

## Copolymerization of cyclic esters, epoxides and anhydrides by a bimetallic salen aluminum complex. Evidences of a dual role of the monomers in the reaction mixture.

Received 00th January 20xx,  
Accepted 00th January 20xx

DOI: 10.1039/x0xx00000x

www.rsc.org/

Florence Isnard,<sup>a</sup> Mario Carratù,<sup>a</sup> Marina Lamberti,<sup>b</sup> Vincenzo Venditto,<sup>a</sup> Mina Mazzeo<sup>a\*</sup>

A bimetallic salen aluminum complex (**1**), where salen is N,N-bis(4,6-di-tert-butyl salicylaldimine)-1,3-propylenediamine, was tested as catalyst for the ring opening polymerization (ROP) and copolymerization (ROCOP) of cyclic esters, such as L-lactide (L-LA),  $\epsilon$ -caprolactone ( $\epsilon$ -CL), and  $\beta$ -butyrolactone ( $\beta$ -BL) with different heterocyclic substrates, such as cyclohexene oxide (CHO) and succinic anhydride (SA). Copolymers ranging from gradient to blocky structures were obtained from the copolymerization of the different couples of lactones. In the copolymerization of CHO with a cyclic ester, block polyether-co-polyesters were prepared by sequential monomer addition while polyesters were obtained, as exclusive products, when both monomers were simultaneously present in the reaction medium. From a mixture of three different monomers: CHO, SA and a cyclic ester, block copolyesters derived from two different catalytic processes, ROCOP of CHO/SA followed by ROP of the lactone, were instead produced. Surprisingly, a perfect selectivity was observed in the CHO/SA copolymerization without any addition of cocatalyst, this suggested that the lactone comonomer could act as an endogen cocatalyst.

### Introduction

Aliphatic polyesters are an important class of polymers gaining increasing attention as potential substitutes to polymers derived from fossil feedstock.<sup>1-3</sup> Noticeable examples of polyesters of industrial interest are polylactide (PLA), poly- $\epsilon$ -caprolactone (PCL) and, more recently, polyhydroxybutyrate (PHB).

The election route for the synthesis of these polymers is the ring opening polymerization (ROP) of the corresponding cyclic esters promoted by metal or organic catalysts.<sup>4-6</sup> This method permits to prepare well-defined polyesters by a punctual control of functional parameters such as the molar masses and their distributions, the microstructure, the tacticity and the structure of the chain end groups. The limit of this synthetic approach consists in the restricted range of properties of the resulting polyesters as consequence of the limited structural diversity of available monomers.

The copolymerization of cyclic esters is a powerful tool to extend the variety of polymer architectures that can be obtained starting from a restricted library of monomers.<sup>7-9</sup> Cyclic esters can be combined into copolymers whose mechanical properties can be finely modulated by changing the composition and the distribution of the co-monomers along the copolymer chain.

Additionally, the copolymerization of cyclic esters with different monomers, such as cyclic carbonates<sup>10-12</sup> or epoxides,<sup>13,14</sup> offers the possibility to further extend the control over structure-property relationships in polymeric materials.

An alternative method to produce polyesters is the ring opening copolymerization (ROCOP) of epoxides and anhydrides. Recent reviews well underlined the vast potential of this method.<sup>15,16</sup> Currently, only few examples of catalysts able to perform both the catalytic processes are reported in the literature.<sup>17-23</sup>

Recently, Williams<sup>24-28</sup> and Rieger<sup>29</sup> reported that, for some of these systems, the shift between the catalytic cycles allows to produce block copolymers via chemoselective polymerization from a complex mixture of monomers.

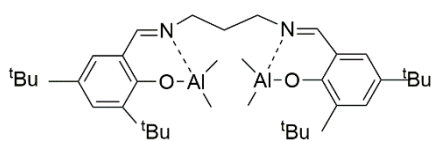
In a previous paper, we reported that a bimetallic aluminum complex supported by a salen ligand showed high activity in the ROP of *rac*-lactide and cyclohexene oxide as consequence of the cooperation between the two metal vicinal reactive centers.<sup>30</sup> The same system revealed to be highly active in the ROCOP of cyclohexene oxide and limonene oxide with different anhydrides.<sup>31</sup>

Since synergies between reactive aluminum centers<sup>32</sup> in multinuclear complexes often cause unexpected activities and performances in the polymerizations<sup>33-39</sup> and copolymerizations of cyclic esters,<sup>40-44</sup> in this paper we extended the use of this catalyst to the copolymerization of diverse heterocyclic substrates. Different combinations of several monomers:  $\epsilon$ -

<sup>a</sup> Department of Chemistry and Biology "A. Zambelli" University of Salerno, Via Giovanni Paolo II, 132, 84084 Fisciano (SA) Italy.

<sup>b</sup> Department of Physics "E. Caianiello" University of Salerno Via Giovanni Paolo II, 132 84084 Fisciano (SA) Italy.

Electronic Supplementary Information (ESI) available: See DOI: 10.1039/x0xx00000x



Scheme 1. Structure of complex 1

caprolactone ( $\epsilon$ -CL), L-lactide (L-LA),  $\beta$ -butyrolactone ( $\beta$ -BL), cyclohexene oxide (CHO) and succinic anhydride (SA) have been investigated. The possibility of chemoselective copolymerization starting from complex monomer mixtures was also explored.

## Results and discussion

### Homopolymerizations.

Initially, the reactivity of catalyst **1** (scheme 1) in the ROP of the single cyclic esters:  $\epsilon$ -CL, L-LA, and *rac*- $\beta$ -BL was studied (scheme 2). The polymerizations were performed under the reaction conditions used for complex **1** in the ROP of *rac*-lactide:<sup>30</sup> at 70 °C, in toluene solution and in the presence of four equivalents of isopropanol as activator.<sup>45</sup>

In the ROP of L-LA, complex **1** revealed the same behavior observed toward the racemic monomer (entries 1 and 2, Table 1), confirming its very high catalytic activity, higher than those observed for the related half-salen aluminum complexes.<sup>46, 47</sup> The quantitative conversion of 200 equivalents of monomer was achieved in eight hours, producing a high molecular weight polymer having predictable molecular weight values and coherent with the growth of a single polymer chain for catalyst unit.

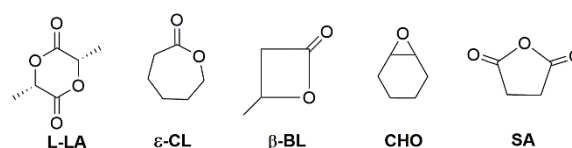
A homonuclear decoupled <sup>1</sup>H NMR spectrum to determine the tacticity did not show any racemization within the polymer.

In the ROP of  $\epsilon$ -caprolactone (see entry 3, Table 1), complex **1** showed very high activity, higher than those observed with most of half-salen aluminum complexes<sup>46</sup> and comparable to those obtained with some of the most efficient aluminum complexes,<sup>48, 49</sup> thus confirming the positive effect of the cooperation between the two metal centers.<sup>50-54</sup> A moderate activity was achieved even at room temperature (entry 4, Table 1).

The good control over the polymerization process was confirmed by the monomodal distributions of the molecular weights and their polydispersities close to 1. The experimental molecular weights of PCLs were coherent with the formation of two chains for catalyst unit, one for each metal center.

Kinetics studies showed that the polymerization rate of the ROP was first-order dependent on the  $\epsilon$ -CL concentration, suggesting no deactivation of active species occurred during the polymerization reaction (Figure 1).

In the polymerization of *rac*- $\beta$ -BL, complex **1** showed good performances allowing the conversion of 130 equivalents of



Scheme 2. Monomers investigated in this work.

monomer in 20 hours at 70 °C. Synergies between the metal centers of complex **1** revealed to be fundamental in the ROP of *rac*- $\beta$ -BL, in fact the related monometallic phenoxy-imine aluminum complex was inactive in this reaction.<sup>55</sup>

As already observed for the ROP of CL, the molecular weights of the obtained polymers were coherent with the hypothesis of the growth of two polymer chains for catalyst unit (entry 5, Table1).

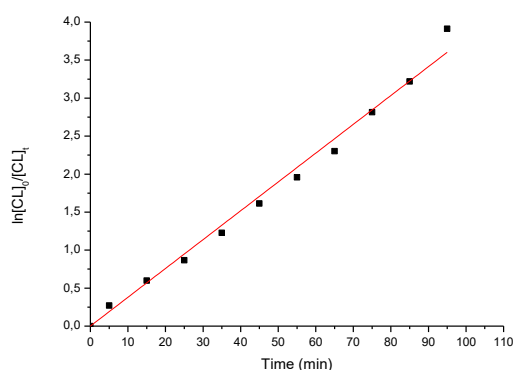
This was confirmed by the <sup>1</sup>H NMR analysis of the propagating species prepared in deuterated benzene (see Fig S1 of SI) with complex **1** (10  $\mu$ mol), four equivalents of <sup>1</sup>PrOH and of *rac*- $\beta$ -BL. After 2 hours at 70 °C, the exhaustive alcoholysis of methyl groups of complex **1** and the almost complete consumption of the monomer were observed. The <sup>1</sup>H NMR spectrum revealed a symmetric structure of the propagating species, as clearly emerged by presence of only three signals in the low field region of the spectrum. This suggested that two polymeric chains grew independently on the two reactive aluminum centers. Otherwise, an asymmetric propagating species was formed from complex **1** in the ROP of LA.<sup>30</sup> The differences observed between the lactones and the lactide could be a consequence of a chelation effect between the two aluminum centers by the

Entry	Monomer (equiv)	Time (h)	T (°C)	Conv. (%)	<sup>b</sup> M <sub>n</sub> GPC (KDa)	M <sub>n</sub> <sup>th</sup> (KDa)	<sup>b</sup> D
1	L-LA (200)	8	70	100	23.6	<sup>c</sup> 28.8	1.07
2	<i>rac</i> -LA (200)	8	70	100	22.1	<sup>c</sup> 28.8	1.09
3	$\epsilon$ -CL (500)	0.33	70	46	10.1	<sup>d</sup> 13.1	1.22
4MC 15	$\epsilon$ -CL (500)	6	25	18	7.0	<sup>d</sup> 5.1	1.05
5MC7	$\beta$ -BL (200)	20	70	64	5.2	<sup>d</sup> 5.5	1.07
6MC2 <sup>e</sup>	$\beta$ -BL (200)	20	70	91	2.4	<sup>f</sup> 2.0	1.06
7	CHO (500)	0.08	70	79	10.7	<sup>g</sup> 9.7	1.79

O-lactate propagating species in the polymerization of LA, as described by several authors.<sup>47, 56, 57</sup>

**Table 1** Polymerizations of cyclic esters promoted by **1**<sup>a</sup>

<sup>a</sup>All reactions were carried out with 10  $\mu$ mol of **1** at 70 °C, in 2 mL of toluene, [1]/[<sup>1</sup>PrOH] = 1:4. <sup>b</sup>Experimental M<sub>n</sub> (corrected using factor 0.58 for PLA, 0.56 for PCL and 0.54 for PHB) and D values were determined by GPC analysis in THF using polystyrene. <sup>c</sup>Calculated M<sub>n</sub> = MM<sub>LA</sub> × ([LA]/[1]) × conv. of LA. <sup>d</sup>Calculated M<sub>n</sub><sup>th</sup> = MM<sub>mon</sub> × ([Mon]/[Al]) × conv. <sup>e</sup>[1]/[<sup>1</sup>PrOH] = 1:8. <sup>f</sup>Calculated M<sub>n</sub> = MM<sub>mon</sub> × ([Mon]/[<sup>1</sup>PrOH]) × conv.



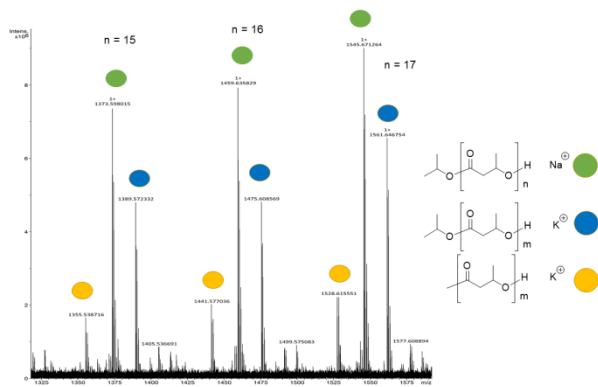
**Figure 1.** Plot of  $\ln([e-CL]_0/[e-CL]_t)$  vs time depicting a reaction order of unity with respect to monomer concentration,  $k_{app} = 0.379 \text{ min}^{-1}$  ( $R^2 = 0.9960$ ).

Remarkably, complex **1** was tolerant to an excess of hexogen alcohol (*i*PrOH) and it exhibited the behavior expected for an “immortal” polymerization (entry 6, Table 1). The molecular weight of the resultant PHB decreased consistently with respect to the *i*PrOH loading, while the dispersity remained constant.

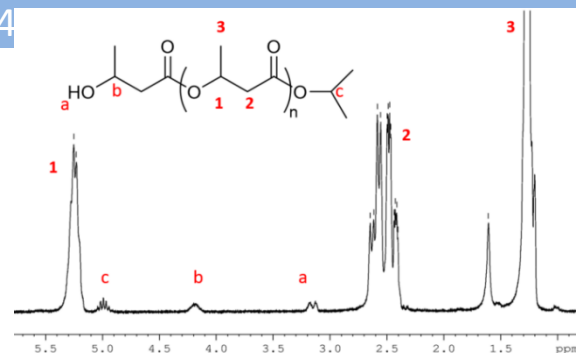
The MALDI-ToF analysis of the low molecular weight PHB sample (entry 6, Table 1) showed that only linear chains were formed (see Figure 2). No cyclic oligomers were detectable confirming that intramolecular transesterification processes did not occur during polymerization.

Coherently, the  $^1\text{H}$  NMR analysis showed the existence of  $\text{HOCH}(\text{CH}_3)\text{CH}_2-$  and  $-\text{OCH}(\text{CH}_3)_2$  groups as exclusive chain end groups (see Figure 3). In the spectrum, no evidence of trans-crotonate species, derived from side termination reactions, emerged.

All these observations are indicative of living polymerization that follows a coordination-insertion mechanism with a ring opening of the monomer through acyl–oxygen bond cleavage. Detailed information regarding the microstructure of the obtained PHB was revealed from the analysis of the methylene resonances (40 ppm) in the  $^{13}\text{C}$  NMR spectrum (Figure S2 of SI). The signals of the *rm*, *mm*-, *rr*-, and *mr*- triads resulted equal in their intensity describing an atactic PHB polymer.



**Figure 2.** MALDI-ToF-MS spectrum of PHB synthesized in entry 6 of Table 1



**Figure 3.**  $^1\text{H}$  NMR spectrum (250 MHz,  $\text{CDCl}_3$ , 298 K) of a PHB produced in entry 6 of Table 1.

The semilogarithmic plot of  $\ln([\beta\text{-BL}]_0/[\beta\text{-BL}]_t)$  versus polymerization time was linear, indicating a first order kinetics in concentration of monomer (Figure 4). The apparent kinetic constant was  $0.00649 \text{ min}^{-1}$  ( $0.389 \text{ h}^{-1}$ ), this value was comparable to that obtained for polymerization of *rac*-LA ( $0.643 \text{ h}^{-1}$ ),<sup>30</sup> and about one order of magnitude lower than that of CL value.

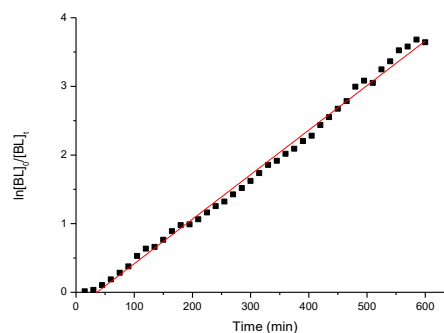
#### Copolymerization of cyclic esters

Aliphatic polyesters show different properties: PLA is a thermoplastic polymer that exhibits excellent mechanical properties but poor elasticity; otherwise PCL has very good elasticity and remarkable drug permeability;<sup>58</sup> isotactic PHB shows excellent physical properties and gas barrier properties similar to those of polypropylene.<sup>59</sup>

The copolymerization of the cited cyclic esters allows to obtain materials with mediated properties in comparison to the related homopolymers, that can be easily tuned by changing the ratio, the composition and the distribution of the monomers along the polymer chain.

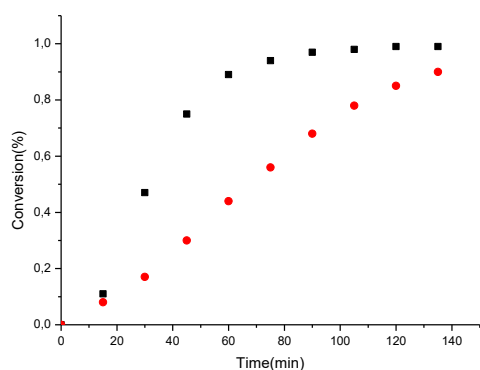
Thus, the catalytic ability of complex **1** in the copolymerization reactions of the cited cyclic esters was investigated. All the reactions were performed under the same reaction conditions used for the related homopolymerizations. The results are summarized in Table 2.

The copolymerization of  $\epsilon\text{-CL}$  and L-LA was performed (entry 1, Table 2) by using 200 equivalents of each monomer that were



**Figure 4.** Plot of  $\ln([\beta\text{-BL}]_0/[\beta\text{-BL}]_t)$  vs time depicting a reaction order of unity with respect to monomer concentration.  $k_{app} = 0.00649 \text{ min}^{-1}$  ( $R^2 = 0.9948$ ).

Figure 5. Plot of conversion vs time for L-LA (black solid squares) and  $\epsilon$ -CL (red solid



circles) concentration

added simultaneously. After 12 hours the complete consumption of both monomers was achieved.

GPC analysis of the obtained polymer revealed a monomodal molecular weight distribution with a narrow dispersity ( $\mathcal{D} = 1.28$ ). The copolymer molar masses ( $M_n = 17.2$  KDa) were higher than those expected for the pure homopolymers on their own (maximum estimated  $M_n = 7.2$  KDa) and in good agreement with the theoretical molar masses ( $M_n^{th} = 12.9$  KDa) for the PCL/PLA copolymer.

The  $^1\text{H}$  NMR spectrum of the crude polymer accounted for a copolymer containing a 1:1 ratio of PLA and PCL, in complete agreement with the initial feed ratio (Figure S3 of the SI). In addition to the signals expected for the homodiads CL-CL and LA-LA, characteristic resonances (less intense) corresponding to the CL-LA heterodiads were also detected at 2.3 and 4.1 ppm. The determination of the polymer microstructure was performed by analysis of the carbonyl region (ranging from 165 to 175 ppm) of the  $^{13}\text{C}$  NMR spectrum (Figure S4 of the SI). Besides the presence of carbonyl resonances due to the homosequences CL-CL and LA-LA (at 173.7 and 169.9 ppm, respectively), additional resonances of lower intensity were observed for the LA-CL heterosequences. No peak at 170.8 ppm, corresponding to sequences in which a lactyl unit, resulting from the cleavage of the lactyl-lactyl bond in the lactidyl unit, is surrounded by two CL units was observed.

The results of the thermal analysis showed the presence of a PLLA crystalline phase having  $T_m = 121$  °C and  $\Delta H_m = 28.8$  J/g (corresponding to a crystallinity degree of  $\approx 20\%$ <sup>60,61</sup> which, as usual occurs in copolymers, in second DCS heating run was reduced to 10%) while none thermal transitions were observed for the PCL phase (Figure S5 of the SI). The  $T_g$  of both phases were also not observed. The wide-angle X-ray diffraction (WAXD) analysis of the same sample showed only the typical peaks of the PLLA alpha form, confirming that only PLA phase was crystalline while the PCL phase was amorphous (Figure S6 of the SI). These results agree with a gradient microstructure of

the sample, in which the crystallization of the most rigid PLA phase hinders that of the more flexible PCL phase.

Table 2. Copolymerizations of cyclic esters promoted by **1**

<sup>a</sup> Entry	Monomer (equiv)	Time (h)	Conv. (%)	<sup>b</sup> $M_n^{\text{GPC}}$ (KDa)	<sup>c</sup> $M_n^{\text{th}}$ (KDa)	<sup>b</sup> $\mathcal{D}$
1 MC11	$\epsilon$ -CL/L-LA	12	100/100	17.2	12.9	1.28
2 MC13	$\epsilon$ -CL/ $\beta$ -BL	12	100/100	16.8	10.5	1.44
3 MC 12	L-LA/ $\beta$ -BL	24	100/50	12.3	9.6	1.07

<sup>a</sup>All reactions were carried out with  $1 \cdot 10^{-5}$  mol of **1** at 70 °C, in 2 mL of toluene,  $[\text{1}]/[\text{iPrOH}]/[\text{Mon1}]/[\text{Mon2}] = 1:4:200:200$ . <sup>b</sup>Experimental  $M_n$  (corrected using factor 0.58 for LA, 0.56 for PCL portions, and 0.54 for PHB portions) and  $\mathcal{D}$  values were determined by GPC analysis in THF using polystyrene standards. <sup>c</sup>Calculated  $M_n = [MM_{\text{mon1}} \times ([\text{Mon1}]/[\text{Al}]) \times \text{conv. of Mon1} + MM_{\text{mon2}} \times ([\text{Mon2}]/[\text{Al}]) \times \text{conversion of Mon2}]$

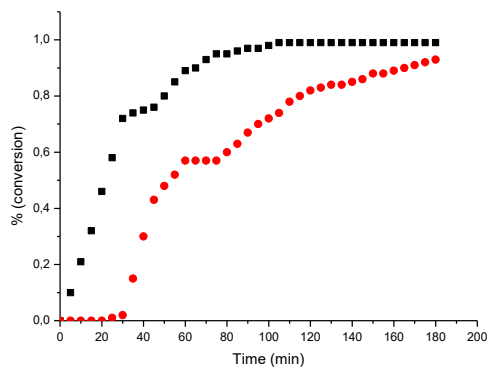
Kinetic measurements of the copolymerization of L-lactide and  $\epsilon$ -CL catalyzed by complex **1** in deuterated toluene was carried out at 70°C and monitored by  $^1\text{H}$  NMR spectroscopy (see figure 5 and S7 of the SI). As often observed for the copolymerization of L-LA with  $\epsilon$ -CL, the rate of enchainment of lactide was faster than that of  $\epsilon$ -CL. Thus, the L-LA incorporation was preferable although a gradual consumption of  $\epsilon$ -CL was observed, as evident by evaluating the conversions of the two monomers versus time. These data supported the gradient microstructure suggested for the copolymer.

In the copolymerization of  $\epsilon$ -CL and  $\beta$ -BL (entry 2 of Table 2), the complete conversions of both monomers were achieved in 12 hours and the composition of resulting copolymer faithfully reflected the feed composition (Figure S8 of the SI).

The absence of thermal transitions in both the first and second DSC heating runs of the thermal analysis indicates that the sample is amorphous (the  $T_g$  of both phases were also not observed). In the WAXD pattern of the sample only a large amorphous halo was observed, confirming the results of the thermal analysis. These results are coherent with a polymer microstructure consisting of short blocks of the two monomers (CL, BBL) randomly distributed along the polymer chain so that the crystallization of both PCL and PHB phases are hindered.

In the carbonyl region of the  $^{13}\text{C}$  NMR spectrum of the sample, in addition to the resonances due to the homosequences CL-CL and BL-BL (at 173.5 and 169.4 ppm, respectively), less intense resonances were observed, attributable to the CL-BL and BL-CL heterosequences (at 172.7 and 170.3 ppm, respectively) (Figure S9 of the SI).<sup>62</sup> The degree of randomness of the copolymer, calculated as reported in the literature, was 0.14.<sup>63</sup> This value suggested that the monomers tend to cluster in blocks of each units. The average sequence length of the blocks was of 18 units for BL and of 12 units for CL. The blocky microstructure proposed for poly[HB-co-CL] was supported by kinetic studies (Figure 6). After 30 min the conversion of 72% of  $\epsilon$ -CL was observed, after at same time the conversion of  $\beta$ -BL was only of 2%. After additional 15 min, the conversion of  $\epsilon$ -CL remained unchanged (74%) while the conversion of  $\beta$ -BL reached 43%.

After additional 30 min the almost complete conversion of  $\epsilon$ -CL was achieved (95%) while the conversion of  $\beta$ -BL changed only weakly (from 43% to 54%).



**Figure 6.** Plot of conversion vs time for  $\epsilon$ -CL (black solid squares) and  $\beta$ -BL (red solid circles) concentration

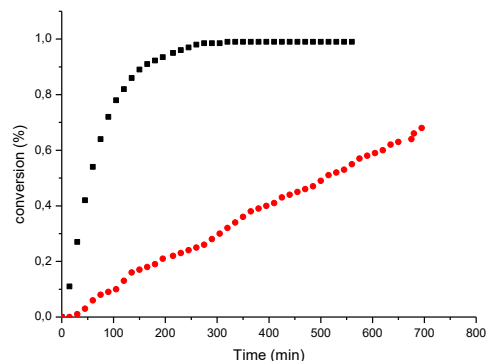
Finally, we extended our studies to the copolymerization of  $\beta$ -BL and L-LA. In the literature, the complexes that promote the ROP of both  $\beta$ -BL and L-LA, and that are effective in their copolymerization are rare.<sup>64-68</sup>

From an equimolar feed ratio of the two monomers, after 12 hours, complex **1** was able to promote the complete conversion of L-LA while  $\beta$ -BL conversion was significantly lower (50%). For classical half-salen aluminum complexes, no incorporation of *rac*- $\beta$ -BL during the copolymerization was achieved, even after extended polymerization times.<sup>69</sup>

The thermal analysis of the obtained sample showed an endotherm peak centered at  $T = 133$  °C with melting enthalpy of 28.7 J/g (Figure S10 of the SI). This melting transition was tentatively attributed to the PLLA phase so that the corresponding degree of crystallinity result in  $\approx 20\%$  (in the second DSC run it was drastically reduced to only 2%). None thermal transitions were attributed to the PHB phase. In the second DSC heating run none endotherm or exothermal phenomena were observed while a single  $T_g$  at about 45 °C was evident. This  $T_g$  value, lower than that of PLLA homopolymer, indicates the presence of inter-crystalline phases, in which the two homopolymers are at least partially miscible. The WAXD pattern of sample only the typical peaks of the PLLA alpha form were present, confirming that only the PLA phase is crystalline (Figure S11 of the SI). These results agree with a polymer tapered microstructure in which the most rigid PLA phase is formed and crystallized before the more flexible and stereoirregular PHB phase, so that the PHB crystallization process is hindered

Kinetic studies by  $^1\text{H}$  NMR spectroscopy revealed that the rate of insertion of *rac*- $\beta$ -BL into the copolymer was significantly slower than that observed for L-LA (Figure 7 and Figure S12). When the conversion of L-LA reached 90%, the *rac*- $\beta$ -BL inserted was only about 10%.

These observations suggested that the obtained copolymer presumably has a tapered microstructure, where the monomer composition varied from all lactydic-units to all BL units over the



length of the polymer chain ( $^{13}\text{C}$  NMR Figure S14 of the SI).

**Figure 7.** Plot of conversion vs time for L-LA (black solid squares) and  $\beta$ -BL (red solid circles) concentration

#### Copolymerizations of cyclohexene oxide with cyclic esters.

In a previous paper we reported that complex **1** showed very high activity in the homopolymerization of cyclohexene oxide (CHO).<sup>30</sup> At 70 °C, in the absence of solvent, complex **1** was able to convert 500 equivalents of CHO in only 5 min (entry 7, Table 1). To further expand the scope of copolymerization in heterocyclic systems, we explored the copolymerization of CHO with structurally distinct cyclic esters.

Polymerization of  $\epsilon$ -CL and cyclohexene oxide was initially conducted by dissolving both monomers in 2 mL of dry toluene at 70 °C, under a nitrogen atmosphere. After 30 minutes the 33% of conversion of  $\epsilon$ -CL was achieved while CHO was completely unreacted. This suggested that the reactivity of  $\epsilon$ -CL was not influenced by the presence of the second monomer, diversely the presence of the cyclic ester inhibited completely the reactivity of **1** toward the epoxide.

Since the polymerization of CHO follows a bimetallic pathway, the possibility of cooperation between the two metal centers is influenced by the fluxionality of the ligand skeleton and thus by the polarity of the polymerization medium. For this reason, we repeated the same polymerization reaction in the absence of solvent but, also in this case, no conversion of the epoxide was achieved. PCL was isolated as unique product and no conversion of CHO was observed, even after prolonged reaction times (24 h).

**Table 3.** Sequential copolymerization of CHO with cyclic esters promoted by **1**.

<sup>a</sup> Entry	Monomer (equiv)	Time (h)	Conv. (%)	<sup>b</sup> <i>M</i> <sub>n</sub> GPC (KDa)	<sup>c</sup> <i>M</i> <sub>n</sub> <sup>th</sup> (KDa)	<sup>b</sup> Đ
1 MC 19	ε-CL	72	93	17.5	10.0	2.27
2 MC 20	L-LA	21	100	11.0	11.9	1.57
3 MC 21	β-BL	48	100	3.2	8.7	1.08

<sup>a</sup>All reactions were carried out with  $1.10^{-5}$  mol of **1** at 110 °C, in 2 mL of toluene, [1]/ [iPrOH]/ [CHO] = 1:4: 200 for 1 hour, then 200 equivalents of lactone were added. <sup>b</sup>Experimental *M*<sub>n</sub> (corrected using factor 0.58 for PLA, 0.56 for PCL and 0.54 for PBH portions, respectively) and Đ values were determined by GPC analysis in THF using polystyrene standards. <sup>c</sup>Calculated *M*<sub>n</sub> = [MM<sub>CHO</sub> × ([CHO]/[iPrOH]) ×

conversion of CHO+ MM<sub>mon</sub> × ([Mon]/[iPrOH]) × conv. of Mon2]

Analogous results were obtained for the combination of CHO with other cyclic esters. Thus, despite the presence of two strained heterocycles, both of which could undergo ROP, in all cases there is no evidence of incorporation of cyclohexene oxide either in the polyester, i.e., no ether linkages, or as a separate polyether.

Diblock copolymers, poly(ether)-co-(ester), were achieved by sequential polymerization of CHO with the three different cyclic esters. The synthesis of the first polyether block was performed at 70 °C for one hour, for the second block the reaction time was chosen depending on the reactivity of the cyclic ester.

The copolymers were characterized by <sup>1</sup>H and <sup>13</sup>C NMR spectroscopy (see Figures S15-S17 of SI) and GPC analysis. The main results are summarized in Table 3.

As expected, molar masses evaluated by GPC increased with the growth of the second block and, in all cases, they agreed with the expected values.

For example, for the PCHO-b-PLA, molar mass goes from 6.7 KDa (Đ =1.51) for the first PCHO block to 11.9 KDa (Đ =1.57) for the diblock copolymer with unimodal peak. Coherently, in the <sup>1</sup>H NMR spectrum (Figure S16 of SI), the expected signals of the copolymer were observed.

### Copolymerizations of cyclohexene oxide with cyclic esters and succinic anhydride.

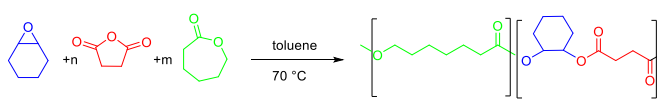
Recently, Williams reported the synthesis of copolymers of defined composition from a mixture of monomers by chemoselective copolymerization promoted by bimetallic zinc complexes and a commercial chromium catalyst.<sup>28</sup> The selectivity toward different monomers was depending on the nature of the functionality at the growing polymer chain bonded to the reactive metal center.<sup>26, 70</sup>

In analogous studies Rieger described the switching between ring-opening polymerization of β-BL and CHO/CO<sub>2</sub> copolymerization triggered by the presence of the gaseous monomer in the reaction mixture.

Thus, we decided to investigate the co-polymerization of cyclohexene oxide with ε-CL, in the presence of an equal amount of succinic anhydride (SA). After 5 hours, poly(cyclohexene succinate) was obtained as unique product while the polymerization of ε-CL was completely inhibited and there was no evidence of incorporation of the cyclic ester in the growing chain, even after extended reaction times.

These observations are in agreement with the literature data<sup>26, 71</sup> which ascribed this inactivity to rapid insertion of the succinic anhydride into the aluminum alkoxide bond, coupled with the

inability of the resulting carboxylate intermediate to initiate the



ROP of the cyclic lactone.

Analogous results were obtained by the combination of CHO and SA with the other cyclic esters.

**Scheme 3.** Copolymerization from a mixture of monomers

**Table 4.** Copolymerizations of CHO/SA with cyclic esters promoted by **1**.

<sup>a</sup> Entry	Monomer (equiv)	Time (h)	Conv. (%)	<sup>b</sup> <i>M</i> <sub>n</sub> GPC (KDa)	<sup>c</sup> <i>M</i> <sub>n</sub> <sup>th</sup> (KDa)	<sup>b</sup> Đ
1 FI121	ε-CL	4	100	13.3	10.2	1.42
2 FI129	L-LA	23	97	9.2	9.5	1.71
3 FI130	β-BL	23	100	4.6	6.8	1.29

<sup>a</sup>All reactions were carried out with  $1.10^{-5}$  mol of **1** at 110 °C, in 2 mL of toluene, [1]/ [iPrOH]/[CHO]/[SA] = 1:4:200:50 and 200 equivalents of each lactone.

<sup>b</sup>Experimental *M*<sub>n</sub> (corrected using factor 0.58 for LA and 0.56 for CL portions, respectively).

The polyesters obtained from all these copolymerization reactions have perfectly alternated microstructures with no evidence of the presence of polyether sequences (see Figures S18-S20 of SI). This is surprising since the same complex was able to promote the selective copolymerization of epoxides/anhydrides only in the presence of a nucleophilic co-catalyst.<sup>31</sup> This suggested that, in the catalytic mixture investigated, the cyclic ester acted as a co-catalyst.

When the same experiment was performed in the presence of less equivalents of anhydride (50 equivalents), a diblock copolymer poly(cyclohexene succinate)- co- polycaprolactone was obtained, confirming that the insertion of the cyclic ester is possible on the alkoxylate- aluminum bond of the growing chain.

Analogous results were obtained when the monomer couple CHO/SA was used in combination with L-lactide and β-butyrolactone. The main relevant data concerning these experiments were reported in Table 4.

The terpolymerization experiments put in evidence the different roles that monomers have in the reaction medium, the anhydride acts as switch promoting the copolymerization

CHO/SA over the ROP of the cyclic ester to produce the first block, at the same time the cyclic ester acts as cocatalyst to guarantee the selectivity of the copolymerization reaction.

## Conclusions

In this contribute we used a bimetallic salen aluminum complex to explore the homo- and co-polymerization of cyclic esters, L-lactide,  $\epsilon$ -caprolactone and  $\beta$ -butyrolactone, and their copolymerization with different heterocyclic substrates such as cyclohexene oxide and succinic anhydride.

Complex **1** was demonstrated to be highly active in the ring-opening polymerization of the cyclic esters showing a good control over the polymerization processes. The copolymerizations with different couples of cyclic esters produced copolymers with diverse microstructures, depending on kinetic control of the process.

In the copolymerization of cyclic esters with cyclohexene oxide, an efficient chemoselectivity of the catalyst emerged, and in all cases, only the related homopolyesters were produced.

Differently, using a mixed monomer feedstock comprising cyclohexene oxide, succinic anhydride and a cyclic ester, a terpolymerization reaction took place producing selectively a block copolymer polycyclohexene succinate-co polyester.

Interestingly, the portion of copolymer obtained by copolymerization of CHO and SA showed a perfectly alternated structure suggesting that, during the production of the first block, the cyclic ester had the role of cocatalyst.

In these reactions, a dual role of the involved monomers emerged. The succinic anhydride switches the catalyst from the ROP of cyclic esters to the ROCOP of epoxide with anhydride while the cyclic ester acts as cocatalyst favoring the production of perfectly alternated polyester.

Future studies will focus on exploiting this behavior to the related phenoxy-imine aluminum complexes.

## Experimental

### Generals.

All manipulations of air- and/or water-sensitive compounds were carried out under a dry nitrogen atmosphere using a Braun Labmaster glove-box or standard Schlenk line techniques. Glassware and vials used in the polymerization were dried in an oven at 120 °C overnight and exposed three times to vacuum–nitrogen cycles.

### Materials and methods.

**Reagents and Solvents.** Benzene, hexane and toluene (Sigma Aldrich) were distilled under nitrogen over sodium benzophenone. The aluminum precursor  $\text{AlMe}_3$  was purchased from Aldrich and was used as received. Deuterated solvents

were dried over molecular sieves. Racemic -BBL, CHO and  $\epsilon$ -CL were purchased from Aldrich freshly distilled from  $\text{CaH}_2$  under nitrogen and degassed thoroughly by freeze–vacuum–thaw cycles prior to use. L-Lactide was purchased from Aldrich and dried in vacuo over  $\text{P}_2\text{O}_5$  for 72 h, and afterward stored at –20 °C in glovebox. All other chemicals were commercially available and used as received unless otherwise stated. The synthesis of complex **1** was performed according published procedure.

### NMR analysis.

The NMR spectra were recorded on Bruker Advance 250, 300, 400 and 600 MHz spectrometers at 25 °C, unless otherwise stated. Chemical shifts ( $\delta$ ) are expressed as parts per million and coupling constants (J) in hertz.  $^1\text{H}$  NMR spectra are referenced using the residual solvent peak at  $\delta = 7.16$  for  $\text{C}_6\text{D}_6$  and  $\delta = 7.27$  for  $\text{CDCl}_3$ .  $^{13}\text{C}$  NMR spectra are referenced using the residual solvent peak at  $\delta = 128.06$  for  $\text{C}_6\text{D}_6$  and  $\delta = 77.23$  for  $\text{CDCl}_3$ .

**Thermal analysis.** Melting points ( $T_m$ ) and Glass transition temperature ( $T_g$ ) of the polymers were measured by differential scanning calorimetry (DSC) using a DSC 2920 apparatus manufactured by TA Instruments under a nitrogen flux of 50 mL  $\text{min}^{-1}$  with a heating and cooling rate of 10 °C  $\text{min}^{-1}$  in the range –10 to 200 °C. All calorimetric data were reported for the second heating cycle.

**MALDI-ToF-MS Analysis.** Mass spectra were acquired using a Bruker solarix XR Fourier transform ion cyclotron resonance mass spectrometer (Bruker Daltonik GmbH, Bremen, Germany) equipped with a 7 T refrigerated actively-shielded superconducting magnet (Bruker Biospin, Wissembourg, France). The samples were ionized in positive ion mode using the MALDI ion source. More details are described in the ESI.

### CHO polymerization.

**Bulk:** The polymerization was carried out in inert atmosphere. In a Braun Labmaster glovebox, a magnetically stirred reactor vessel (10 mL) was charged with a solution of metal-complex (and  $^i\text{PrOH}$ ) in CHO. The reaction mixture was stirred at 70 °C. At desired times, small aliquots of the reaction mixture were sampled, dissolved in  $\text{CDCl}_3$  and analyzed by  $^1\text{H}$  NMR spectroscopy. At the end of the polymerization the product was dissolved in hexane and then precipitated in HCl: Ethanol 1:3.

### $\beta$ -BL and $\epsilon$ -CL polymerization.

The polymerizations were carried out in inert atmosphere. In a Braun Labmaster glovebox, a reactor vessel (10 mL), equipped with a Teflon-coated stirring bar, was charged with the opportune amount of the monomer dissolved in 1.8 mL of toluene. Subsequently, a toluene solution of metal-complex and  $^i\text{PrOH}$  (0.2 mL) was added. The reaction mixture was stirred at 70 °C. At desired times; small aliquots of the reaction mixture were sampled, dissolved in wet  $\text{CDCl}_3$  and analyzed by  $^1\text{H}$  NMR spectroscopy. At the end of the polymerization, the product was

dissolved in chloroform to give viscous solution, which was subsequently poured into excess methanol. The precipitated polymer was filtered and dried under vacuum oven.

### Synthesis of Diblock Copolymers

The same procedure is followed for the synthesis of all diblock copolymers. In a typical polymerization, a magnetically stirred flame dried reaction vessel (10 cm<sup>3</sup>) was charged with the first monomer (CHO) and the opportune amount of catalyst/isopropanol and the solution was heated at 70 °C. The polymerization was performed until the required polymerization time. An aliquot (0.01 mL) was taken from the polymerization mixture and quenched in wet CDCl<sub>3</sub>; completion of reaction was deduced from the <sup>1</sup>H NMR spectroscopy.

Subsequently, the second monomer (LA, ε-CL or β-BL) was added to the polymerization mixture and heated at the same temperature (70 °C). The polymerization was continued until the complete monomer conversion as described in the Table 3. An aliquot was checked to verify the percentage of conversion of the second monomer.

The polymerization was terminated by the addition of 5 mL of CH<sub>3</sub>OH. The reaction mixture was dissolved in chloroform and precipitated in hexane. The resulting polymer (white solid) was filtered, washed with methanol, dried in vacuum, and weighed for calculating the yield.

**Kinetic Studies for Homopolymers.** In a typical experiment carried out in the nitrogen filled glovebox, a J. Young NMR tube containing 100 equiv. of an appropriate monomer (β-butyrolactone, or ε-caprolactone) was added 0.1 mL of a stock solution of complex (5 μmol) in deuterated toluene. Next, 0.4 mL of deuterated toluene was added to adjust the total volume to 0.5 mL. The NMR tube was then placed to the preheated NMR spectrometer at corresponding temperature (70° C), and the % conversion was investigated from the integration of polymer and monomer signals. The characteristic chemical for each monomer in deuterated toluene is 4.12 (q, -CH-; lactide), 3.93 (m, -CH-; β-butyrolactone), and 3.63 (m, CH<sub>2</sub>; ε-caprolactone). The characteristic chemical shift for each polymer is 5.31 (m, -CH-; poly-β-butyrolactone), 3.95 (t, -CH- in deuterated toluene is 5.12 (q, -CH-; polylactide), and 4.00 (t, -CH-; poly-ε-caprolactone).

**Kinetic Studies for Copolymers.** In a typical experiment carried out in the nitrogen filled glovebox a J. Young NMR tube containing of catalyst, 50 equivalents of each monomer and 0.1 mL of a stock solution of iPrOH in toluene. Next, 0.4 mL of deuterated toluene was added to adjust the total volume to 0.5 mL. The NMR tube was then placed to the preheated NMR spectrometer at corresponding temperature (70°C) and the % conversion was investigated from the integration of polymer and monomer signals.

### Conflicts of interest

There are no conflicts to declare.

### Acknowledgements

The authors acknowledge the Cariplo Foundation (Apollo project 2016-0643) for financial support.

### Notes and references

1. S. Mecking, *Angew. Chem., Int. Ed.*, 2004, **43**, 1078-1085.
2. Y. Zhu, C. Romain and C. K. Williams, *Nature*, 2016, **540**, 354-362.
3. X. Zhang, M. Fevre, G. O. Jones and R. M. Waymouth, *Chem. Rev.*, 2018, **118**, 839-885.
4. R. H. Platel, L. M. Hodgson and C. K. Williams, *Polym. Rev.*, 2008, **48**, 11-63.
5. C. M. Thomas, *Chem. Soc. Rev.*, 2010, **39**, 165-173.
6. S. Dagonne and C. Fliedel, *Top. Organomet. Chem.*, 2013, **41**, 125-171.
7. E. Stirling, Y. Champouret and M. Visseaux, *Polym. Chem.*, 2018, **9**, 2517-2531.
8. A. Pilone, N. De Maio, K. Press, V. Venditto, D. Pappalardo, M. Mazzeo, C. Pellecchia, M. Kol and M. Lamberti, *Dalton Trans.*, 2015, **44**, 2157-2165.
9. I. D'Auria, M. Mazzeo, D. Pappalardo, M. Lamberti and C. Pellecchia, *Journal of Polymer Science, Part A: Polymer Chemistry*, 2011, **49**, 403-413.
10. F. Hild, N. Neehaul, F. Bier, M. Wirsum, C. Gourlaouen and S. Dagonne, *Organometallics*, 2013, **32**, 587-598.
11. D. J. Darensbourg, O. Karroonnirun and S. J. Wilson, *Inorg. Chem.*, 2011, **50**, 6775-6787.
12. M. Helou, N. Ajellal, M. Bouyahyi, C. M. Thomas, A. Trifonov, S. M. Guillaume and J.-F. Carpentier, *PMSE Preprints*, 2009, **100**, 387-388.
13. N. J. Van Zee and G. W. Coates, *Chem. Commun.*, 2014, **50**, 6322-6325.
14. M. Chwatko and N. A. Lynd, *Macromolecules*, 2017, **50**, 2714-2723.
15. S. Paul, Y. Zhu, C. Romain, R. Brooks, P. K. Saini and C. K. Williams, *Chem. Commun.*, 2015, **51**, 6459-6479.
16. J. M. Longo, M. J. Sanford and G. W. Coates, *Chem. Rev.*, 2016, **116**, 15167-15197.
17. L. R. M. Rieth, D. R.; Lobkovsky, E. B.; Coates, G. W., *J. Am. Chem. Soc.*, 2002, **124**, 15239-15248.
18. S. I. Vagin, R. Reichardt, S. Klaus and B. Rieger, *J. Am. Chem. Soc.*, 2010, **132**, 14367-14369.
19. T. Aida, K. Sanuki and S. Inoue, *Macromolecules*, 1985, **18**, 1049-1055.
20. O. Coulembier, S. Moins, R. Todd and P. Dubois, *Macromolecules*, 2014, **47**, 486-491.
21. E. Hosseini Nejad, C. G. W. van Melis, T. J. Vermeer, C. E. Koning and R. Duchateau, *Macromolecules*, 2012, **45**, 1770-1776.



22. C.-H. Chang, H.-J. Chuang, T.-Y. Chen, C.-Y. Li, C.-H. Lin, T.-Y. Lee, B.-T. Ko and H.-Y. Huang, *J. Polym. Sci., Part A: Polym. Chem.*, 2016, **54**, 714-725.
23. N. D. Harrold, Y. Li and M. H. Chisholm, *Macromolecules*, 2013, **46**, 692-698.
24. C. Romain, Y. Zhu, P. Dingwall, S. Paul, H. S. Rzepa, A. Buchard and C. K. Williams, *J. Am. Chem. Soc.*, 2016, **138**, 4120-4131.
25. S. Paul, C. Romain, J. Shaw and C. K. Williams, *Macromolecules*, 2015, **48**, 6047-6056.
26. C. Romain and C. K. Williams, *Angew. Chem., Int. Ed.*, 2014, **53**, 1607-1610.
27. Y. Zhu, M. R. Radlauer, D. K. Schneiderman, M. S. P. Shaffer, M. A. Hillmyer and C. K. Williams, *Macromolecules*, 2018, **51**, 2466-2475.
28. T. Stoesser and C. K. Williams, *Angew. Chem., Int. Ed.*, 2018, **57**, 6337-6341.
29. S. Kernbichl, M. Reiter, F. Adams, S. Vagin and B. Rieger, *J. Am. Chem. Soc.*, 2017, **139**, 6787-6790.
30. F. Isnard, M. Lamberti, L. Lettieri, I. D'Auria, K. Press, R. Troiano and M. Mazzeo, *Dalton Trans.*, 2016, **45**, 16001-16010.
31. F. Isnard, M. Lamberti, C. Pellecchia and M. Mazzeo, *ChemCatChem*, 2017, **9**, 2972-2979.
32. M. Fernandez-Millan, M. Temprado, J. Cano, T. Cuenca and M. E. G. Mosquera, *Dalton Trans.*, 2016, **45**, 10514-10518.
33. A. Arbaoui, C. Redshaw and D. L. Hughes, *Chem. Commun.*, 2008, 4717-4719.
34. S. M. Kirk, H. C. Quilter, A. Buchard, L. H. Thomas, G. Kociok-Kohn and M. D. Jones, *Dalton Trans.*, 2016, **45**, 13846-13852.
35. X. Pang, R. Duan, X. Li, C. Hu, X. Wang and X. Chen, *Macromolecules*, 2018, **51**, 906-913.
36. S. Gong, P. Du and H. Ma, *Chinese Journal of Polymer Science*, 2018, **36**, 190-201.
37. X. Pang, R. Duan, X. Li and X. Chen, *Polym. Chem.*, 2014, **5**, 3894-3900.
38. W. Li, W. Wu, Y. Wang, Y. Yao, Y. Zhang and Q. Shen, *Dalton Trans.*, 2011, **40**, 11378-11381.
39. X. Pang, R. Duan, X. Li, B. Gao, Z. Sun, X. Wang and X. Chen, *RSC Adv.*, 2014, **4**, 22561-22566.
40. Y. Wang and H. Ma, *Chem. Commun.*, 2012, **48**, 6729-6731.
41. C. Kan and H. Ma, *RSC Adv.*, 2016, **6**, 47402-47409.
42. D. Osorio Melendez, J. A. Castro-Osma, A. Lara-Sanchez, R. S. Rojas and A. Otero, *J. Polym. Sci., Part A: Polym. Chem.*, 2017, **55**, 2397-2407.
43. Z. Sun, R. Duan, J. Yang, H. Zhang, S. Li, X. Pang, W. Chen and X. Chen, *RSC Adv.*, 2016, **6**, 17531-17538.
44. L. Li, B. Liu, D. Liu, C. Wu, S. Li, B. Liu and D. Cui, *Organometallics*, 2014, **33**, 6474-6480.
45. The addition of four equivalents of alcohol allows the exhaustive conversions of the alkyl groups into isopropoxide groups.
46. D. Pappalardo, L. Annunziata and C. Pellecchia, *Macromolecules*, 2009, **42**, 6056-6062.
47. M. Normand, V. Dorcet, E. Kirillov and J.-F. Carpentier, *Organometallics*, 2013, **32**, 1694-1709.
48. Y. Liu, W.-S. Dong, J.-Y. Liu and Y.-S. Li, *Dalton Transactions*, 2014, **43**, 2244-2251.
49. S. Dagonne and R. Wehmschulte, *ChemCatChem*, 2018, DOI: 10.1002/cctc.201800045, Ahead of Print.
50. W. Li, W. Wu, Y. Wang, Y. Yao, Y. Zhang and Q. Shen, *Dalton Trans.*, 2011, **40**, 11378-11381.
51. L. Chen, W. Li, D. Yuan, Y. Zhang, Q. Shen and Y. Yao, *Inorg. Chem.*, 2015, **54**, 4699-4708.
52. H.-C. Huang, B. Wang, Y.-P. Zhang and Y.-S. Li, *Polym. Chem.*, 2016, **7**, 5819-5827.
53. M. Normand, T. Roisnel, J. F. Carpentier and E. Kirillov, *Chem. Commun.*, 2013, **49**, 11692-11694.
54. W. Li, H. Ouyang, L. Chen, D. Yuan, Y. Zhang and Y. Yao, *Inorg. Chem.*, 2016, **55**, 6520-6524.
55. The related half salen was inactive in the ROP of BL under the same reaction conditions (200 eq of BL, 70 °C, 24 h).
56. J. Lewiński, P. Horeglad, K. Wójcik and I. Justyniak, *Organometallics*, 2005, **24**, 4588-4593.
57. J. S. Klitzke, T. Roisnel, E. Kirillov, O. d. L. Casagrande and J.-F. Carpentier, *Organometallics*, 2014, **33**, 5693-5707.
58. A.-C. Albertsson and I. K. Varma, *Biomacromolecules*, 2003, **4**, 1466-1486.
59. Z. T. Dobroth, S. Hu, E. R. Coats and A. G. McDonald, *Bioresource Technology*, 2011, **102**, 3352-3359.
60. Crystallinity degree was calculated by comparing the observed melting enthalpy with the value of 142 J/g of a PLLA crystal of infinite size.
61. H. Tsuji, *Macromol. Biosci.*, 2005, **5**, 569-597.
62. H. Abe, Y. Doi, H. Aoki, T. Akehata, Y. Hori and A. Yamaguchi, *Macromolecules*, 1995, **28**, 7630-7637.
63. C. Chen, B. Fei, S. Peng, H. Wu, Y. Zhuang, X. Chen, L. Dong and Z. Feng, *Journal of Polymer Science Part B: Polymer Physics*, 2002, **40**, 1893-1903.
64. Y. Hori, Y. Takahashi, A. Yamaguchi and T. Nishishita, *Macromolecules*, 1993, **26**, 4388-4390.
65. M. S. Reeve, S. P. McCarthy and R. A. Gross, *Macromolecules*, 1993, **26**, 888-894.
66. D. C. Aluthge, C. Xu, N. Othman, N. Noroozi, S. G. Hatzikiriakos and P. Mehrkhodavandi, *Macromolecules*, 2013, **46**, 3965-3974.
67. B. J. Jeffery, E. L. Whitelaw, D. Garcia-Vivo, J. A. Stewart, M. F. Mahon, M. G. Davidson and M. D. Jones, *Chem. Commun.*, 2011, **47**, 12328-12330.
68. E. D. Cross, L. E. N. Allan, A. Decken and M. P. Shaver, *J. Polym. Sci., Part A: Polym. Chem.*, 2013, **51**, 1137-1146.
69. D. J. Darensbourg, O. Karroonnirun and S. J. Wilson, *Inorg. Chem.*, 2011, **50**, 6775-6787.
70. Y. Zhu, C. Romain and C. K. Williams, *J. Am. Chem. Soc.*, 2015, **137**, 12179-12182.
71. P. K. Saini, C. Romain, Y. Zhu and C. K. Williams, *Polym. Chem.*, 2014, **5**, 6068-6075.