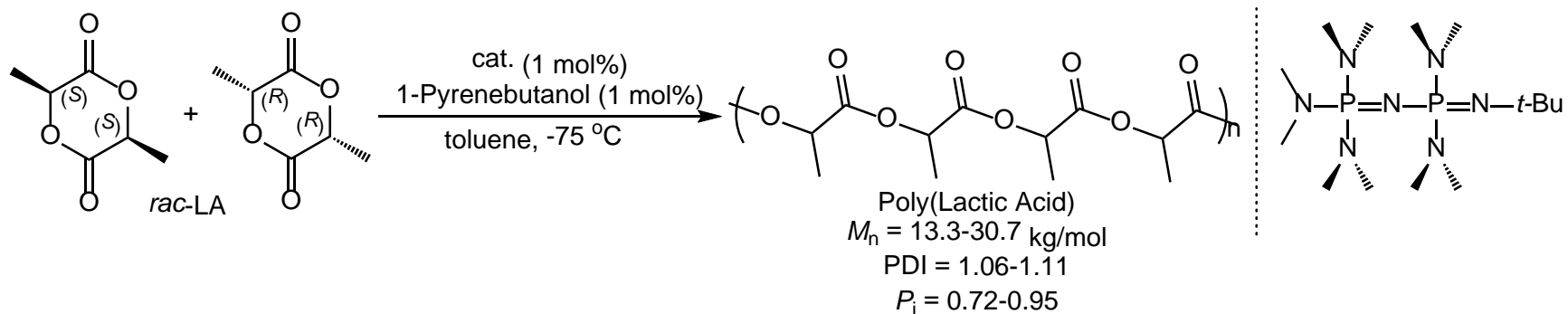
B: (R = 2,4,6-Me₃-C₆H₂)

C: (R = CH(Me)Ph)

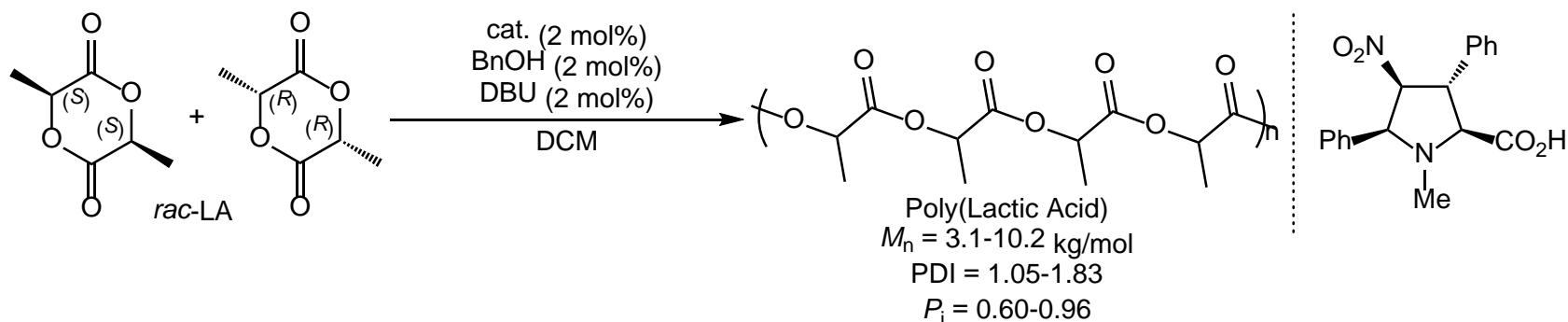
Entry	cat	T(°C)	conv. (%)	M_n	PDI	P_i
1	B	25	95	14.0	1.24	0.59
2	B	-15	89	13.8	1.18	0.72
3	B	-40	88	13.7	1.21	0.80
4	B	-70	91	13.7	1.20	0.90
5	A	-70	92	13.5	1.19	0.83
6	(R,R)-C	-70	96	13.7	1.26	0.88
7	(R,R)-C + (S,S)-C	-70	96	13.7	1.48	0.88

Hedrick, J. L. *et al. Chem. Commun.* **2006**, 2881.

Organocatalytic ROP of *rac*-Lactide

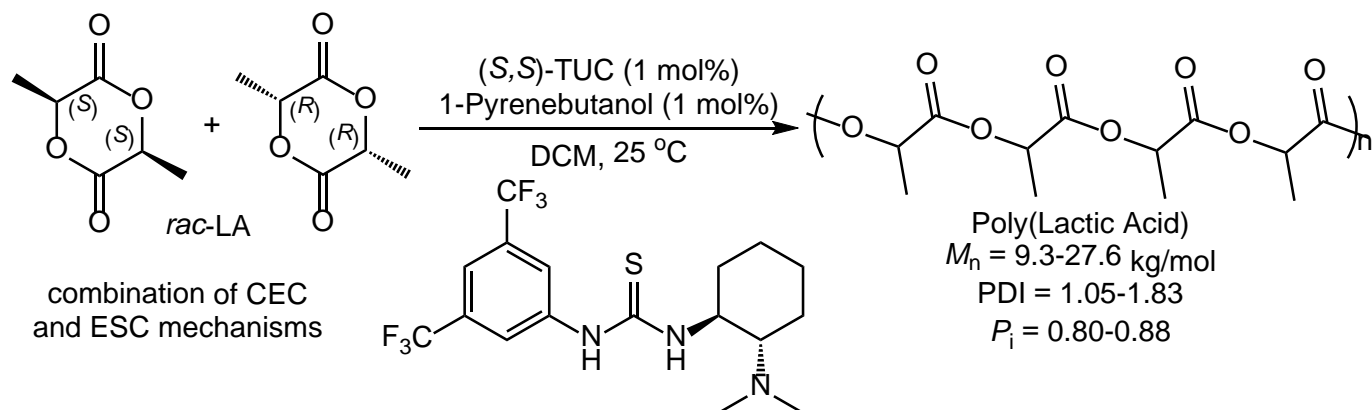


Wade, C. G. *et al.* *J. Am. Chem. Soc.* **2007**, 129, 12610.

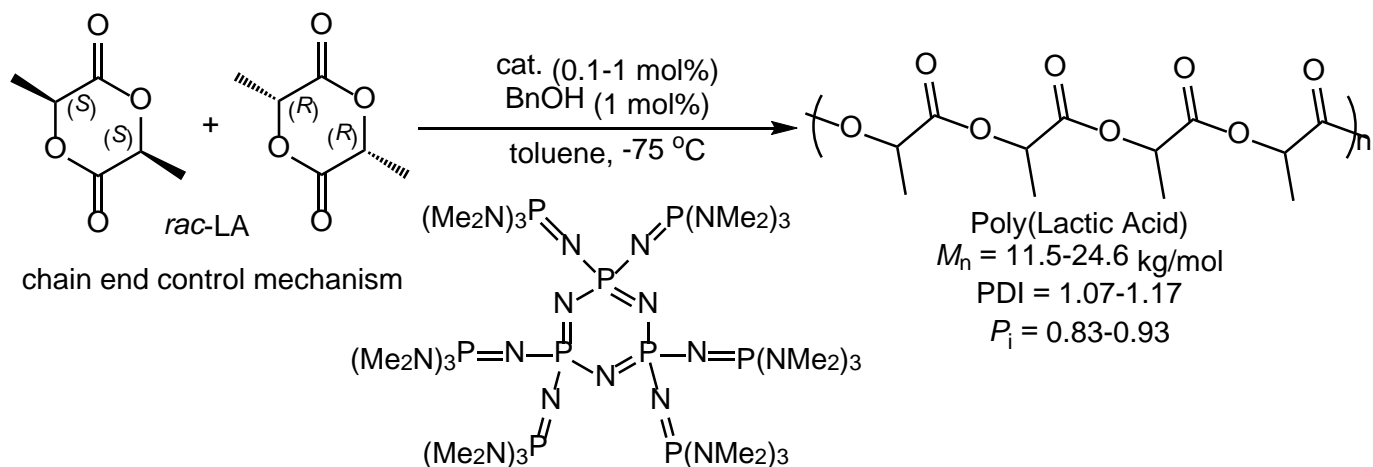


Cossío, F. P. *et al.* *J. Am. Chem. Soc.* **2017**, 139, 4805.

Organocatalytic ROP of *rac*-Lactide

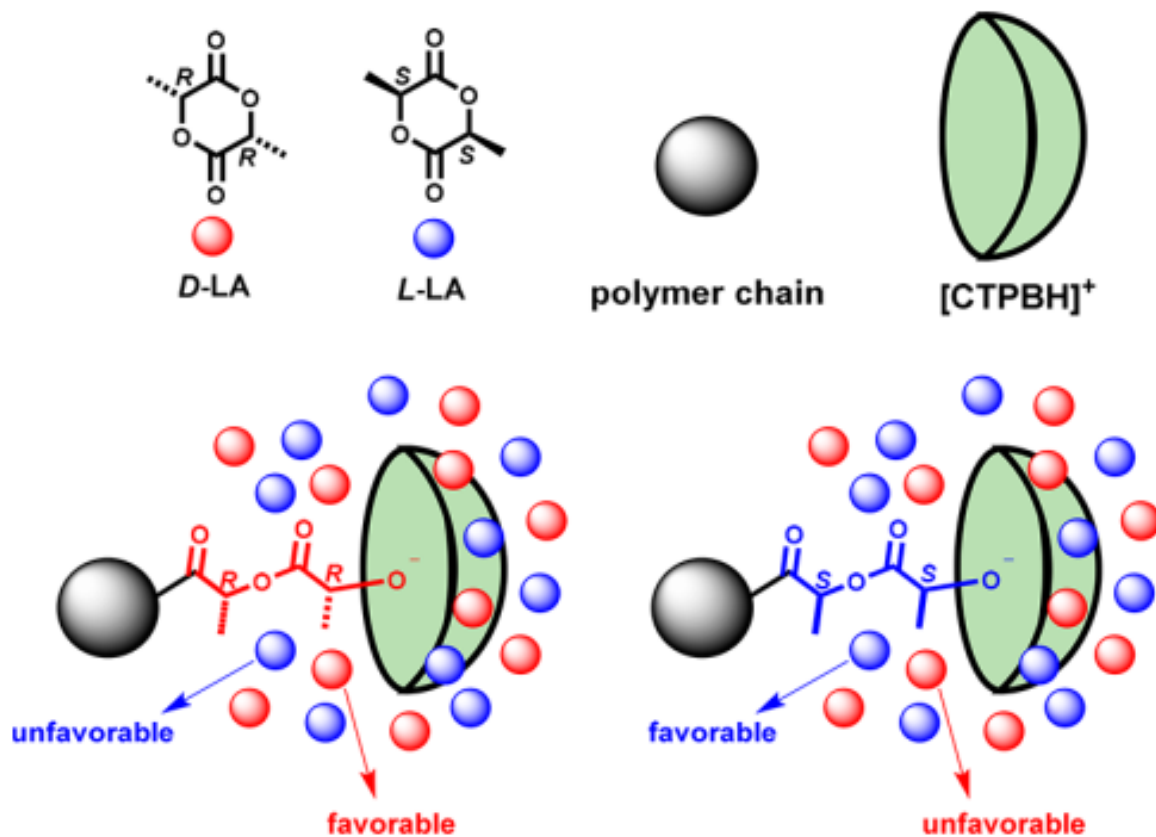


Taton, D. *et al.* *ACS Macro Lett.* **2018**, 7, 1413.



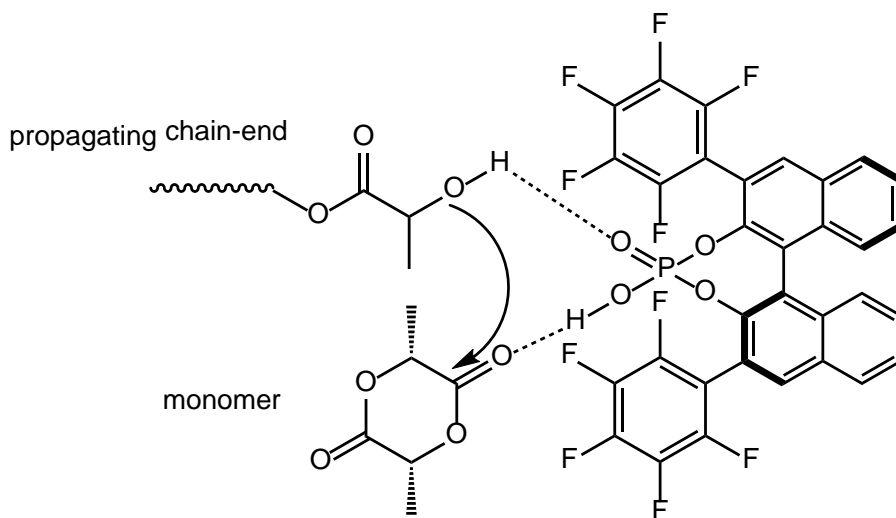
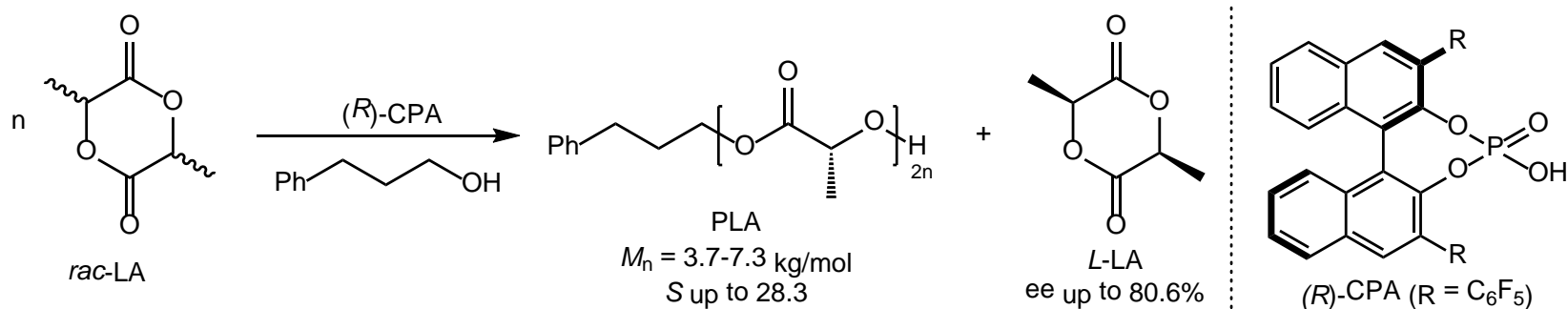
Li, Z. *et al.* *ACS Macro Lett.* **2018**, 7, 624.

Organocatalytic ROP of *rac*-Lactide



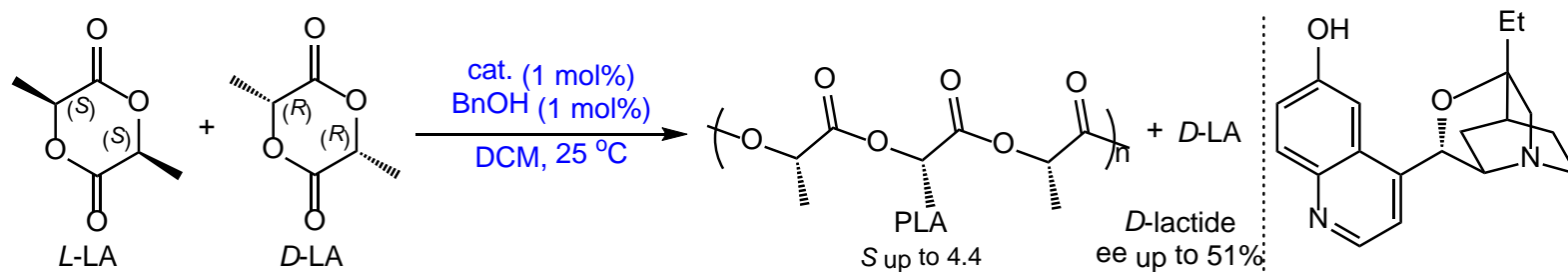
Li, Z. *et al.* *ACS Macro Lett.* **2018**, 7, 624.

Kinetic Resolution ROP of *rac*-Lactide

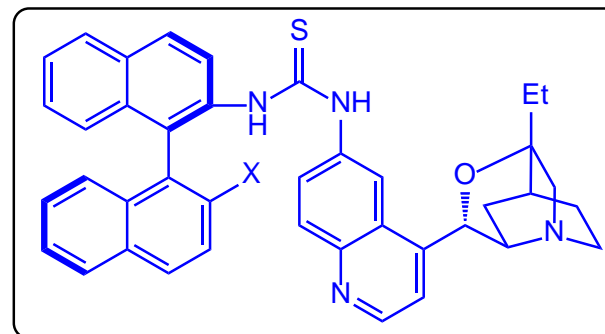
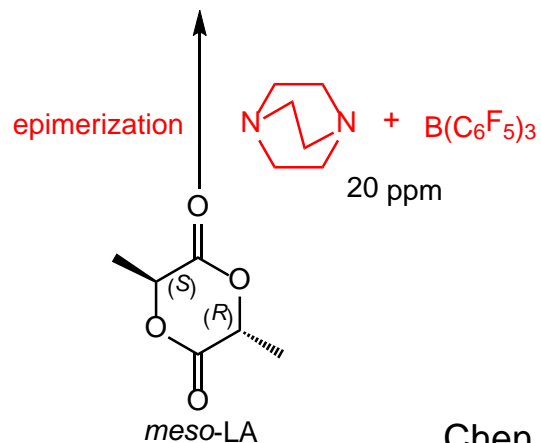
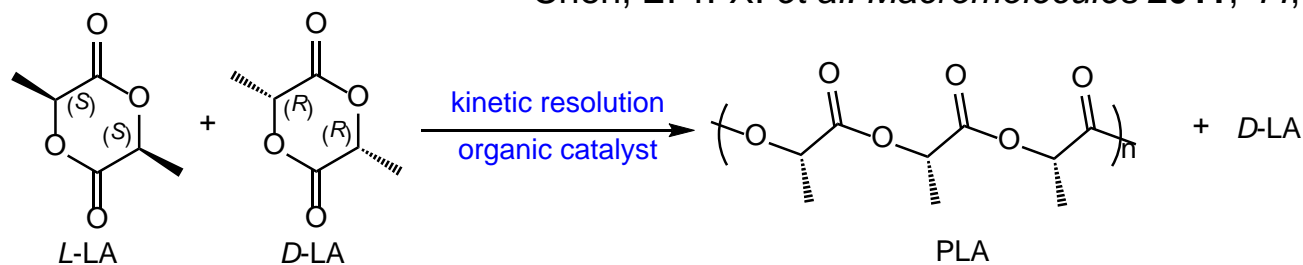


Sato, T. et al. *Chem. Commun.* **2014**, 50, 2883.

Kinetic Resolution ROP of *rac*-Lactide

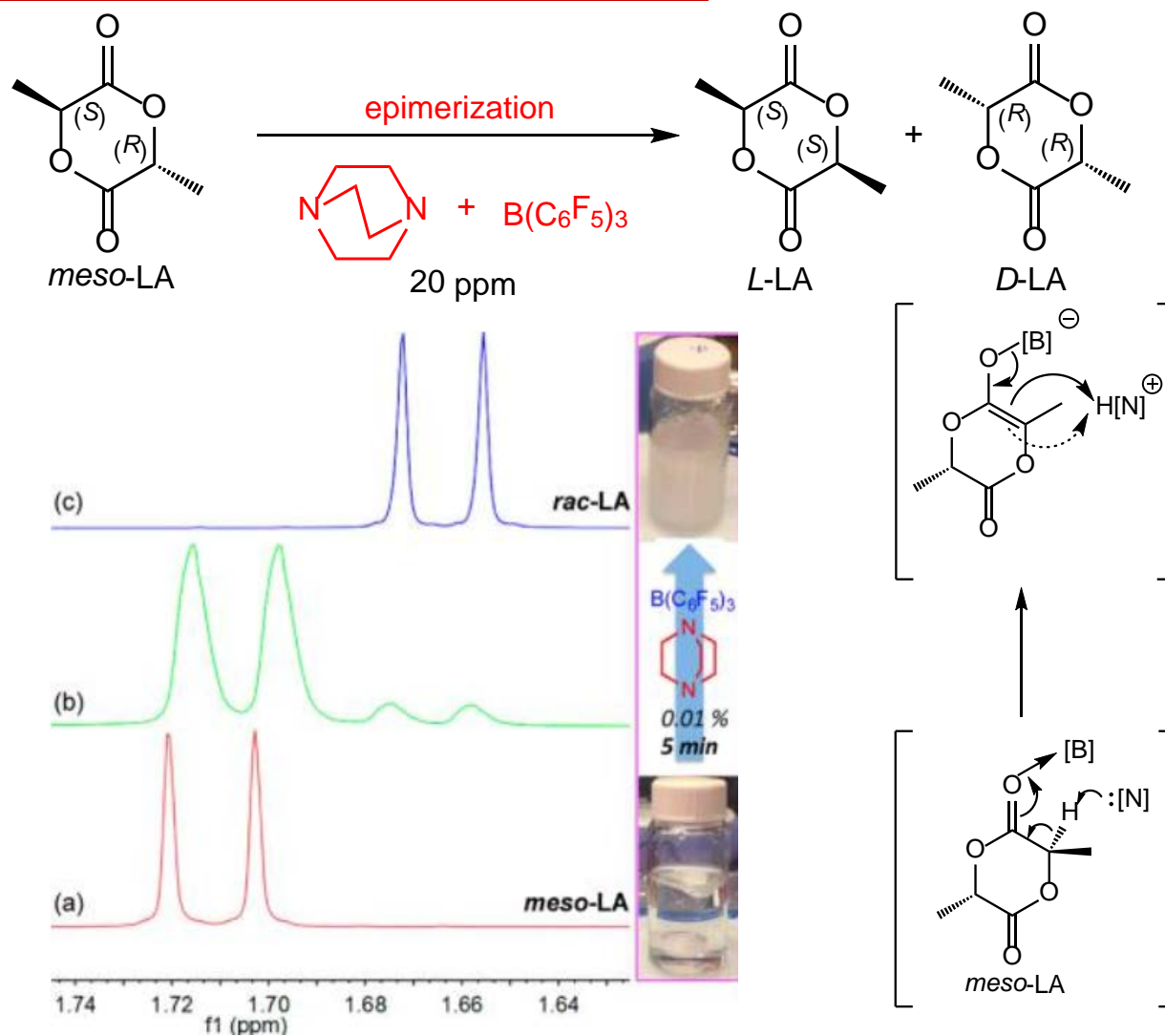


Chen, E. Y.-X. *et al. Macromolecules* **2011**, *44*, 4116.

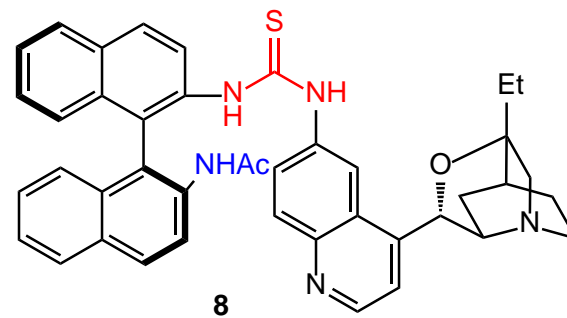
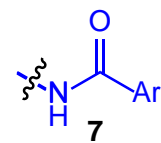
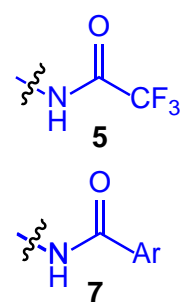
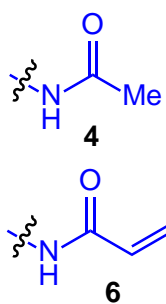
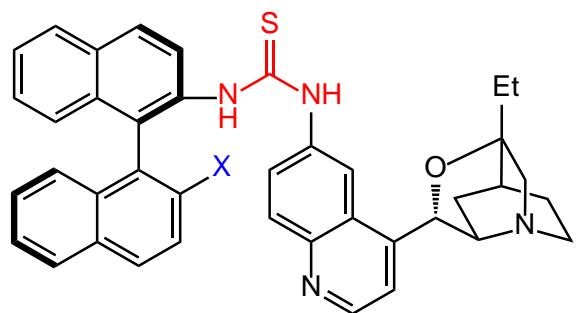
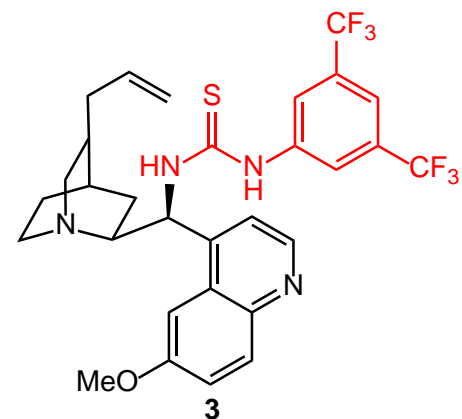
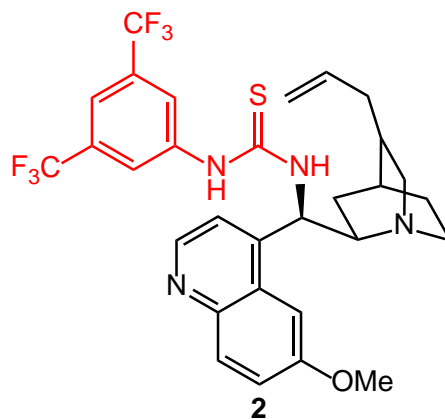
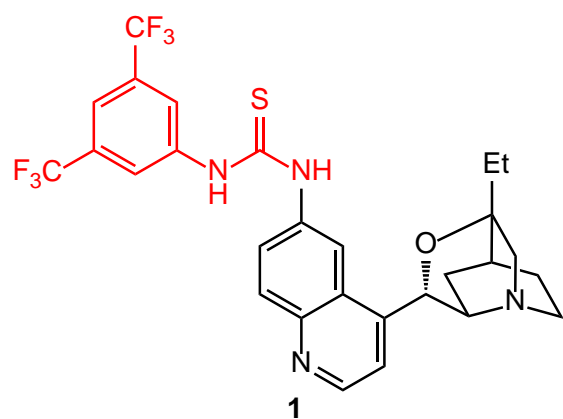


Chen, E. Y.-X. *et al. J. Am. Chem. Soc.* **2015**, *137*, 12506.

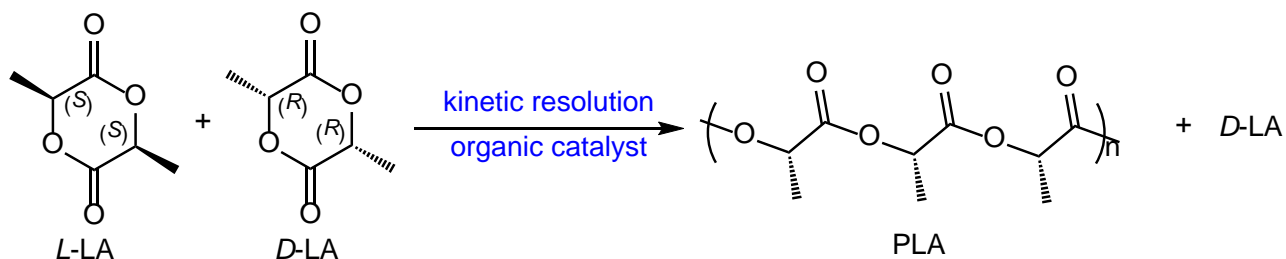
Kinetic Resolution ROP of *rac*-Lactide



Kinetic Resolution ROP of *rac*-Lactide



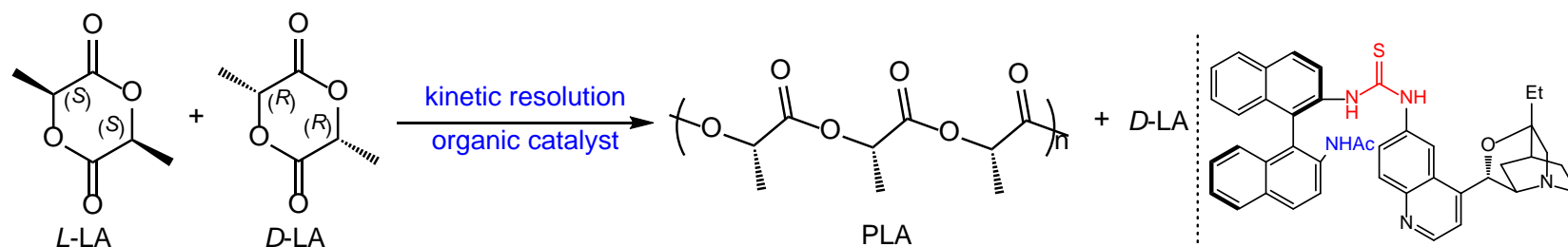
Kinetic Resolution ROP of *rac*-Lactide



Entry	cat	t (h)	conv. (%) ^b	ee (%) ^c	k_S/k_R ^d	M_n (kg/mol) ^e	PDI ^e
1	1	7	47.8	63	10	11.3	1.13
2 ^f	2	36	53.5	25	1.9	6.7	1.10
3 ^f	3	22	52.4	-33	0.4	6.9	1.11
4	4	25	50.2	83	26	10.3	1.14
5	5	18	49.5	64	8.8	11.0	1.12
6	6	48	51.0	67	9.0	10.9	1.15
7	7	29	48.8	64	9.7	10.0	1.12
8	8	18	49.0	-24	0.5	11.1	1.13

^a Reaction conditions: *rac*-LA (5 mol), cat (1 mol%), BnOH (1 mol%), DCM (3 mL), 25 °C. ^b Determined by ¹H NMR. ^c Determined by chiral HPLC. ^d Calculated from $\{\ln[(1 - \text{conv.})(1 - \text{ee})]\}/\{\ln[(1 - \text{conv.})(1 + \text{ee})]\}$. ^e Determined by GPC. ^f cat (2 mol%).

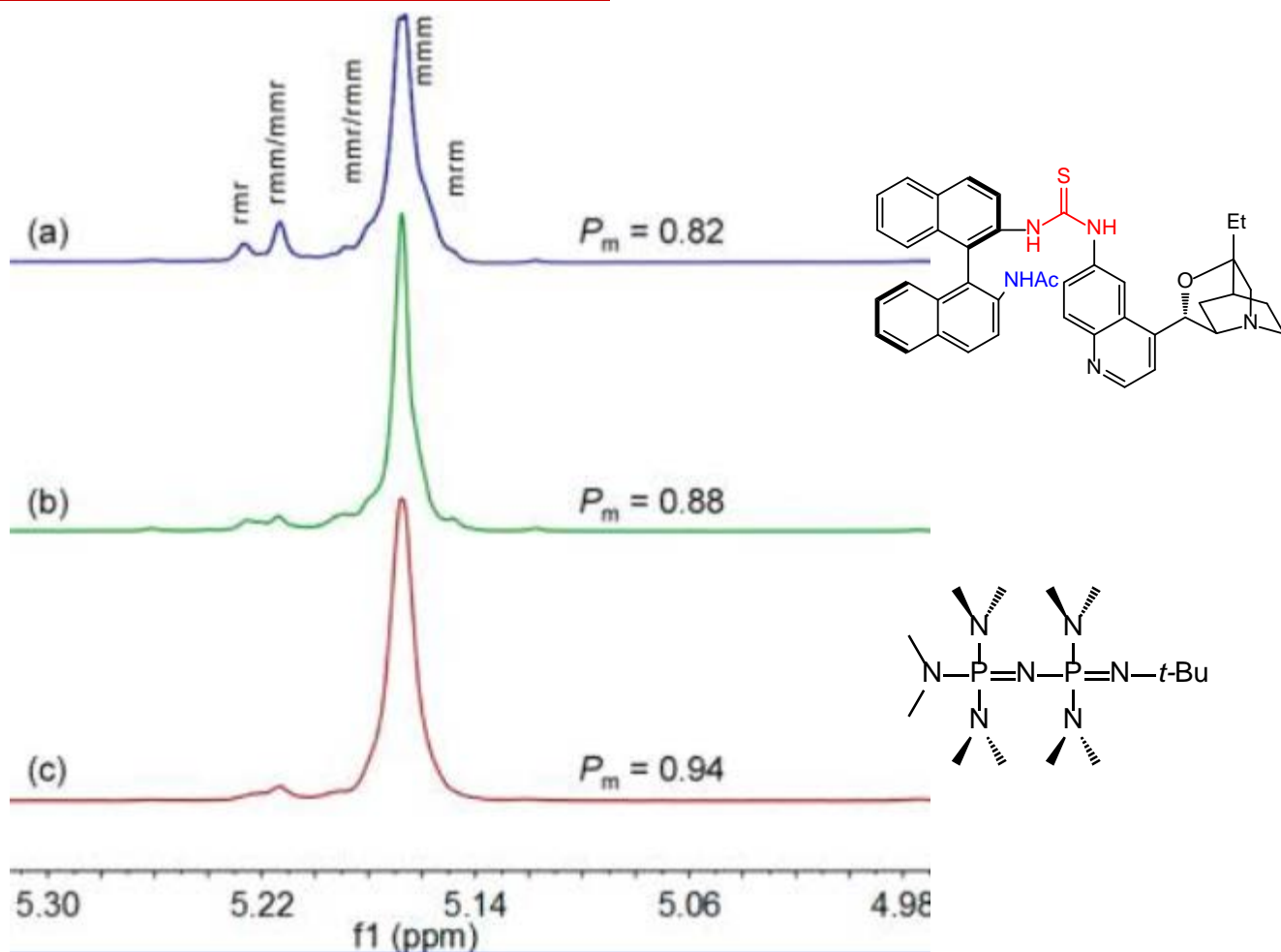
Kinetic Resolution ROP of *rac*-Lactide



Entry	solvent	t (h)	conv. (%) ^b	ee (%) ^c	k_S/k_R ^d	M_n (kg/mol) ^e	PDI ^e
1	DCM	25	50.2	83	26	10.3	1.14
2 ^f	DCM	7	50.1	85	32	6.4	1.16
3 ^f	FB	30	50.8	89	41	6.1	1.12
4 ^f	DFB	17	50.6	91	53	7.2	1.14
5 ^{fg}	DFB	40	51.0	88	35	10.4	1.13

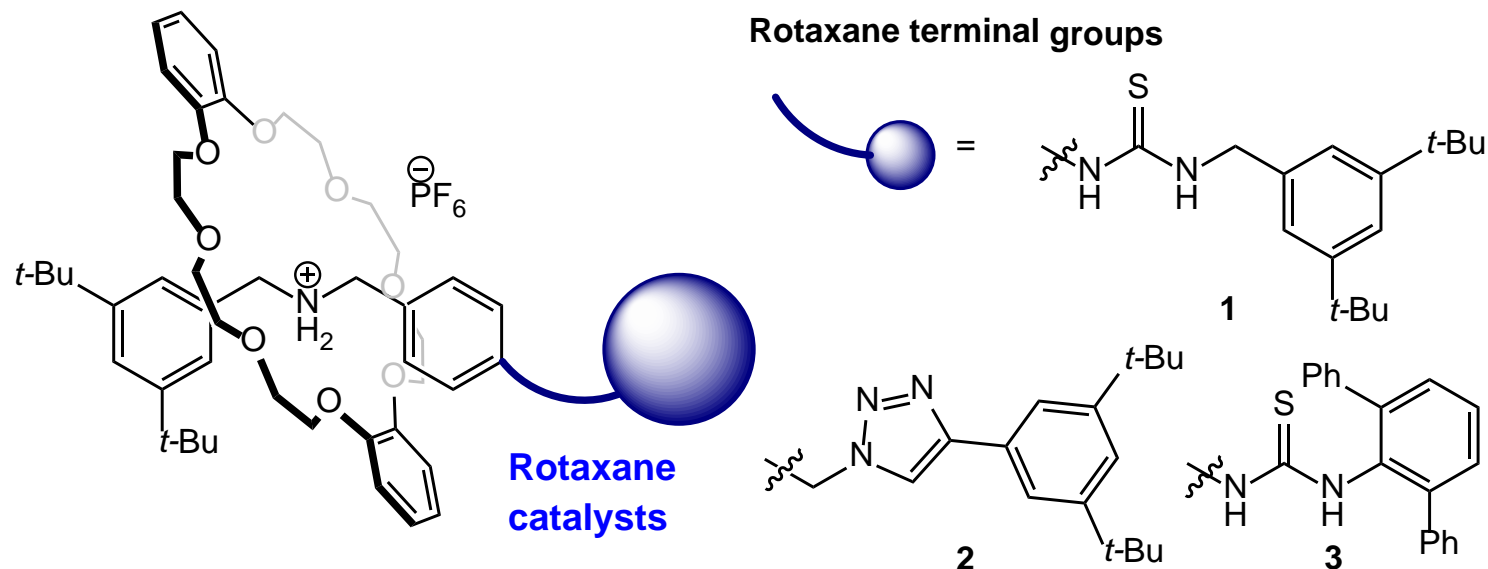
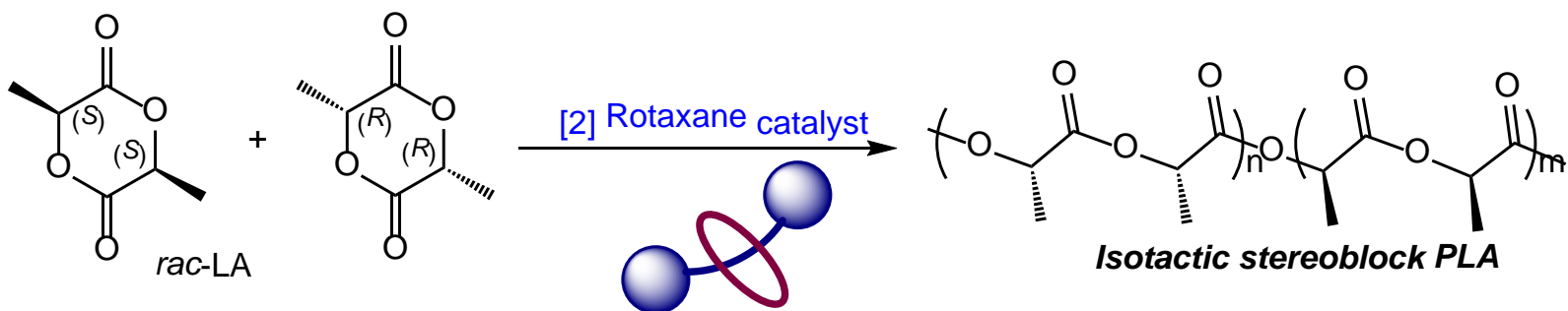
^a Reaction conditions: *rac*-LA (5 mol), **cat 4** (1 mol%), BnOH (1 mol%), DCM (3 mL), 25 °C. ^b Determined by ¹H NMR. ^c Determined by chiral HPLC. ^d Calculated from $\{\ln[(1 - \text{conv.})(1 - \text{ee})]\}/\{\ln[(1 - \text{conv.})(1 + \text{ee})]\}$. ^e Determined by GPC. ^f cat (2 mol%). ^g One-pot reaction from *meso*-LA.

Kinetic Resolution ROP of *rac*-Lactide



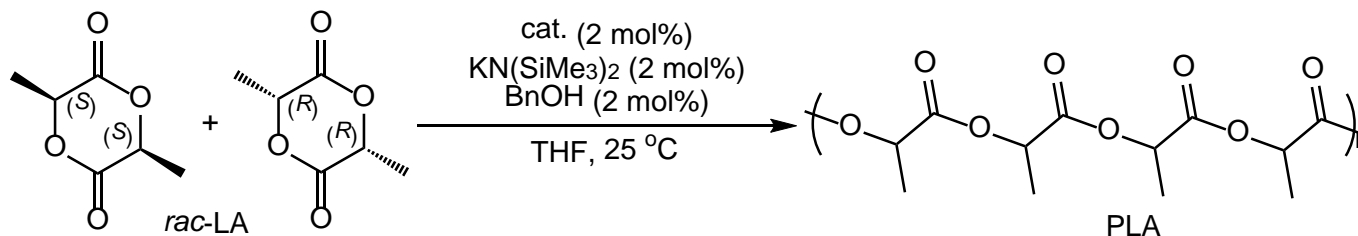
Homonuclear decoupled ¹H NMR spectra of the methine region of PLAs from *rac*-LA: (a) **catalyst 4**, 82.9% conversion; (b) **catalyst 4**, 50.5% conversion; (c) *t*-BuP₂, >99% conversion.

ROP of *rac*-Lactide with Rotaxane Catalysts



Williams, C. K. *et al. Angew. Chem. Int. Ed.* **2019**, 58, 6007.

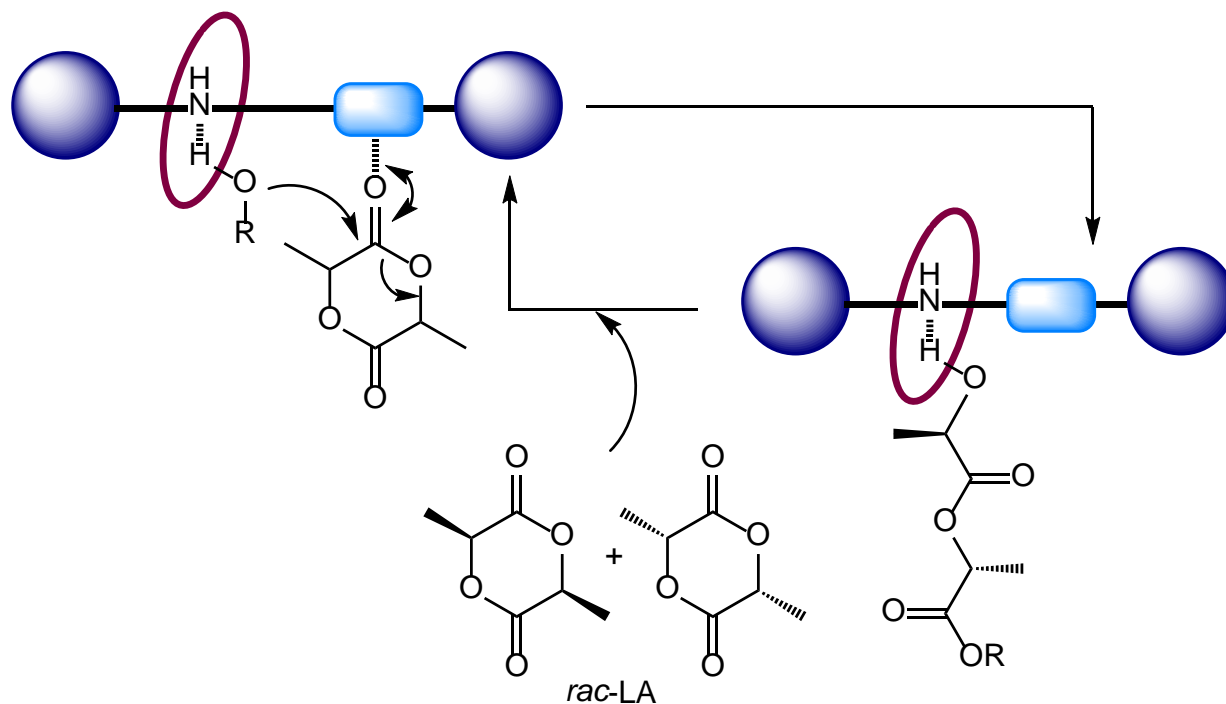
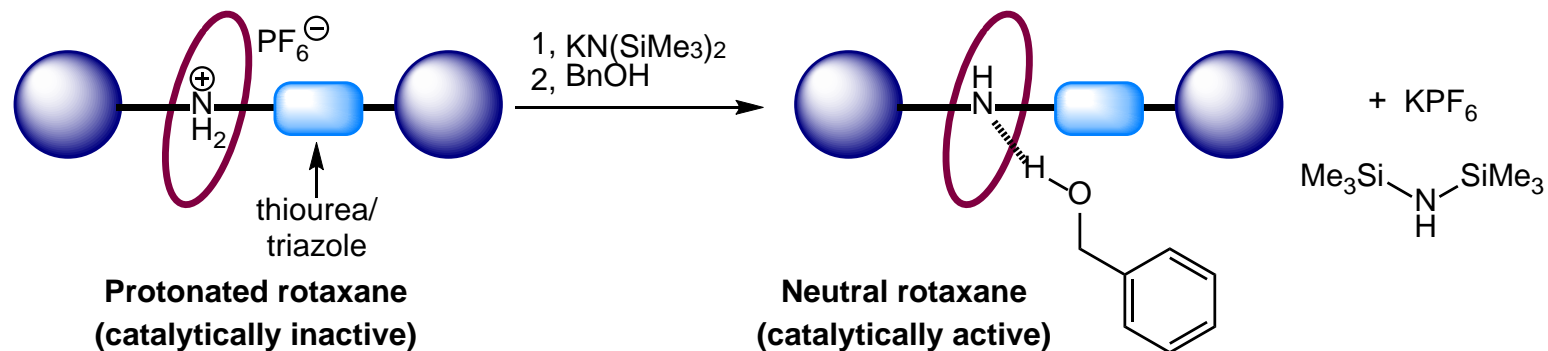
ROP of *rac*-Lactide with Rotaxane Catalysts



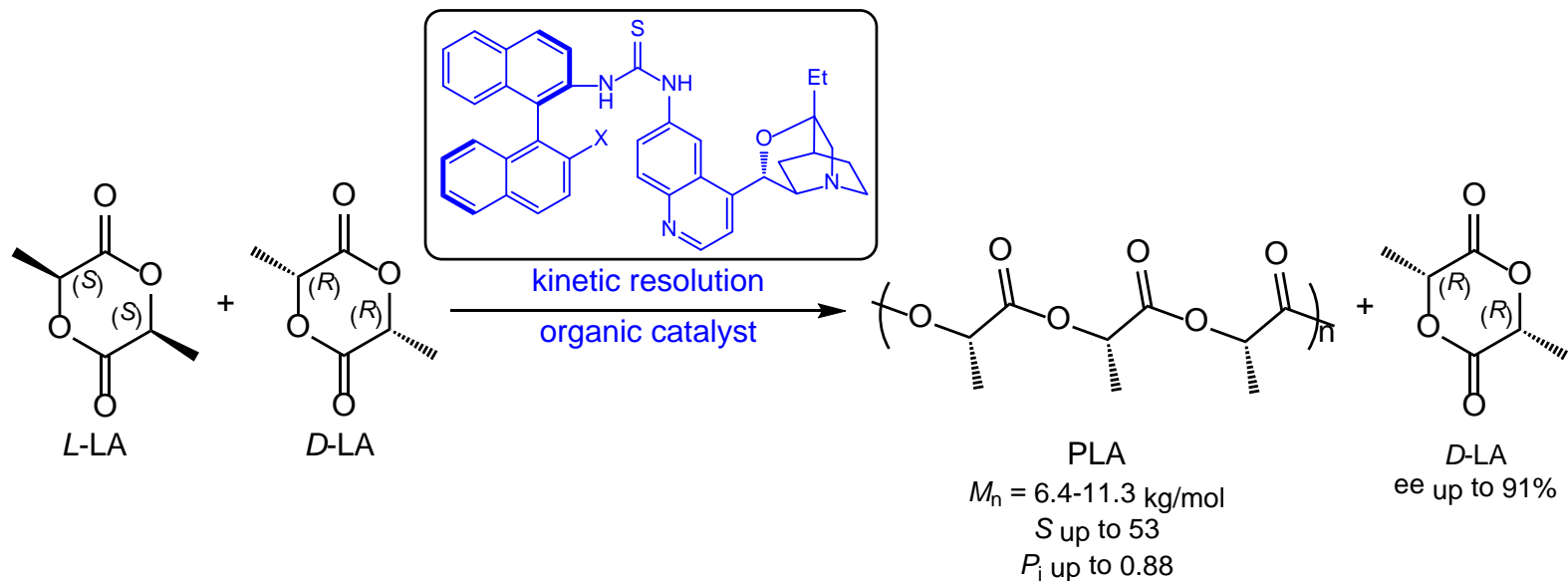
Entry	cat	[LA]/[cat.]/[base]/[BnOH]	t (h)	conv. (%) ^b	P_i^b	M_n (kg/mol) ^c	PDI ^c
1	1	50:1:1:1	96	80	0.81	6.5	1.08
2	-	50:0:1:1	1	99	0.56	8.3	1.72
3	1	50:1:0:1	48	0	-	-	-
4	1	50:1:1:0	48	0	-	-	-
5	1	100:1:2:2	1	99	0.54	8.8	1.47
6 ^d	1	50:1:1:1	72	80	0.66	5.4	1.11
7	2	50:1:1:1	11	80	0.66	8.8	1.16
8	3	50:1:1:1	3	90	0.73	6.2	1.13

^a Reaction conditions: *rac*-LA (0.5 mol), cat (2 mol%), BnOH (2 mol%), base (2 mol%), THF (3 mL), 25 °C. ^b Determined by ¹H NMR. ^c Determined by GPC. ^d 50 °C.

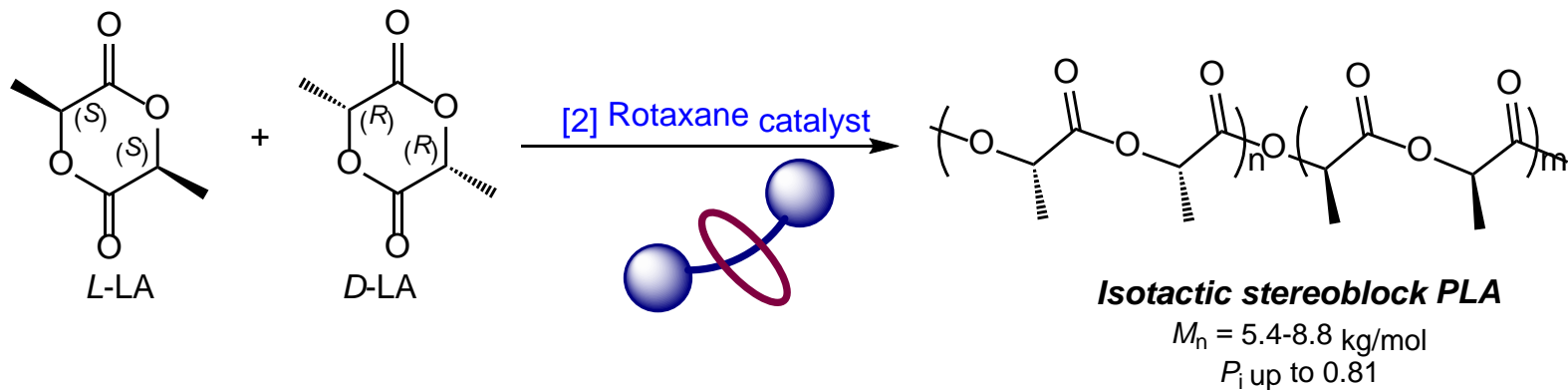
ROP of *rac*-Lactide with Rotaxane Catalysts



Summary



Chen, E. Y.-X. *et al.* *J. Am. Chem. Soc.* **2015**, *137*, 12506.



Williams, C. K. *et al.* *Angew. Chem. Int. Ed.* **2019**, *58*, 6007.

The First Paragraph

Poly(lactide) (PLA) is a commercially available bio-derived thermoplastic; its biocompatibility and biodegradability have enabled substitution of petro-polymers in medical, packaging and fibre applications. PLA's thermal-mechanical properties depend upon its microstructure: atactic PLA is amorphous whilst isotactic stereoblock PLA is semi-crystalline. Stereoblock PLA shows an even higher melting temperature (T_m) than isotactic PLLA. All tacticities of PLA are produced by the ring opening polymerization (ROP) of lactide. A current challenge is to deliver stereoblock PLA from racemic lactide (*rac*-LA) using selective catalysis.

The Last Paragraph

In conclusion, these are the first rotaxane catalysts for lactide ROP and they show isoselectivity. The polymerization selectivity correlates with macrocycle–axle translocation rates and with sterically-accessible, strong monomer coordination sites. The conformational dynamism appears to be responsible for both rates and stereoselectivity and provides a new means by which to control tacticity. This new type of stereocontrol is expected to be applicable to transesterifications, transamidations and other ring-opening polymerizations of epoxides, cyclic carbonates and lactones.

Thanks

for your attention