A SIMPLE In-BASED DUAL CATALYST ENABLES SIGNIFICANT PROGRESS IN ϵ - DECALACTONE RING-OPENING (CO)POLYMERIZATION

Somprasong Thongkham, Julien Monot, Blanca Martin-Vaca, Didier Bourissou**

Laboratoire Hétérochimie Fondamentale et Appliquée (UMR 5069), Université de Toulouse
(UPS), CNRS, 118 route de Narbonne, F-31062 Toulouse, France.

ABSTRACT. A dual catalyst associating InCl_3 and triethylamine was found to promote controlled ring-opening polymerization of ϵ -decalactone (ϵ -DL), a monomer derived from sustainable resources. Polydecalactones (PDL) of well-defined structures with M_n up to 30 000 g/mol ($\text{Đ} \sim 1.2$) have been obtained free of catalytic residues under mild conditions (toluene, 3M, 60 °C, 1-20 h). Besides the typical ester end-capped PDLs, amide end groups have been installed thanks to the ability of the dual catalyst to perform with primary amines as initiators. Block PDL-*b*-PCL / PCL-*b*-PDL and random P(DL-*r*-CL) copolymers have been also prepared by sequential and simultaneous ROP with ϵ -caprolactone, respectively. The absence of undesirable

transesterifications reactions, as apparent from NMR, SEC, and DSC analyses, enable the preparation of well-defined copolymers.

Introduction.

The development of new sustainable polymers endowed with improved performances but minimal environmental impact has become a major concern.^{1,2,3} In this context, biodegradable aliphatic polyesters are particularly attractive, and polyesters such as PLA, PVL, and PCL have already been investigated and used for a few decades.^{4,5,6,7} Their biodegradable and biocompatible properties have been leveraged in many applications, for specialty uses (medical devices, drug release) and also commodity purposes such as food-packaging, cutlery, organic waste bags, and other short-term uses. The disposal of the polymer materials at the “end of life”, once it has served its purpose, is a key aspect to take into account when dealing with sustainability.^{8,9}

The origin of the raw material and its accessibility from renewable sources is also an aspect that attracts increasing interest.^{10,11,12} From the different methodologies applied to the preparation of aliphatic polyesters, ring-opening polymerization (ROP) of lactones is the one enabling for the best control/tuning of the polymer properties. Accordingly, PLA, PVL, and PCL are typically prepared by ROP of lactide, δ -valerolactone (δ -VL), and ϵ -caprolactone (ϵ -CL). If lactide is a renewable monomer,^{12,13} it is not the case for δ -VL and ϵ -CL that are prepared industrially from petrol.¹⁴ Recently, the replacement of the two latter monomers by δ - and ϵ -decalactones (δ - and ϵ -

DL) has attracted growing attention. These lactones, which are obtained from castor oil as a mixture of stereoisomers via fungal transformations, are widely used in flavor and fragrance industries.^{15,16,17}

Over the past few years, ϵ -DL has in particular been envisioned as a co-monomer in the preparation of random and block copolymers with modified properties compared to PCL.¹⁸ A. C. Albertsson,^{19,20,21} C. Alexander, and D. J. Irvine²² have investigated separately the influence of the amorphous character of PDL compared to semi-crystalline PCL on the capacity of PEG-PDL(PCL) amphiphilic block copolymers to form micelles and perform drug release. This amorphous character and the low T_g (resulting from the lateral *n*-butyl group and an atactic microstructure) is also at the origin of the introduction of PDL as soft blocks in thermoplastic elastomers and shape-memory materials by M. Hillmyer,^{23,24} A. C. Albertsson,^{19,25} and J. Shin.^{26,27} C. Williams has also reported ϵ -DL copolymerization of tri and tetra component monomer mixtures (epoxide / anhydride / ϵ -DL and epoxide / anhydride / ϵ -DL / CO₂) promoted by Cr or Zn-based catalysts.^{28,29,30} Here, the secondary metal-alkoxide propagating moiety resulting from the ring-opening of ϵ -DL imparts well-balanced kinetics and prevents chain-transfer reactions.

In contrast to the interest devoted to ϵ -DL as co-monomer to modulate polymer properties, only few studies have focused on the ROP of this monomer whose polymerization is challenging, and for which known catalysts present significant drawbacks and limitations. Most of the studies involving ϵ -DL as (co)-monomer make use of SnOct₂ and operate in bulk conditions at high temperatures (110-180 °C).^{19-21,23,24,27} The *n*-butyl substituent present on the propagating position significantly affects the polymerization kinetics, reducing the reaction rate.^{31,32} Despite the required harsh polymerization conditions and long reaction times (few days at 110°C), PDLs with M_n in range of the targeted ones (up to 40 000 g/mol) and rather narrow molecular distributions

($\bar{D} < 1.30$) have been reported with SnOct₂. The organocatalyst TBD has also been evaluated in the ROP of ϵ -DL under similar reaction conditions (bulk at 110 °C).^{19,22} Shorter reaction times are observed, but the polymerization is less controlled ($\bar{D} < 1.45$). Considering the high application potential of PDL materials, it is necessary to develop new catalytic systems able to promote the controlled ROP of ϵ -DL. Better knowledge is needed about the different classes of catalysts, to assess their behavior towards ϵ -DL and enable ultimately rational choice of the most suitable system to a given target / application. Last but not least, the reported ROP promoted by SnOct₂ or TBD were carried out in bulk conditions. This implies that the catalyst remains inside the polymer material. This may be an issue from a toxicity viewpoint,^{33,34} and can also dramatically alter the polymer properties during thermal treatments at high temperatures, thermo-modeling or extrusion for instance.^{35,36,37} Therefore, while the results obtained with SnOct₂ and TBD are to be valued, new catalysts operating in solution under milder conditions are highly desirable to develop further the use of ϵ -DL.

Only few examples of catalysts promoting ROP of ϵ -DL in solution have been reported, and for most of them (La(OAr)₃,³⁸ Ca and Zn aryloxiamine complexes,³⁹ and the dual system MgI₂/cyclic isothiourea⁴⁰), a unique example of ϵ -DL ROP has been reported. Only in the work of C. C. Lin with NNO tridentate ketimines Zn complexes, the control of the polymerization has been briefly explored, although the advantages and limitations of the catalyst have not been explored.⁴¹ Nevertheless, PDL of $M_n > 15\,000$ and narrow molecular distributions ($\bar{D} < 1.15$) can be prepared in mild conditions (50 °C, 3-5h), which is also the case of the sole example reported using the dual catalytic system combining MgI₂ and a cyclic isothiourea.⁴⁰

Dual catalysis, based on the cooperativity between a metallic Lewis acid and an organic Lewis base, is a concept widely used in organic synthesis⁴² that has only been extended over the last

decade to the field of polymer chemistry, and more particularly to the ROP of lactones and cyclic carbonates.^{43,44} The strength of dual catalysis is the association of a Lewis acid with a Lewis base (to activate the monomer and the protic initiator, respectively), that are inactive separately while their combination and cooperation enables polymerization under mild conditions. This constitutes an interesting approach to increase activity, while maintaining good selectivity towards chain-transfer reactions (transesterifications). Most of the recent reports involve simple, readily available Lewis acids (MgX_2 , ZnX_2 , LiX ...) with a more sophisticated Lewis base such as N-heterocyclic carbenes NHC,^{45,46} N-heterocyclic olefins NHO,^{47,48,49} or cyclic isothioureas.^{40,50} However, dual catalysts based on readily available Lewis acids and Lewis bases are rare. We recently used the association of Zn derivatives with tertiary amines (DMAP, TMP) to polymerize lactide (and ϵ -caprolactone) and access macrocyclic polymers.^{51,52} In addition, M Hillmyer reported in 2010⁵³ a detailed study on the ability of the $\text{InCl}_3/\text{NEt}_3$ association to act as catalyst for the controlled ROP of lactide. In the same article, preliminary results were disclosed on the ROP of several lactones including one example with ϵ -Me- ϵ -CL, suggesting that this dual catalytic system is able to propagate ROP via secondary In-alkoxide moieties. Note that several well-defined In complexes have been reported over the last years as efficient catalysts for the ROP of lactide and β -BL, as reviewed recently by P. Mehrkhodavandi, J.-F. Carpentier and C. Williams.^{54,55,56,57,58} The good results reported for the $\text{InCl}_3/\text{NEt}_3$ association with ϵ -Me- ϵ -CL prompted us to investigate the behavior of this very simple dual catalyst towards ϵ -DL, which is a heavier analog of ϵ -Me- ϵ -CL. As reported hereafter, the $\text{InCl}_3/\text{Et}_3\text{N}$ association indeed promotes the ROP in a controlled and living manner, leading to PDL free of residual catalyst. Different types of initiators can be used (alcohols, amines) leading to ester and amide end-capped PDLs. Block and random copolymers with PLC can also be easily prepared.

Experimental.

Materials

All reactions were performed under an inert atmosphere of argon using standard Schlenk techniques. Toluene (> 99.9%) was dried prior to use with a Braun solvent-purifier system. CDCl_3 was dried prior to use by distillation over molecular sieves. The alcohols, benzyl amine, triethyl amine, and PEG-NH₂ were purchased from Aldrich, dried and stored under argon prior to use. All initiators were dried either under vacuum in the presence of P_2O_5 or over molecular sieves and then filtrated prior to use. ϵ -DL (99%, Aldrich) and ϵ -CL (98%, Aldrich) were purified by distillation over CaH_2 and stored under argon. InCl_3 (99.999%) was purchased from Aldrich, dried over P_2O_5 under vacuum, and stored under argon in a glove box.

SEC Analyses. The number-average, weight-average molar masses (M_n and M_w , respectively), and molar mass distributions (D) of the polymer samples were determined by size exclusion chromatography (SEC) at 35 °C with a Waters 712 WISP high-speed liquid chromatograph equipped with a R410 refractometer detector. Tetrahydrofuran (THF) was used as the eluent, and the flow rate was set up at 1.0 mL/min. A SHODEX precolumn (polystyrene AT806M/S M_w = 50000000 g/mol) and two STYRAGEL columns (HR1, 100–5000 g/mol, and HR 4E, 50–100000 g/mol) were used. Calibrations were performed using polystyrene standards (400–100000 g/mol).

NMR Analyses. NMR spectra were recorded in CDCl_3 on BRUKER Avance 300 MHz spectrometers at room temperature, and chemical shifts are reported in ppm relative to Me_4Si as an external standard. ^1H measurements were used for determination of the monomer conversion, the degree of polymerization (DP_{NMR}), and the end-group analysis for copolymers architectures.

In ϵ -DL polymerisations the conversion was assessed by comparing the peak area integral of $-\text{O}-\text{CH}(\text{C}_4\text{H}_9)-$ (proton attached to ϵ -carbon; $\delta = 4.22$ ppm) of ϵ -DL to the integral of the same peak within the PDL polymer (PDL; $\delta = 4.84$ ppm) in the ^1H NMR spectrum. In ϵ -CL based reactions the integral intensity of $-\text{O}-\text{CH}_2-$ ($\delta = 4.14$ ppm) for the ϵ -CL monomer was compared to the intensity of the same peak for PCL polymer ($\delta = 4.08$ ppm). DP_{NMR} was determined from the relative intensities of the OCH signals for polymer (multiplet at $\delta = 4.84$ and 4.08 ppm respectively for PDL and PCL) and the signal of initiator used as reference. Copolymers architectures were confirmed by the end-group analysis from ^1H measurements and ^{13}C measurements. 2D COSY NMR was used for determination of one polymer chain growth at N atom of benzyl amine.

MALDI-TOF MS analyses. MALDI-TOF-MS analyses were performed on a MALDI MicroMX from Waters equipped with a 337 nm nitrogen laser. An accelerating voltage of 20 kV was applied. Mass spectra of 1000 shots were accumulated. The polymer sample was dissolved in THF at a concentration of 1 mg mL^{-1} . The cationization agent used was NaI dissolved in THF at a concentration of 1 mg mL^{-1} . The matrix used was dithranol and was dissolved in THF at a concentration of 10 mg mL^{-1} . Solutions of matrix, salt, and polymer were mixed in a volume ratio of 10 : 1 : 1 respectively. The mixed solution was hand-spotted on a stainless steel MALDI target and left to dry. The spectrum was recorded in the reflectron mode. Baseline corrections and data analyses were performed using MassLynx version 4.1.

Differential Scanning Calorimetry. The thermal properties of the copolymers were measured on a NETZCH DSC 204 system under a nitrogen atmosphere at heating and cooling rates of 20 and $10 \text{ }^\circ\text{C min}^{-1}$, respectively. The T_g and T_m values were extracted from the second heating curves.

Thermal Gravimetric Analysis. The thermal stability of the copolymers was measured on a PerkinElmer DIAMOND TG/TDA thermobalance, under air from 30 to $650 \text{ }^\circ\text{C}$ at a heating rate

of 10 °C/min. The degradation temperatures correspond to the temperature from which the curves switched off the baseline.

Methods

Typical procedure for homopolymerization of ϵ -DL. Polymerization experiments were performed under Ar atmosphere at ambient temperature by adding ϵ -DL in a stirring suspension of initiator (1 equiv.), NEt₃ (2 equiv.), and InCl₃ (1 equiv.), [M]₀ = 3M in Toluene. The reaction mixture was stirred at 60 °C until complete consumption of ϵ -DL as determined by ¹H NMR spectroscopy. An excess of benzoic acid was added to quench the catalyst, and the solvent was evaporated under vacuum. The polymer was then dissolved in a minimum of dichloromethane and precipitated two consecutive times in cold methanol, then filtered, and dried under vacuum, only 10 ppm of Indium remained in pure polymer. Conversion: 92% to >99%; isolated yield: 85% to 95%;

Benzyl alcohol as initiator, example for M/I = 20: ¹H NMR (CDCl₃, 300 MHz, ppm): 7.30 (s Br, 5H, Ph), 5.10 (s, 2H, PhCH₂O), 4.88 – 4.79 (m, 21H, -CHO-), 3.58 (br s, 1H, -CH-OH, chain end), 2.28 – 2.23 ppm (m, 44H, CH₂), 1.60-1.46 (m, 142H, CH₂), 0.89-0.84 (m, 66H, CH₃). DP_{NMR} = 22; SEC (THF): M_n = 3800, $\bar{D}$ = 1.10.

Benzyl amine as initiator, example for M/I = 30: ¹H NMR (δ , CDCl₃, 300 MHz, ppm): 7.30 – 7.24 (m, 5H, CH), 6.09 – 6.01 (br t, 1H, NH), 4.85 – 4.81 (m, 31H, -CHO-), 4.42 (d, 2H, J = 5.6 Hz, PhCH₂N-), 3.58 (br s, 1H, -CH-OH, chain end), 2.28 – 2.23 (m, 60H, CH₂), 1.60-1.46 (m, 360H, CH₂), 0.89-0.84 (m, 90H, CH₃). DP_{NMR} = 31; SEC (THF): M_n = 7300, $\bar{D}$ = 1.12.

Typical procedure for the preparation of block copolymer PCL-*b*-PDL. Copolymerization experiments were performed under Ar atmosphere at ambient temperature by adding ϵ -CL in a stirring suspension of dimethoxybenzyl alcohol (DMBA) (1 equiv.), NEt₃ (2 equiv.), and InCl₃ (1 equiv.), [CL]₀ = 3M in Toluene. The reaction mixture was stirred at 60 °C until complete consumption of ϵ -CL, as determined by ¹H NMR spectroscopy. ϵ -DL in Toluene was then added to the stirring solution of PCL and catalysts. The reaction mixture was stirred at 60 °C until the complete consumption of ϵ -DL. An excess of benzoic acid was added to quench the catalyst, and the solvent was evaporated under vacuum. The block copolymer was then dissolved in a minimum of dichloromethane and precipitated in cold methanol, then filtered, and dried under vacuum. Conversion: > 99% (for both monomers); yield: 90%. SEC: M_n = 22000 g/mol, D = 1.24. DSC: T_g = -57.8 °C and T_m = 55.2 °C. TGA: T_d = 337 °C. ¹H NMR (CDCl₃, 300 MHz, ppm): 6.47 (d, J = 2.3 Hz, 2H, *ortho*-C₆H₃-CH₂-O-), 6.37 (t, J = 2.3 Hz, 1H, *para*-C₆H₃-CH₂-O-), 5.03 (s, 2H, ArCH₂O-), 4.88 – 4.79 (m, 50H, -CHO-), 4.04 (m, 100H, -CH₂O-), 3.75 (s, 6H, 2(-OCH₃)), 3.58 (br s, 1H, -CH-OH, chain end by DL unit), 2.29 – 2.22 (m, 200 H, CH₂), 1.60-1.46 (m, 450 H, CH₂), 1.40 – 1.22 (m, 450 H, CH₂), 0.89-0.84 (m, 150 H, CH₃).

Typical Procedure for the Preparation of sequential block copolymer PDL-*b*-PCL

The block copolymer PDL-*b*-PCL was synthesized by adding ϵ -DL in a stirring suspension of DMBA (1 equiv.), NEt₃ (2 equiv.), and InCl₃ (1 equiv.), [ϵ -DL]₀ = 3M in Toluene. The reaction mixture was stirred at 60 °C until the complete consumption of ϵ -DL. ϵ -CL in Toluene, was then added to the stirring suspension of PDL and catalysts. The reaction mixture was stirred at 60 °C until the complete consumption of ϵ -CL. An excess of benzoic acid was added to quench the catalyst, and the solvent was evaporated under vacuum. The block copolymer was then dissolved in a minimum of dichloromethane and precipitated in cold methanol, then filtered, and dried under

vacuum. Conversion: > 99% (for both monomers); yield: 92%. SEC: $M_n = 16300$ g/mol, $D = 1.25$. DSC: $T_g = -54.8$ °C and $T_m = 55.2$ °C. TGA: $T_d = 362$ °C. ^1H NMR (CDCl_3 , 300 MHz, ppm): 6.47 (d, $J = 2.3$ Hz, 2H, *ortho*- C_6H_3 - CH_2 -O-), 6.39 (t, $J = 2.3$ Hz, 1H, *para*- C_6H_3 - CH_2 -O-), 5.02 (s, 2H, ArCH_2O -), 4.88 – 4.79 (m, 50H, -CHO-), 4.06 – 4.02 (m, 100H, - CH_2O -), 3.77 (s, 6H, 2(-OCH₃)), 3.67 – 3.60 (m, 2H, - CH_2 -OH, chain end by CL unit), 2.31 – 2.22 (m, 200 H, CH_2), 1.69 – 1.46 (m, 450 H, CH_2), 1.40 – 1.22 (m, 450 H, CH_2), 0.89 – 0.84 (m, 150 H, CH_3).

Typical Procedure for the Preparation of random copolymer P(CL-*r*-DL).

Copolymerization experiments were performed under Ar atmosphere at ambient temperature by adding ϵ -CL and ϵ -DL in a stirring suspension of DMBA (1 equiv.), NEt_3 (2 equiv.), and InCl_3 (1 equiv.), $[\text{CL} + \text{DL}]_0 = 3\text{M}$ in Toluene. The reaction mixture was stirred at 60 °C until complete consumption of both monomers, as determined by ^1H NMR spectroscopy. An excess of benzoic acid was added to quench the catalyst, and the solvent was evaporated under vacuum. The copolymer was then dissolved in a minimum of dichloromethane and precipitated in cold methanol, then filtered, and dried under vacuum. Conversion: >99% (for both monomers); yield: 95%. SEC: $M_n = 19400$ g/mol, $D = 1.17$. DSC: $T_g = -60$ °C. TGA: $T_d = 351$ °C. ^1H NMR (CDCl_3 , 300 MHz, ppm): 6.45 (d, $J = 2.3$ Hz, 2H, *ortho*- C_6H_3 - CH_2 -O-), 6.37 (t, $J = 2.3$ Hz, 1H, *para*- C_6H_3 - CH_2 -O-), 5.01 (s, 2H, ArCH_2O -), 4.88 – 4.79 (m, 50H, -CHO-), 4.04 – 3.99 (m, 100H, - CH_2O -), 3.75 (s, 6H, 2(-OCH₃)), 3.64 – 3.58 (m, 2H, - CH_2 -OH, chain end by CL unit), 3.56 (br, 1H, - CH -OH, chain end by DL unit), 2.30 – 2.22 (m, 200 H, CH_2), 1.67 – 1.43 (m, 450 H, CH_2), 1.41 – 1.16 (m, 450 H, CH_2), 0.86 – 0.82 (m, 150 H, CH_3).

Results and discussion.

Figure 1. Comparative kinetic plot of ROP of ϵ -DL (**DP50**, toluene, $[\epsilon\text{-DL}]_0 = 3$ mol/L) catalyzed by $\text{InCl}_3/\text{NEt}_3/\text{BnOH}$ 1:2:1 at 60 °C (red line and dots), TBD/BnOH 1:1 at 60 °C (black line and rhombus), $\text{Sn}(\text{Oct})_2/\text{BnOH}$ 1:1 at 60 °C (violet line and triangles), $\text{Sn}(\text{Oct})_2/\text{BnOH}$ 1:1 at 110 °C (blue line and squares).

ROP of ϵ -DL promoted by $\text{InCl}_3/\text{Et}_3\text{N}$. ROP of ϵ -DL promoted by the $\text{InCl}_3/\text{Et}_3\text{N}$ association (1/2 ratio) and initiated by benzyl alcohol with a ϵ -DL/BnOH ratio of 50 was first achieved in 3 mol/L toluene solution at 60 °C. The dual system was then compared with SnOct_2 and TBD under similar reaction conditions. As depicted by Figure 1, the reaction is significantly faster for the $\text{InCl}_3/\text{Et}_3\text{N}$ association. Only 4 h is needed to achieve full conversion, while after 24 h of reaction, 90% and 5 % of conversion are reached with TBD and SnOct_2 , respectively. Due to the very low conversions observed for SnOct_2 at 60 °C, the reaction was also carried out at 110 °C, but even at this temperature, conversion is slower than with the $\text{InCl}_3/\text{Et}_3\text{N}$ association (~24 h to reach full conversion). The association of InCl_3 and Et_3N is thus a rare catalyst to promote the ROP of ϵ -DL in solution under mild conditions. The PDL sample obtained with $\text{InCl}_3/\text{Et}_3\text{N}$ (after quenching the

polymerization with an excess of PhCO₂H and precipitation) features a molecular weight of 9800 g/mol ($M_{n\text{ th}}$ 8600 g/mol) and low molar distribution ($\mathcal{D} = 1.13$), suggesting rather good control of the polymerization, as in the case of the ROP of ϵ -DL with SnOct₂ at 110°C ($M_n = 6\,116$ g/mol, vs $M_{n\text{ th}} = 6978$ g/mol, and $\mathcal{D} = 1.19$).

Table 1. Polymerization of ϵ -DL promoted by InCl₃/Et₃N and initiated by BnOH or DMBA^a

ϵ -DL $\xrightarrow[\text{Toluene, T}]{\text{InCl}_3 / \text{X Et}_3\text{N}, \text{ROH (1 equiv)}}$ PDL

Run	M_0/I_0^a	InCl ₃ / NEt ₃	I/ InCl ₃	ROH (I)	T (°C)	t (h)	Conv ^b (%)	M_n (th)	M_n^c NMR	M_n^d SEC	$\mathcal{D}^d$
1	50	1:2	1	BnOH	60	4	>99	8600	9000	9100	1.09
2	20	1:2	1	BnOH	60	1	>99	3500	3800	5400	1.10
3	25	1:2	1	BnOH	60	2	>99	4400	4500	6000	1.08
4	30	1:2	1	BnOH	60	2	>99	5200	4900	5600	1.10
5	70	1:2	1	BnOH	60	8	98	11 700	11 500	11 400	1.10
6	90	1:2	1	BnOH	60	12	99	15 300	15 800	13 100	1.12
7	150	1:2	1	DMBA	60	18	>99	25 700	26 700	25 100	1.13
8	175	1:2	1	DMBA	60	20	>99	29 900	31 900	27 960	1.24
9	50	1:2	1	BnOH	30	12	12	1100	1100	n.d.	n.d.
10	150	1:2	1	DMBA	80	20	>99	25 700	26 300	25 500	1.39
11 ^e	350	1:2	1	DMBA	60	40	98	55 500	n.d.	57 490	1.35
12	50	1:2	0	DMBA	60	24	NR	-	-	-	-
13	20	1:0	1	BnOH	60	24	26	1000	1000	n.d.	n.d.
14	50	0:1	1	BnOH	60	18	NR	-	-	-	-

^a I_0 = initiator, (benzyl alcohol BnOH or 3,5-dimethoxybenzyl alcohol, DMBA). ^bCalculated by ¹H NMR spectroscopy. ^c M_n NMR = [(DP_{NMR})*170.25 (M_w of ϵ -DL)] + M_w of initiator. ^d M_n SEC from polymer after purification, using PS calibration. ^eReaction performed with two monomer feeds 175 + 150 equiv. n.d. = not determined, NR = no reaction.

Using the same reaction conditions, and benzyl alcohol or 3,5-dimethoxybenzyl alcohol (DMBA) as initiator (depending on the M/I ratio, so that accurate integration of the ¹H NMR

spectra could be done for calibration), the control of the polymerization was probed for monomer to initiator ratios of 20 to 175 (Table 1, runs 1 to 8). For these M/I ratios, all the typical characteristics of a controlled and living polymerization were observed (Figure 2). As showed in Figure 2a,b, the molecular weight of the resulting PDL increases linearly with the M_0/I_0 ratio, while maintaining low $\bar{D}$ (1.08-1.13). Moreover, the number of active-growing chains remains constant all over the polymerization process, as demonstrated by the kinetic semi-logarithmic plot, consistent with a first partial kinetic order in monomer, and by the linear evolution of the molecular weight of the polymer with monomer conversion (Figures 2c and 2d, respectively).

Figure 2. Controlled character of ROP of ϵ -DL catalyzed by $InCl_3/Et_3N/BnOH$ 1:2:1 in toluene ($[\epsilon\text{-DL}]_0 = 3$ mol/L) at 60 °C for DP20 to DP175: a) Plot of M_n vs $[\epsilon\text{-DL}]_0/[BnOH]_0$. b) Stack of SEC traces of the obtained PDL. c) Semi-logarithmic plot for $[\epsilon\text{-DL}]_0/[BnOH]_0 = 100$. d) Evolution of M_n with the conversion for $[\epsilon\text{-DL}]_0/[BnOH]_0 = 50$, $\bar{D}$ values on the graph.

Chain-end group fidelity was investigated by ^1H NMR spectroscopy and MALDI-TOF MS. The ^1H NMR spectrum in Figure 3a depicts the typical signals expected for a PDL polymer chain at 4.85 (a), 2.52 (i), 1.71-1.45 (b,c,d,f,g,h) and 0.87 (e) ppm. In addition, the spectrum also displays two singlet signals at 7.30 (k) and 5.10 (j) ppm corresponding to the benzyl ester group resulting from ROP initiation by BnOH, and a broad signal at 3.55 (a') ppm corresponding to the terminal *CHOH* group. The relative 2 to 1 value of the integration of signals j and a' is consistent with all the chains featuring the same ester/alcohol chain-ends and demonstrates high end-group fidelity. Moreover, the relative integration value between signals a and a' (or a+a' and j) is close to 20, indicating that the DP_{NMR} value matches well the initial monomer / initiator feed.

Further information is supplied by the MALDI-TOF MS analysis (Figure 3b). No sign of macrocycles is detected. A very major population is observed with molar mass $M = n \times 170(M_{\text{DL}}) + 108(M_{\text{BnOH}}) + 23(M_{\text{Na}^+})$, corresponding to the linear polymer chains initiated by BnOH and terminated by a hydroxyl group. All these data indicate that PDL of well-defined structures with M_n up to ~30 000 g/mol and narrow molar distributions ($D < 1.13$) can be prepared in a controlled manner by fixing the M/I ratio (good reproducibility of the polymerization was substantiated for a monomer to initiator ratio of 50, see Table S1 and Figure S1). Another noticeable point is that ICP-OES analysis of the polymers, obtained after precipitation by addition of a concentrated DCM solution on cold methanol, showed an In content of ~ 10 ppm which means that more than 99 % of the introduced In catalyst has been removed. This low content in catalyst residue should limit the risk of polymer alteration upon thermal treatments at high temperature.^{35,36,37}

Figure 3. a) ¹H NMR spectrum (CDCl₃, 300 MHz) of a PDL of DP 21. b) Mass spectrum (MALDI-TOF) (region m/z 1700 to 4500 g/mol) of a PDL sample prepared with a [ε-DL]₀/[BnOH]₀/[InCl₃]₀/[Et₃N]₀ = 20/1/1/2 in toluene at 60 °C, [ε-DL]₀ = 3 mol/L (SEC analysis; M_n = 5400, D = 1.10)

We then explored the impact of the reaction conditions on the polymerization process and the polymer properties. Carrying out the reaction at 30°C resulted in very slow conversion (less than 12% after 12 h, run 9, Table 1), while increasing the temperature reaction to 80°C (run 10) enabled rapid conversion and yielded high molecular weight PDL (M_n = 26 300 g/mol). However, lower control of the polymerization is indicated by the higher molar distributions observed (D of 1.39 vs

1.13 at 60°C). In line with this result, bulk polymerization at 100 °C led to higher $\bar{D}$ values (entry 26 in Table S2, 1.50 vs 1.15 at 60 °C, using DMBA as initiator and M/I = 50). Chloroform can be used as solvent instead of toluene without impact on kinetic or controlled character of the polymerization (entries 13-16 in Table S1, Figure 4a). Toluene was preferred for the rest of study. To push further the system in terms of DP, a polymerization was performed with two consecutive feeds of 175 and 150 equiv. of ϵ -DL. A PDL with $M_n = 57\,490$ g/mol and $\bar{D} = 1.35$ was thereby obtained (run 11, Table 1). Although the $\bar{D}$ value increases slightly, the M_n value is in the range of the targeted one ($M_{n\,th}$ 55 500 g/mol).

Figure 4. a) Plot of $M_{n,NMR}$ vs $([\epsilon\text{-DL}]_0/[\text{BnOH}]_0)$ for DP20 to DP90) for the polymerization at 60 °C of ϵ -DL by BnOH/ $\text{InCl}_3/\text{Et}_3\text{N}$ 1:1:2 in Toluene (blue line, triangles), in CDCl_3 (yellow line, squares) and BnOH/ $\text{InCl}_3/\text{Et}_3\text{N}$ 1:1:1 in Toluene (red line, circles) ($[\epsilon\text{-DL}]_0 = 3\text{M}$). b) Plot of $M_{n,NMR}$ vs $([\epsilon\text{-DL}]_0/[\text{BnOH}]_0)$ for DP20 to DP90) for the polymerization at 60 °C in Toluene of ϵ -

DL by by BnOH/InCl₃/Et₃N **1:1:2** (red line, circles) and BnOH/InCl₃/Et₃N **2:1:2** as immortal conditions (blue line, triangles).

The presence of the two partners InCl₃ and Et₃N is necessary for the polymerization to take place efficiently. Removing any of them resulted in low or no conversion (runs 13&14 in Table 1 for ROP in the absence of Et₃N or InCl₃, respectively). This observation is consistent with a dual character of the catalytic system. In the case of lactide, Hillmyer proposed that InCl₃ and Et₃N form alkoxy-bridged dinuclear In compounds as key species for a coordination-insertion polymerization. An alternative scenario consists in the concomitant activation of the monomer and alcohol by InCl₃ and Et₃N, respectively. Both mechanisms are conceivable with ϵ -DL. The ability of InCl₃ to bind and activate ϵ -DL has been evidenced by NMR spectroscopy. ¹H and ¹³C NMR analyses of 1:1 and 1:2 ϵ -DL:InCl₃ mixtures in CDCl₃ (Figure S2) revealed shifts to lower fields of the signals corresponding to the C(=O)O–CH and C(=O)O–CH moieties.

The initiator/InCl₃/Et₃N ratio was varied. As showed in Figure 4a, using one equivalent of Et₃N ([BnOH]₀/[InCl₃]₀/[Et₃N]₀ = 1/1/1, runs 17-21, Table S2) instead of two gives similar results, but from a practical point of view, it makes the purification of the polymer easier. Moreover, the ratio between the initiator (benzyl alcohol, runs 22-25 in Table S2) and the two partners InCl₃/Et₃N can be raised up to 2, without marked impact on the polymerization control (Figure 4b), which means that the InCl₃/Et₃N association can be used in sub-stoichiometric conditions related to the initiator, in so-called immortal conditions.⁵⁹

The possibility of varying the initiator, so that one of the polymer chain-ends can be modified, was also evaluated (Figure S3). In addition to primary alcohols, such as BnOH, DMBA, and 1-pentanol (runs 1&2, Table 2), secondary alcohols can be used (run 3). In all cases, the incorporation of the initiator is complete (Figures S4-S6) and the *M_n* value of the obtained PDL matches well that

expected. Notably, initiation with 1,4-benzenedimethanol (run 4) yielded a telechelic dihydroxylated PDL (^1H NMR spectroscopy indicates initiation from both alcohol moieties, see Figure S6).

Table 2. Polymerization of ϵ -DL, promoted by $\text{InCl}_3/\text{Et}_3\text{N}$ and initiated by various initiators^a

Run	M_0/I_0	I	t (h)	M_n^{Th}	$M_n^d_{\text{NMR}}$	$M_n^c_{\text{SEC}}$	$\bar{D}^c$
1	50	DMBA ^b	3	8700	8800	9 400	1.11
2	25	1-pentanol	2	4400	4200	5600	1.11
3	50	2-propanol	3	8700	8700	8700	1.09
4	70	HOBnOH ^b	4	12000	12000	13600	1.12
5	30	BnNH ₂	2	5200	5600	7300	1.12
6	60	BnNH ₂	4	10000	10500	11300	1.18
7 ^f	1	BnNH ₂	18	NR		-	-
8 ^g	20	PEGNH ₂	4	5400	5600	6700	1.13
9 ^g	50	PEGNH ₂	14	10500	11200	14300	1.18
10 ^h	50	BnSH	24	8624	nd	nd	nd
11 ^h	50	BzCH ₂ SH	24	8680	nd	nd	nd

^aReaction conditions: $\text{InCl}_3/\text{Et}_3\text{N}$ 1:2, 3 M solution in toluene at 60 °C, conv > 96%. ^bDMBA = 3,5-dimethoxybenzyl alcohol, HOBnOH = 1,4-benzenedimethanol. ^c $M_n^c_{\text{SEC}}$ from polymer (after purification) calibrated by polystyrene standards. ^d $M_n^d_{\text{NMR}} = [(\text{DP}_{\text{NMR}}) * 170.25, \text{Mw of DL}] + \text{Mw of initiator}$. ^e $\text{DP}_{\text{NMR}} = \text{Integration of } ^1\text{H at CH-O, 4.8 ppm divided by integration of } ^1\text{H of the initiator signal used as reference}$. ^f $\text{InCl}_3:\text{NEt}_3$ 0:2. ^gMeOPEG-NH₂, $M_n^c_{\text{SEC}} = 2100$, $\bar{D} = 1.03$. ^hMonomer conversion < 20 %. NR = No reaction. nd not determined

Interestingly, primary amines can also be used as initiators, enabling the preparation of PDLs capped with amide end groups which are noticeably stronger than the ester moieties.^{60,61,62} More precisely, ROP of 30 equiv. of ϵ -DL using benzyl amine as initiator ($\text{BnNH}_2/\text{InCl}_3/\text{NEt}_3$ 1/1/2) resulted in a PDL of targeted M_n (7300 g/mol, run 5 Table 2) and low $\bar{D}$ (1.12). Note that in the absence of $\text{InCl}_3/\text{NEt}_3$, polymerization does not occur. Benzyl amine alone is not able to promote the polymerization, neither to ring open ϵ -DL. This last point markedly contrasts with the ROP of

lactide promoted by DBU and initiated by primary amines in a two-step one-pot process (first ring opening of one unit of lactide by the amine alone, and then addition of the catalyst DBU to promote polymerization).⁶³ The incorporation of the benzyl amine as an amide chain-end was carefully analyzed by ¹H NMR to determine whether one or the two N-H bonds were implicated in the initiation (Figure 5a).^{63,64} Besides the expected signals for the PDL chain, the spectrum displays a multiplet and a doublet signals at 7.25 and 4.45 ppm (integrating for 5 and 2 H, respectively) that can be attributed to the Ph and the CH₂-N groups of the benzyl moiety. An additional broad signal that disappears when the NMR analysis is performed in the presence of D₂O is observed at 6.00 ppm, which is consistent with the presence of an NH group and suggests initiation of only one polymer chain. Final confirmation of the incorporation of the amine as an amide chain-end was obtained by a 2D COSY analysis, where cross-marks between the signals attributed to the NH and CH₂N groups were clearly observed (Figure 5b). This result also confirms the initiation of a unique polymer chain per amine unit. We then took advantage of the ability of amines to act as initiators to prepare amphiphilic block copolymers featuring a robust link between the two blocks using a PEG-NH₂ (*M*_{n SEC} = 2100, *D* = 1.03) as macro-initiator.⁶⁰⁻⁶² The polyethyleneglycol polymer chain did not prevent the polymerization reaction, but ROP took place at a slower rate (runs 8&9). Nevertheless, block copolymers exempt of any homo-polymer (non-incorporated macro-initiator or PDL initiated by other protic residues), featuring *M*_n values close to those expected and narrow molar distributions could be obtained (*D* < 1.18) (see Figures S6 and S7 for the ¹H NMR spectra of the PEG-NH₂ macro-initiator and of the PEG-NH-PDL block copolymer). As observed with the initiating alcohols, modifying the monomer over amine ratio allows to finely tune the molecular weight of the polymers (runs 5&6 and 8&9 for activation with BnNH₂ and PEG-NH₂, respectively).

Figure 5. a) ^1H NMR spectrum (CDCl_3 , 300 MHz) and b) Extract of the 2D COSY, of a PDL of DP 30 initiated by BnNH_2 , $[\epsilon\text{-DL}]_0/[\text{BnNH}_2]_0/[\text{InCl}_3]_0/[\text{Et}_3\text{N}]_0 = 30/1/1/2$ in toluene at 60°C , $[\epsilon\text{-DL}]_0 = 3 \text{ mol/L}$.

In line with the growth of only one PDL polymer chain with primary amines as initiator, no polymerization reaction occurred with the secondary amine benzyl-methyl amine. Thiols were also tried as initiators (entries 10&11), but low conversions ($< 20\%$) were observed even after 24 h of reaction (Figure S9).

Preparation of $\epsilon\text{-DL}$ and $\epsilon\text{-CL}$ random and block copolymers. At this stage, we decided to probe the capacity of this catalytic system to copolymerize $\epsilon\text{-DL}$ and $\epsilon\text{-CL}$ in a controlled manner to give access to well-defined block and random copolymers.

Table 3. Preparation of PCL/PDL block and copolymers by ROP with $\text{InCl}_3/\text{Et}_3\text{N}^a$

Run	polymer	CL_0/DL_0	t (h)	M_n^{Th}	$M_n^{\text{b NMR}}$	$M_n^{\text{c SEC}}$	$\bar{D}^c$	$\text{DP}_{\text{NMR}}^{\text{d}}$ CL/DL	T_g^e (°C)	T_m^e (°C)	T_d^e (°C)	χ^f
1	PDL	0:50	3	8700	8800	11200	1.11	-/52	-53	-	356	-
2	PCL	60:0	0.5	7000	6900	7200	1.18	59/-	-61 ^g	55 ^g	330	55 ^g
3	PCL- <i>b</i> -PDL	50:50	5.5	14400	14400	22000	1.24	50/50	-57.8	55.2	337	27
4	PDL- <i>b</i> -PCL	50:50	10	14400	15000	16300	1.25	56/50	-54.8	55.2	362	30
5	P(CL- <i>r</i> -DL)	50:50	2.5	14400	15500	19400	1.17	55/53	-60	-	351	-
6	P(CL- <i>r</i> -DL)	40:40	3.2	11500	11000	11700	1.13	40/37	-60.2	-	339	-

^aPolymerizations carried out in toluene, $[\text{monomer}]_0 = 3\text{M}$, at 60 °C, using DMBA = 3,5-dimethoxybenzyl alcohol as initiator, and $\text{InCl}_3/\text{Et}_3\text{N}/\text{DMBA} = 1:2:1$. ^bCalculated by ^1H NMR, $\{[(\text{DP}_{\text{NMR of DL}})*170.25, \text{Mw of } \epsilon\text{-DL}] + [(\text{DP}_{\text{NMR of CL}})*114.14, \text{Mw of } \epsilon\text{-CL}]\} + M_w \text{ of DMBA}$. ^c $M_{n\text{SEC}}$ determined on polymer after purification using calibration by polystyrene standards. ^d $\text{DP}_{\text{NMR}} = \text{Integration of the CH-O (PDL) or CH}_2\text{-O (PCL) signal in } ^1\text{H NMR divided by the integration of the reference signal of the initiator (DMBA = 6H, reference position at } -(\text{OCH}_3)_2)$. ^eDetermined by DSC. ^fDetermined by DSC, using a heat of fusion value for a 100% crystalline PCL⁶⁵ of 136.0 J g⁻¹. ^gData from ref 24. n.d. = not determined.

A PDL-*b*-PCL block copolymer was first prepared by addition of 50 equiv. of $\epsilon\text{-CL}$ to the reaction media after polymerization of 50 equiv. of $\epsilon\text{-DL}$ in the presence of $[\text{BnOH}]_0/[\text{InCl}_3]_0/[\text{Et}_3\text{N}]_0 = 1/1/2$ in toluene at 60 °C (Table 3, run 3). Formation of the block copolymer was confirmed by NMR spectroscopy and by SEC analysis (Figure 6a, right&left, respectively). The ^1H NMR spectrum shows the disappearance of the broad signal at 3.58 ppm, corresponding to the CHOH_{PDL} chain-end of the PDL block, giving rise to the typical triplet signal (b') at 3.65 ppm for the $\text{CH}_2\text{OH}_{\text{PCL}}$ chain-end of the added PCL block. Moreover, SEC analysis clearly shows the increase of M_n upon monomer feeding (from 11 800 g/mol at the end of consumption of $\epsilon\text{-DL}$, to 16 300 g/mol for the diblock copolymer), while rather narrow molar mass distributions are retained ($\bar{D} \sim 1.25$). Sequential copolymerization with reverse order of addition of the monomers (first $\epsilon\text{-CL}$ then $\epsilon\text{-DL}$, with similar conditions to the previous one, run 4) provides a PCL-*b*-PDL block copolymer. Again, ^1H NMR spectroscopy and SEC analysis are diagnostic

for the formation of the block copolymer (Figure 6b right&left, respectively). We can note the disappearance on the ^1H spectrum of the triplet signal at 3.65 ppm associated to the $\text{CH}_2\text{OH}_{\text{PCL}}$ chain-end of the first PCL block and the appearance of the broad signal (a') at 3.58 ppm attributed to the CHOH_{PDL} chain-end of the PDL block. SEC analysis shows an increase of M_n upon monomer feeding (from 7 200 to 22 000 g/mol, with $\bar{D} \sim 1.24$). In addition, the ^{13}C NMR spectra of these two block copolymers display only one signal for each type of $\text{C}=\text{O}$ groups at δ 173.54 ppm (PDL) and 173.26 ppm (PCL) (note that a similar observation can be made in the CH_2O and CH_2CO region, Figure S10-11), confirming the block architecture of the copolymers.

Figure 6. ^1H NMR spectrum (CDCl₃, 300 MHz) of a) a PDL-*b*-PCL block copolymer, and b) a PCL-*b*-PDL block copolymer. initiated by BnOH, $[\epsilon\text{-DL}]_0/[\epsilon\text{-CL}]_0/[\text{BnNH}_2]_0/[\text{InCl}_3]_0/[\text{Et}_3\text{N}]_0 = 50/50/1/1/2$ in toluene at 60 °C, $[\epsilon\text{-DL}]_0$ or $[\epsilon\text{-CL}]_0 = 3$ mol/L.

Two important conclusions can be drawn from these results. First, cross-propagation occurs efficiently, as demonstrated by the initiation of the ROP of ϵ -CL and ϵ -DL by the hydroxyl chain-end of PDL and PCL homopolymers, respectively. Secondly, the fact that the block architecture is retained at the end of the polymerization indicates very low, if any, occurrence of side-reactions leading to redistribution of polymer segments (chain reshuffling). All these features suggest that simultaneous copolymerization of ϵ -DL and ϵ -CL is possible, although the different reactivity of these monomers in homo-polymerization may favor the formation of copolymers with blocky rather than random structure (60 equiv. of ϵ -CL are fully converted in less than 30 min while 3 h are necessary for ϵ -DL under the same conditions, see entries 1&2 of Table 3). The simultaneous polymerization of ϵ -DL and of ϵ -CL was carried out at 60 °C in toluene solution with $\text{InCl}_3/\text{NEt}_3$ in the presence of 1 equiv. of DMBA (ϵ -DL/ ϵ -CL of 50/50 and 40/40 for entries 5&6, respectively). ^1H NMR monitoring of the monomer conversion showed full conversion of the two monomers in a little bit more than three hours, and, more surprisingly, a slow-down on the consumption rate of CL (less than 80 % of conversion in 30 min, Figure 7a). Consequently, a random $\text{P}(\text{CL-}r\text{-DL})$ copolymer with regular monomer distribution along the polymer chain was obtained, as supported by NMR spectroscopy. The ^1H NMR spectrum displays the triplet and broad signals at δ 3.63 and 3.58 ppm characteristic of the presence of $\text{CH}_2\text{OH}_{\text{PCL}}$ and CHOH_{PDL} hydroxyl chain-ends, respectively (Figure 7b). Furthermore, the ^{13}C NMR spectrum shows, in marked contrast with those of the PDL-PCL block copolymers, broad or multiple signals in the C=O region, indicating the presence of different environments for the CO groups of each monomer as a result of a statistical distribution (Figure S12). With the dual catalyst $\text{InCl}_3/\text{NEt}_3$, it is thus possible to prepare block as well as random PCL/PDL copolymers of controlled structures under mild conditions. Thanks to the high initiation efficiency and low impact of chain-redistribution side-reactions, the

nature of the chain-ends can also be finely tuned. DSC analysis illustrates the impact of the block or random structure of the copolymers on their thermal properties. Both block copolymers feature a glass transition at T_g values (-54.8 and -57.8 °C for PDL-*b*-PCL and PCL-*b*-PDL, respectively) in the range of those of the two homopolymers (-53 and -60 °C, for PDL and PCL, respectively), and a melting transition at $T_m = 55.5$ °C associated to the semi-crystalline PCL block. The value of the T_m is slightly lower to that of PCL, as is the crystallinity parameter (27 and 30 % compared to the typical 45-50 %, Table 3). In marked contrast, the random copolymer is totally amorphous and presents only a glass transition at -60 °C. Although CL is converted at a slightly higher rate, the CL sequences are not long enough to bring crystallinity, which is consistent with the random character of the copolymer.

Figure 7. Simultaneous ROP of ϵ -DL and ϵ -CL, $[\epsilon\text{-DL}]/[\epsilon\text{-CL}]/\text{DMBA}/\text{InCl}_3/\text{NEt}_3 = 40/40/1/1/2$

a) Kinetic plot of ROCoP of ϵ -DL and ϵ -CL showing that both monomers are consumed at similar rate, b) ^1H NMR spectrum (CDCl_3 , 300 MHz) of the obtained copolymer.

Conclusions.

In summary, we have demonstrated that the association of InCl_3 and Et_3N is a readily available, easy to remove and efficient catalyst for the ROP of ϵ -DL under mild conditions (toluene, 3M, 60°C). Besides the typical ester end-capped PDLs obtained by initiation of the polymerization with alcohols (primary or secondary), amide end-capped PDLs were prepared thanks to the ability of this dual catalyst to perform with primary amines as initiators. As a result, amphiphilic PEG-NH-PDL block copolymers, with a strong amide bond between the two blocks could be prepared. PDL-*b*-PCL / PCL-*b*-PDL and P(DL-*r*-CL) copolymers were also prepared by sequential or simultaneous ROP with ϵ -caprolactone. NMR spectroscopy, SEC, and DSC analyses confirmed their well-defined structures, substantiating the controlled character of the polymerization and the low impact of transfer reactions.

The use of the InCl_3 / Et_3N association thus enables significant progress ϵ -DL polymerization under mild conditions, and is complementary to SnOct_2 , the latter being more adapted for ROP at high temperatures in bulk conditions. It provides access to a variety of polymers and copolymers derived from this renewable monomer. This work also highlights further the interest of dual catalysis and expands its application scope to ϵ -DL, a lactone propagating via a sterically hindered secondary alcohol and thus rather challenging to polymerize.

ASSOCIATED CONTENT

Supporting Information. Electronic Supplementary Information (ESI) available: Tables containing all the ROP tests, ^1H NMR spectra of PDL dressed with different end-groups, ^{13}C spectra of block and random copolymers. This material is available free of charge via the Internet at <http://pubs.acs.org>

AUTHOR INFORMATION

Corresponding Author

*bmv@chimie.ups-tlse.fr

*dbouriss@chimie.ups-tlse.fr

Author Contributions

The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENT

This work was supported financially by the Centre National de la Recherche Scientifique, the Université de Toulouse and the Agence Nationale de la Recherche (ANR CE6-CYCLOOP). S. T. acknowledges CAMPUS France for the Franco-Thai program PhD scholarship.

REFERENCES

(1) Schneiderman, D. K.; Hillmyer, M. A. There Is a Great Future in Sustainable Polymers. *Macromolecules* **2017**, *50*, 3733-3749.

-
- (2) Garcia, J. M.; Robertson, M. L. The future of plastics recycling. *Science* **2017**, 358(6365), 870.
- (3) Zhang, X.; Fevre, M.; Jones, G. O.; Waymouth, R. M. Catalysis as an Enabling Science for Sustainable Polymers. *Chem. Rev.* **2018**, 118(2), 839-885.
- (4) Albertsson, A. C.; Hakkarainen, M. Designed to degrade. *Science* **2017**, 358(6365), 872.
- (5) Brannigan, R. P.; Dove, A. P. Synthesis, properties and biomedical applications of hydrolytically degradable materials based on aliphatic polyesters and polycarbonates. *Biomater. Sci.* **2017**, 5(1), 9-21.
- (6) Haider, T. P.; Völker, C.; Kramm, J.; Landfester, K.; Wurm, F. R. Plastics of the Future? The Impact of Biodegradable Polymers on the Environment and on Society. *Angew. Chem. Int. Ed.* **2019**, 58(1), 50-62.
- (7) Pappalardo, D.; Mathisen, T.; Finne-Wistrand, A. Biocompatibility of Resorbable Polymers: A Historical Perspective and Framework for the Future. *Biomacromolecules* **2019**, 20(4), 1465-1477.
- (8) Researches have also been devoted to polymers prone to chemical recyclability, see ref 9 and: Zhu, J. B.; Watson, E. M.; Tang, J.; Chen, E. Y. X. A synthetic polymer system with repeatable chemical recyclability. *Science* **2018**, 360(6387), 398-403.
- (9) Alberti, C.; Damps, N.; Meissner, R. R. R.; Enthaler, S. Depolymerization of End-of-Life Poly(lactide) via 4-Dimethylaminopyridine-Catalyzed Methanolysis. *ChemistrySelect* **2019**, 4(23), 6845-6848.
- (10) Zhu, Y.; Romain, C.; Williams, C. K. Sustainable polymers from renewable resources. *Nature* **2016**, 540(7633), 354-362.

-
- (11) Lambert, S.; Wagner, M. Environmental performance of bio-based and biodegradable plastics: the road ahead. *Chem. Soc. Rev.* **2017**, *46*(22), 6855-6871.
- (12) Hillmyer, M. A. The promise of plastics from plants. *Science* **2017**, *358*(6365), 868-870.
- (13) Vink, E. T. H.; Rábago, K. R.; Glassner, D. A.; Gruber, P. R. Applications of life cycle assessment to NatureWorks® polylactide (PLA) production. *Polym. Degrad. Stab.* **2003**, *80*(3), 403-419.
- (14) Recently, preparation of ϵ -CL from renewable raw material has been reported, see: Buntara, T.; Noel, S.; Phua, P. H.; Melián-Cabrera, I.; de Vries, J. G.; Heeres, H. J. Caprolactam from Renewable Resources: Catalytic Conversion of 5-Hydroxymethylfurfural into Caprolactone. *Angew. Chem. Int. Ed.* **2011**, *50*(31), 7083-7087.
- (15) Romero-Guido, C.; Belo, I.; Ta, T. M. N.; Cao-Hoang, L.; Alchihab, M.; Gomes, N.; Thonart, P.; Teixeira, J. A.; Destain, J.; Waché, Y. Biochemistry of lactone formation in yeast and fungi and its utilisation for the production of flavour and fragrance compounds. *Appl. Microbiol. Biotechnol.* **2011**, *89*(3), 535-547.
- (16) Endrizzi, A.; Pagot, Y.; Clainche, A. L.; Nicaud, J. M.; Belin, J. M. Production of Lactones and Peroxisomal Beta-Oxidation in Yeasts. *Crit. Rev. in Biotechnol.* **1996**, *16*(4), 301-329.
- (17) For other bio resourced lactones see: Hillmyer, M. A.; Tolman, W. B. Aliphatic Polyester Block Polymers: Renewable, Degradable, and Sustainable. *Acc. Chem. Res.* **2014**, *47*(8), 2390-2396.
- (18) Low T_c for δ -DL ROP restricts synthetic potential in preparation of polymer, see: Martello, M. T.; Burns, A.; Hillmyer, M. Bulk Ring-Opening Transesterification Polymerization of the Renewable delta-Decalactone Using an Organocatalyst. *ACS Macro Lett.* **2011**, *1*(1), 131-135.

-
- (19) Olsén, P.; Borke, T.; Odelius, K.; Albertsson, A. C. ϵ -Decalactone: A Thermoresilient and Toughening Comonomer to Poly(*l*-lactide). *Biomacromolecules* **2013**, *14*(8), 2883-2890.
- (20) Glavas, L.; Olsén, P.; Odelius, K.; Albertsson, A. C. Achieving Micelle Control through Core Crystallinity. *Biomacromolecules* **2013**, *14*(11), 4150-4156.
- (21) Glavas, L.; Odelius, K.; Albertsson, A. C. Tuning loading and release by modification of micelle core crystallinity and preparation. *Polym. Adv. Technol.* **2015**, *26*(7), 880-888.
- (22) Kakde, D.; Taresco, V.; Bansal, K. K.; Magennis, E. P.; Howdle, S. M.; Mantovani, G.; Irvine, D. J.; Alexander, C. Amphiphilic block copolymers from a renewable ϵ -decalactone monomer: prediction and characterization of micellar core effects on drug encapsulation and release. *J. Mater. Chem. B* **2016**, *4*(44), 7119-7129.
- (23) Martello, M. T.; Schneiderman, D. K.; Hillmyer, M. A. Synthesis and Melt Processing of Sustainable Poly(ϵ -decalactone)-block-Poly(lactide) Multiblock Thermoplastic Elastomers. *ACS Sustainable Chem. Eng.* **2014**, *2*(11), 2519-2526.
- (24) Schneiderman, D. K.; Hill, E. M.; Martello, M. T.; Hillmyer, M. A. Poly(lactide)-block-poly(ϵ -caprolactone-co- ϵ -decalactone)-block-poly(lactide) copolymer elastomers. *Polym. Chem.* **2015**, *6*(19), 3641-3651.
- (25) Arias, V.; Olsen, P.; Odelius, K.; Hoglund, A.; Albertsson, A. C. Selective degradation in aliphatic block copolyesters by controlling the heterogeneity of the amorphous phase. *Polym. Chem.* **2015**, *6*(17), 3271-3282.
- (26) Lee, S.; Lee, K.; Jang, J.; Choung, J. S.; Choi, W. J.; Kim, G. J.; Kim, Y. W.; Shin, J. Sustainable poly(ϵ -decalactone)-poly(L-lactide) multiarm star copolymer architectures for thermoplastic elastomers with fixed molar mass and block ratio. *Polymer* **2017**, *112*, 306-317.

-
- (27) Lee, S.; Lee, K.; Kim, Y. W.; Shin, J. Preparation and Characterization of a Renewable Pressure-Sensitive Adhesive System Derived from ϵ -Decalactone, *L*-Lactide, Epoxidized Soybean Oil, and Rosin Ester. *ACS Sustainable Chem. Eng.* **2015**, 3(9), 2309-2320.
- (28) Stösser, T.; Williams, C. K. Selective Polymerization Catalysis from Monomer Mixtures: Using a Commercial Cr-Salen Catalyst To Access ABA Block Polyesters. *Angew. Chem. Int. Ed.* **2018**, 57(21), 6337-6341.
- (29) Chen, T. T. D.; Zhu, Y.; Williams, C. K. Pentablock Copolymer from Tetracomponent Monomer Mixture Using a Switchable Dizinc Catalyst. *Macromolecules* **2018**, 51(14), 5346-5351.
- (30) Stösser, T.; Sulley, G. S.; Gregory, G. L.; Williams, C. K. Easy access to oxygenated block polymers via switchable catalysis. *Nat. Commun.* **2019**, 10(1), 2668.
- (31) Olsén, P.; Odelius, K.; Albertsson, A. C. Thermodynamic Presynthetic Considerations for Ring-Opening Polymerization. *Biomacromolecules* **2016**, 17(3), 699-709.
- (32) Schneiderman, D. K.; Hillmyer, M. A. Aliphatic Polyester Block Polymer Design. *Macromolecules* **2016**, 49(7), 2419-2428.
- (33) Although Sn(Oct)₂ is approved by the FDA as a food additive, the tin content in polymers should be lower than 20 ppm as it has been found to have some cytotoxicity. See: Tanzi, M. C.; Verderio, P.; Lampugnani, M. G.; Resnati, M.; Dejana, E.; Sturani, E. Cytotoxicity of some catalysts commonly used in the synthesis of copolymers for biomedical use. *Journal of Materials Science: Materials in Medicine* **1994**, 5 (6), 393-396.
- (34) Moderate cytotoxicity has been reported for TBD related to other organocatalysts such as thioureas. See: Nachtergaele, A.; Coulembier, O.; Dubois, P.; Helvenstein, M.; Duez, P.; Blankert, B.; Mespouille, L. Organocatalysis Paradigm Revisited: Are Metal-Free Catalysts Really Harmless? *Biomacromolecules* **2014**, 16 (2), 507-514.

-
- (35) Cam, D.; Marucci, M. Influence of residual monomers and metals on poly(*l*-lactide) thermal stability. *Polymer* **1997**, *38*(8), 1879-1884.
- (36) Mori, T.; Nishida, H.; Shirai, Y.; Endo, T. Effects of chain end structures on pyrolysis of poly(*l*-lactic acid) containing tin atoms. *Polym. Degrad. Stab.* **2004**, *84*(2), 243-251.
- (37) Coulembier, O.; Moins, S.; Raquez, J. M.; Meyer, F.; Mespouille, L.; Duquesne, E.; Dubois, P. Thermal degradation of poly(*l*-lactide): Accelerating effect of residual DBU-based organic catalysts. *Polym. Degrad. Stab.* **2011**, *96*(5), 739-744.
- (38) Lin, J. O.; Chen, W.; Shen, Z.; Ling, J. Homo- and Block Copolymerizations of ϵ -Decalactone with *l*-Lactide Catalyzed by Lanthanum Compounds. *Macromolecules* **2013**, *46*(19), 7769-7776.
- (39) Jasinska-Walc, L.; Bouyahyi, M.; Rozanski, A.; Graf, R.; Hansen, M. R.; Duchateau, R. Synthetic Principles Determining Local Organization of Copolyesters Prepared from Lactones and Macrolactones. *Macromolecules* **2015**, *48*(3), 502-510.
- (40) Bai, J.; Wang, J.; Wang, Y.; Zhang, L. Dual catalysis system for ring-opening polymerization of lactones and 2,2-dimethyltrimethylene carbonate. *Polym. Chem.* **2018**, *9*(39), 4875-4881.
- (41) Chuang, H. J.; Chen, H. L.; Huang, B. H.; Tsai, T. E.; Huang, P. L.; Liao, T. T.; Lin, C. C. Efficient zinc initiators supported by NNO-tridentate ketiminate ligands for cyclic esters polymerization. *J. Polym. Sci. A Polym. Chem.* **2013**, *51*(5), 1185-1196.
- (42) Peters, R. Cooperative Catalysis. Wiley, New York. **2015**.
- (43) Piedra-Arroni, E.; Amgoune, A.; Bourissou, D. Dual catalysis: new approaches for the polymerization of lactones and polar olefins. *Dalton Trans.* **2013**, *42*(25), 9024-9029.

-
- (44) Hong, M.; Chen, J.; Chen, E. Y. X. Polymerization of Polar Monomers Mediated by Main-Group Lewis Acid–Base Pairs. *Chem. Rev.* **2018**, *118*(20), 10551-10616.
- (45) Naumann, S.; Schmidt, F. G.; Frey, W.; Buchmeiser, M. R. Protected N-heterocyclic carbenes as latent pre-catalysts for the polymerization of ϵ -caprolactone. *Polym. Chem.* **2013**, *4*(15), 4172-4181.
- (46) Naumann, S.; Scholten, P. B. V.; Wilson, J. A.; Dove, A. P. Dual Catalysis for Selective Ring-Opening Polymerization of Lactones: Evolution toward Simplicity. *J. Am. Chem. Soc.* **2015**, *137*(45), 14439-14445.
- (47) Naumann, S.; Wang, D. Dual Catalysis Based on N-Heterocyclic Olefins for the Copolymerization of Lactones: High Performance and Tunable Selectivity. *Macromolecules* **2016**, *49*(23), 8869-8878.
- (48) Walther, P.; Naumann, S. N-Heterocyclic Olefin-Based (Co)polymerization of a Challenging Monomer: Homopolymerization of ω -Pentadecalactone and Its Copolymers with β -Butyrolactone, δ -Valerolactone, and ϵ -Caprolactone. *Macromolecules* **2017**, *50*(21), 8406-8416.
- (49) Walther, P.; Frey, W.; Naumann, S. Polarized olefins as enabling (co)catalysts for the polymerization of γ -butyrolactone. *Polym. Chem.* **2018**, *9*(26), 3674-3683.
- (50) Bai, J.-H.; Wang, X.-Q.; Wang, J.-H.; Zhang, L.-F. Homo- and random copolymerizations of ω -pentadecalactone with ϵ -caprolactone using isothiourea-based dual catalysis. *J. Polym. Sci. A Polym. Chem.* **2019**, *57*(11), 1189-1196.
- (51) Piedra-Arroni, E.; Ladavière, C.; Amgoune, A.; Bourissou, D. Ring-Opening Polymerization with $\text{Zn}(\text{C}_6\text{F}_5)_2$ -Based Lewis Pairs: Original and Efficient Approach to Cyclic Polyesters. *J. Am. Chem. Soc.* **2013**, *135*(36), 13306-13309.

-
- (52) Wang, B.; Wei, Y.; Li, Z. J.; Pan, L.; Li, Y. S. From $\text{Zn}(\text{C}_6\text{F}_5)_2$ to ZnEt_2 -based Lewis Pairs: Significantly Improved Catalytic Activity and Monomer Adaptability for the Ring-opening Polymerization of Lactones. *ChemCatChem* **2018**, *10*(22), 5287-5296.
- (53) Pietrangelo, A.; Knight, S. C.; Gupta, A. K.; Yao, L. J.; Hillmyer, M. A.; Tolman, W. B. Mechanistic Study of the Stereoselective Polymerization of *d,l*-Lactide Using Indium(III) Halides. *J. Am. Chem. Soc.* **2010**, *132*(33), 11649-11657.
- (54) Osten, K. M.; Mehrkhodavandi, P. Indium Catalysts for Ring Opening Polymerization: Exploring the Importance of Catalyst Aggregation. *Acc. Chem. Res.* **2017**, *50*(11), 2861-2869.
- (55) Kremer, A. B.; Andrews, R. J.; Milner, M. J.; Zhang, X. R.; Ebrahimi, T.; Patrick, B. O.; Diaconescu, P. L.; Mehrkhodavandi, P. A Comparison of Gallium and Indium Alkoxide Complexes as Catalysts for Ring-Opening Polymerization of Lactide. *Inorg. Chem.* **2017**, *56*(3), 1375-1385 and references therein.
- (56) Dagorne, S.; Normand, M.; Kirillov, E.; Carpentier, J. F. Gallium and indium complexes for ring-opening polymerization of cyclic ethers, esters and carbonates. *Coord. Chem. Rev.* **2013**, *257*(11–12), 1869-1886.
- (57) Myers, D.; White, A. J. P.; Forsyth, C. M.; Bown, M.; Williams, C. K. Phosphasalen Indium Complexes Showing High Rates and Isoselectivities in *rac*-Lactide Polymerizations. *Angew. Chem. Int. Ed.* **2017**, *56*(19), 5277-5282.
- (58) Maudoux, N.; Roisnel, T.; Dorcet, V.; Carpentier, J. F.; Sarazin, Y. Chiral (1,2)-Diphenylethylene-Salen Complexes of Triel Metals: Coordination Patterns and Mechanistic Considerations in the Isoselective ROP of Lactide. *Chem. Eur. J.* **2014**, *20*(20), 6131-6147.

-
- (59) Ajellal, N.; Carpentier, J. F.; Guillaume, C.; Guillaume, S. M.; Helou, M.; Poirier, V.; Sarazin, Y.; Trifonov, A. Metal-catalyzed immortal ring-opening polymerization of lactones, lactides and cyclic carbonates. *Dalton Trans.* **2010**, 39(36), 8363-8376.
- (60) Buwalda, S. J.; Dijkstra, P. J.; Calucci, L.; Forte, C.; Feijen, J. Influence of Amide versus Ester Linkages on the Properties of Eight-Armed PEG-PLA Star Block Copolymer Hydrogels. *Biomacromolecules* **2010**, 11(1), 224-232.
- (61) Buwalda, S. J.; Dijkstra, P. J.; Feijen, J. Stereocomplexed & photocrosslinked poly(ethylene glycol)-poly(lactide) star block copolymer hydrogels. *J. Control. Rel.* **2010**, 148(1), e23-e24.
- (62) Buwalda, S. J.; Calucci, L.; Forte, C.; Dijkstra, P. J.; Feijen, J. Stereocomplexed 8-armed poly(ethylene glycol)-poly(lactide) star block copolymer hydrogels: Gelation mechanism, mechanical properties and degradation behavior. *Polymer* **2012**, 53(14), 2809-2817.
- (63) Alba, A.; Thillaye du Boullay, O.; Martin-Vaca, B.; Bourissou, D. Direct ring-opening of lactide with amines: application to the organo-catalyzed preparation of amide end-capped PLA and to the removal of residual lactide from PLA samples. *Polym. Chem.* **2015**, 6(6), 989-997.
- (64) Coulembier, O.; Kiesewetter, M. K.; Mason, A. F.; Dubois, P.; Hedrick, J. L.; Waymouth, R. M. A Distinctive Organocatalytic Approach to Complex Macromolecular Architectures. *Angew. Chem. Int. Ed.* **2007**, 46(25), 4719-4721.
- (65) Determined by DSC, using a heat of fusion value for 100 % crystalline PCL of 136.0 J g⁻¹: Avella, M.; Errico, M. E.; Rimedio, R.; Sadocco, P. Preparation of biodegradable polyesters/high-amylose-starch composites by reactive blending and their characterization. *J. Appl. Polym. Sci.* **2002**, 83(7), 1432-1442.