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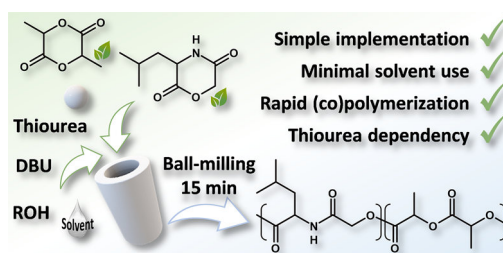
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Simple and Rapid Mechanochemical Synthesis of Lactide and 3S-(Isobutyl)morpholine-2,5-dione-Based Random Copolymers Using DBU and Thiourea

Tobias F. Burton, Julien Pinaud, Nicolas Pétry, Frédéric Lamaty,* and Olivia Giani*

ABSTRACT: There is a growing interest surrounding morpholine-2,5-dione-based materials due to their impressive biocompatibility as well as their capacity to break down by hydrolytic and enzymatic pathways. In this study, the ring-opening (co)polymerization of leucine-derived 3S-(isobutyl)morpholine-2,5-dione (MD) and lactide (LA) was performed via ball-milling using a catalytic system composed of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) and 3-[3,5-bis(trifluoromethyl)phenyl]-1-cyclohexylthiourea (TU). Once the homopolymerizations of MD and LA optimized and numerous parameters were studied, the mechanochemical ring-opening copolymerization of these monomers was explored. The feasibility of ring-opening copolymerizations in mechanochemical systems was demonstrated and a range of P(MD-co-LA) copolymers were produced with varying proportions of MD (23%, 48%, and 69%). Furthermore, the beneficial cocatalytic effects of TU with regards to ROP control were found to be operative within mechanochemical systems. Further parallels were observed between solution- and mechanochemical-based ROPs.



Polydepsipeptides (PDPs) are an increasingly attractive category of polyesteramides possessing alternating α -amino acid (AA) and α -hydroxyacid motifs and obtained via the ring-opening polymerization (ROP) of AA-derived morpholine-2,5-diones.^{1–3} The ring-opening copolymerization (ROCP) of morpholine-2,5-diones with lactide (LA), glycolide, or ϵ -caprolactone permits the inclusion of peptide motifs and hydrogen bonds into those polyesters, enhancing their biocompatibility, degradability, and mechanical and thermal properties.^{1,3–16} Furthermore, the possibility of selecting a specific AA as a starting material for these PDPs enables the incorporation of a particular hydrocarbon or functional group into the (co)polymer, tuning the resulting material's hydrophilic properties.² Nevertheless, depending on the initial AA employed, some morpholine-2,5-diones display limited solubility in organic solvents. Consequently, the (co)polymerization of morpholine-2,5-diones is conventionally performed in bulk with 2-ethylhexanoate tin(II) ($\text{Sn}(\text{Oct})_2$) as the catalyst.^{1–3} However, $\text{Sn}(\text{Oct})_2$ combined with the high reaction temperatures required to melt the monomer (>100 °C) is often at the origin of backbiting and other side reactions, leading to low end-group fidelity and limited control over the ROP.^{17–23} Thus, if the ROP of morpholine-2,5-diones could be performed in bulk and at a much lower temperature, PDPs and derived copolymers with desired molecular weights, compositions, and chain-ends could be obtained.

Recently, Kim et al. demonstrated that trimethylene carbonate and lactide can be homopolymerized in bulk and at room temperature within ball-milling mechanochemical

systems using 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU).^{24–26} Mechanochemistry, that is, using mechanical forces to perform chemical reactions, is a discipline undergoing rapid development.²⁷ Many areas of organic synthesis could be revisited while highlighting the undeniable advantages of this approach: a reduced environmental impact due to the absence of organic solvents, high process efficiency, and simplified purification procedures.^{24,28–32} As such, controlling solid-state mechanochemical polymerizations is a new and exciting frontier for polymer and mechanochemical scientists.^{33–35}

To date, besides those studies by Kim et al., the field of mechanochemical ROP (mechaROP) is unexplored and mechanochemical copolymerization (mechaROCP) has yet to be investigated.^{24–26} Taking these considerations into account, we propose to combine the recent developments in organic catalysis to the pioneering field of mechanochemistry with the aim of developing a cleaner and simplified manner of producing PDP and polyester-based materials.

Based on our recent investigation into the solution-based controlled ROP of leucine derived 3S-(isobutyl)morpholine-2,5-dione (MD) and ROCP with LA using DBU and a thiourea cocatalyst (3-[3,5-bis(trifluoromethyl)phenyl]-1-cy-

Scheme 1. MechaROP of MD Catalysed by DBU and TU Using BnOH as an Initiator

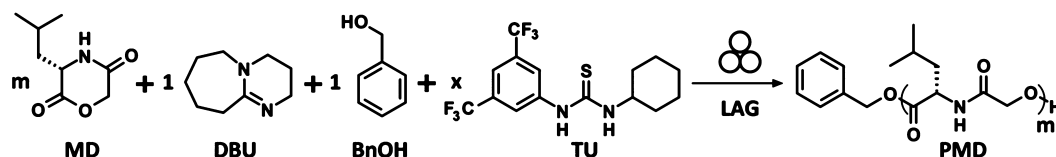


Table 1. DBU-Catalysed MechaROPs of MD Using 50:1:1: x MD:BnOH:DBU:TU^a

| name | material | TU (equiv) | solvent; η ($\mu\text{L mg}^{-1}$) | time (min) | conv. ^b (%) | $M_{n,\text{calc}}$ ^c (kg mol^{-1}) | $M_{n,\text{exp}}$ ^d (kg mol^{-1}) | \bar{D} |
|--------------------|------------------|------------|---|------------|------------------------|---|--|-----------|
| PMD1 | S.S. | 0 | | 60 | 0 | | | |
| PMD2 | S.S. | 0 | DCM; 0.2 | 60 | 5 | | | |
| PMD3 | PTFE | 0 | DCM; 0.2 | 60 | 99 | 8.6 | 4.0 | 1.79 |
| PMD4 | ZrO ₂ | 0 | DCM; 0.2 | 60 | 99 | 8.6 | 4.7 | 1.83 |
| PMD5 ^e | ZrO ₂ | 0 | DCM; 0.2 | 60 | 0 | | | |
| PMD6 | ZrO ₂ | 0 | DCM; 0.1 | 60 | 80 | 6.9 | 3.9 | 1.80 |
| PMD7 | ZrO ₂ | 0 | | 60 | 0 | | | |
| PMD8 | ZrO ₂ | 0 | DCM; 0.2 | 15 | 99 | 8.6 | 4.8 | 1.74 |
| PMD9 | ZrO ₂ | 0 | DCM; 0.2 | 5 | 86 | 7.5 | 4.0 | 2.15 |
| PMD10 | ZrO ₂ | 2.5 | DCM; 0.2 | 15 | 95 | 8.3 | 5.0 | 1.48 |
| PMD11 | ZrO ₂ | 5 | DCM; 0.2 | 15 | 97 | 8.4 | 5.1 | 1.39 |
| PMD12 | ZrO ₂ | 5 | DCM; 0.2 | 10 | 46 | 3.9 | 2.5 | 1.31 |
| PMD13 | ZrO ₂ | 5 | DCM; 0.2 | 5 | 30 | 2.8 | 2.0 | 1.30 |
| PMD14 ^f | ZrO ₂ | 5 | DCM; 0.2 | 15 | 34 | 30 | 2.1 | 1.26 |
| PMD15 ^g | ZrO ₂ | 5 | DCM; 0.2 | 15 | 29 | 2.6 | 1.8 | 1.21 |
| PMD16 | ZrO ₂ | 5 | MeTHF; 0.2 | 15 | 37 | 4.1 | 1.9 | 1.31 |
| PMD17 | ZrO ₂ | 5 | toluene; 0.2 | 15 | 99 | 8.6 | 4.4 | 1.50 |

^aBall-milling at 30 Hz with one 10 mm ball. $M_{n,\text{target}} = 8.7 \text{ kg mol}^{-1}$. S.S.: Stainless steel. ^bDetermined via ¹H NMR spectroscopy. ^c $M_{n,\text{calc}} = 50 \times \text{conv.} \times M_{\text{MD}} + M_{\text{BnOH}}$. ^dDetermined by SEC in THF using PS standards. ^eNo DBU used. ^fEight 5 mm balls. ^g20 Hz.

clohexylthiourea (TU)),³⁶ we report herein on the mechaROP of 3S-(isobutyl)morpholine-2,5-dione (MD) and mechaROCP with LA. This permits a direct and pertinent comparison with our previous solvent-based study.

The first objective was to study the DBU catalyzed mechaROP of MD using benzyl alcohol (BnOH) as an initiator (see Scheme 1). All MD homopolymerization results are reported in Table 1. A preliminary test was performed in a stainless-steel reactor using DBU and BnOH with the ratios 50:1:1 in MD:BnOH:DBU (PMD1). This reactor was vibrated with a frequency of 30 Hz for 1 h however no monomer conversion was observed. It is well-known that adding of small amounts of solvent to ball milling systems (liquid-assisted grinding (LAG)) has beneficial effects on mechanochemical reactions by enhancing mixing and reaction kinetics.^{37–39} Renewing this test with 0.2 $\mu\text{L mg}^{-1}$ of DCM resulted in a monomer conversion of 5% (PMD2). Although LAG slightly improved the kinetics, the low monomer conversion obtained was unexpected as the same catalytic system proved highly efficient when polymerizing MD in solution, achieving total monomer conversion in 5 min.³⁶ In addition to a low monomer conversion, the peaks in the ¹H NMR spectrum of the crude product obtained from PMD2 were remarkably broad, a characteristic that disappears when the sample was filtered through cotton (see Figure S1). This is a tell-tale sign that paramagnetic species are present within the sample. Indeed, when performing ball milling with stainless steel reactors, a certain amount of paramagnetic species such as iron and chromium leach into the reaction.⁴⁰ As iron- and chromium-based compounds can form coordination bonds with cyclic esters, it is possible that the DBU catalytic process could be hindered.^{41–43} On that account, the polymerization

was renewed in polytetrafluoroethylene (PTFE) and ZrO₂ based reactors (PMD3 and PMD4). Both types of reactors granted total monomer conversion and produced polymers with molecular weights (4.0 and 4.7 kg mol^{-1} for PTFE and ZrO₂ respectively) lower than that targeted ($M_{n,\text{target}} = 8.7 \text{ kg mol}^{-1}$) and with broad distributions of molecular weights ($\bar{D} = 1.79$ and 1.83). The polymer produced in the PTFE reactor had a slightly lower molecular weight, suggesting that ZrO₂ is more appropriate for the mechaROP of MD. This type of reactor was thus chosen for the rest of the study. In both PMD3 and PMD4, no unusual broadening of the ¹H NMR spectra was observed, suggesting that no or negligible amounts of paramagnetic compounds leached from the reactors. In order to confirm that the ring-opening reactions observed in PMD4 were indeed catalyzed by the DBU, a test was carried out with no DBU (PMD5). No reactions occurred, implying that no impurity, nor any other factor inherent to the mechanochemical system, can catalyze the ROP of MD. Furthermore, in order to verify whether DCM is also essential when using ZrO₂ reactors, two tests were carried out using 0.1 $\mu\text{L mg}^{-1}$ (PMD6) and no solvent (PMD7). In the case of PMD6, the monomer conversion (80%) was lower than PMD4, where 0.2 $\mu\text{L mg}^{-1}$ was used, as was the molecular weight of the polymer (3.9 kg mol^{-1}). In the case of PMD7, where no solvent was used, no polymerization was observed. It can be concluded that, in these conditions, 0.2 $\mu\text{L mg}^{-1}$ of DCM is required in order to obtain complete monomer consumption.

In comparison, when this reaction was performed in solution (10 $\mu\text{L mg}^{-1}$), complete monomer conversion was achieved in 5 min.³⁶ Hence, the mechaROP was performed over shorter periods as to determine when total monomer consumption was

achieved. Using the same conditions as PMD4, experiments PMD8 and PMD9 were performed over 15 and 5 min, respectively. Monomer conversions of 99% and 86% were observed for PMD8 and PMD9 respectively. In each case, the molecular weights were low and chain distributions were broad. This lack of control was equally observed for the solution-based ROP of MD wherein detrimental intra- and intermolecular transesterifications occurred.^{36,44–46} Furthermore, DBU may deprotonate the amide proton on MD, forming a cyclic imidate which can in turn catalyze the polymerization of other monomers.^{36,45,47} To overcome these effects, hydrogen bond donors such as 3-[3,5-bis-(trifluoromethyl)phenyl]-1-cyclohexylthiourea (TU) can be used, granting better control over the polymerization of MD and other monomers.^{36,45,48–50} In solution-based systems, 5 equiv of TU were necessary for the controlled synthesis of different PMDs (ranging from 8 to 18 kg mol⁻¹).³⁶ Hence, as to determine whether TU acts in the same fashion during the mechaROP of MD, two tests were carried out with 2.5 equiv (PMD10) and 5 equiv (PMD11) of TU. When compared to PMD8, where no TU was employed, the distribution of molecular weights are narrower (\bar{D} = 1.48 and 1.39) and the molecular weight slightly higher (5.0 and 5.1 kg mol⁻¹ for PMD10 and PMD11, respectively). The ¹³C and ¹H NMR spectra of the precipitated polymer obtained from PMD11 display benzyl end-groups. The area of those benzyl peaks, when compared to the polymer backbone peaks, indicates that the polymer formed in PMD11 has a DP of 43: $M_{n,NMR} = 7.5$ kg mol⁻¹ (see Figure S2). The TU-cocatalyzed mechaROP of MD with 5 equiv of TU was then carried out over shorter periods: 10 and 5 min (PMD12 and PMD13, respectively). When plotting the molecular weight against the monomer conversion, it can be observed that the lower molecular weight polymers obtained at 5 and 10 min were closer to their theoretical molecular weights than the sample at 15 min while having similar values of dispersity (Figure 1).

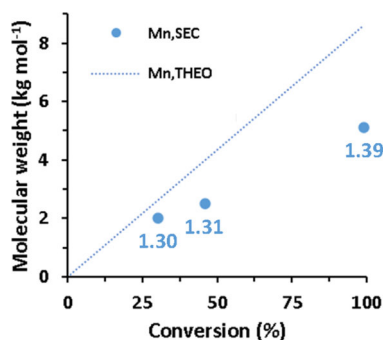


Figure 1. Evolution of the molecular weight and dispersity in the DBU/TU catalyzed mechaROP of MD with 50:1:1:5 (MD:BnOH:DBU:TU). Reactions were performed in ZrO₂ reactors with one 10 mm ball at 30 Hz. $\eta_{DCM} = 0.2 \mu\text{L mg}^{-1}$. $M_{n,theo} = n_{MD}/n_{BnOH} \times \text{conv.} \times M_{MD} + M_{BnOH}$.

Next, in order to better understand the different parameters in play, a number of variables were explored using 5 equiv of TU such as in PMD11. In PMD14, eight 5 mm balls were used instead of one 10 mm ball ($8 \times V_{5mm} = V_{10mm}$); in PMD15, the reactor was milled at 20 Hz rather than 30 Hz and in PMD16 and 17, MeTHF and toluene were used in place of DCM.

As was observed by Kim et al., milling with lighter balls or with a reduced frequency lowered the reaction kinetics and led to lower monomer conversions (34 and 29%, respectively). When the reaction was performed with MeTHF, the polymerization evolved at a lower rate (37% monomer conversion) in contrast to toluene, which permitted total monomer conversion. However, the polymer produced with toluene possessed a lower molecular weight and a broader distribution of molecular weights. None of these variations permitted an improvement with respect to PMD11.

Finally the MD:BnOH ratio was investigated (all results are reported in Table S1). When targeting PMDs with higher weights, 17.3 and 25.9 kg mol⁻¹, the monomer conversion remained low even when the reaction was carried out over 30 min (approximately 50 and 25%, respectively). Two lower weight PMDs of 4.4 and 2.7 kg mol⁻¹ were then targeted. Total conversion was achieved after 10 min and slightly better distributed polymers (\bar{D} = 1.28 and 1.30, respectively) with molecular weights close to those targeted were obtained (4.2 and 2.5 kg mol⁻¹, respectively; see Figure S3).

It was observed that mechanochemical forces alone are capable of inducing polymer chain modifications. Indeed, in a series of experiments where different purified PMDs produced via solution and mechanochemical routes were milled with and without LAG, sharp decreases in molecular weights accompanied by dispersity increases were observed (see Table S2 and Figure S4). We suggest these are driven by transesterification type reactions that could potentially limit the production of longer chain PMDs via mechaROP. Furthermore, this underscores the importance of quenching the reaction once the monomer conversion has ceased to evolve, an observation which is analogous to the solution-based ROPs.^{36,44–46}

Complementary to this study, the mechaROP of LA was also undertaken using the optimized conditions (PMD11) elaborated hereabove (see Figure S5). The effect of TU on the mechaROP of LA is identical and three PLAs of different molecular weight were successfully produced (4.0, 5.5, and 6.9 kg mol⁻¹ with \bar{D} = 1.26, 1.16, and 1.29, respectively; see Table S3).

The homopolymerization of MD and LA mastered, the mechaROCP of these monomers was then investigated (Scheme 2). Using the optimal conditions determined previously (1:1:5 (BnOH:DBU:TU); ZrO₂ reactor; one 10 mmball; DCM (0.2 $\mu\text{L mg}^{-1}$); 30 Hz; 15 min), three copolymers of P(MD-co-LA) were produced with different monomer compositions in the feed: C1 (12MD:38LA), C2 (38MD:12LA), and C3 (25MD:25LA). All copolymerization results are reported in Table 2. In each instance, the LA was

Scheme 2. MechaROCP of MD and LA

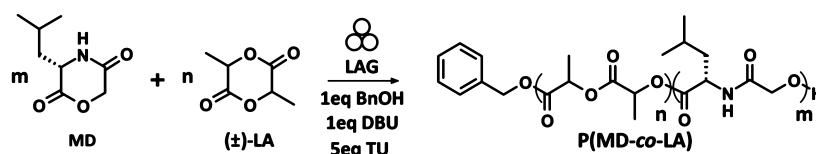


Table 2. DBU/TU Catalysed MechaROCP of MD and LA^a

| name | MD:LA:BnOH:DBU:TU | time (min) | MD conv. ^b (%) | LA conv. ^b (%) | $M_{n,target}$ ^c (kg mol ⁻¹) | $M_{n,calc}$ ^d (kg mol ⁻¹) | $M_{n,SEC}$ ^e (kg mol ⁻¹) | \bar{D} | m_{MD} ^f |
|------|-------------------|------------|---------------------------|---------------------------|---|---|--|-----------|-----------------------|
| C1 | 12:38:1:1:5 | 15 | 80 | 98 | 7.6 | 7.1 | 8.5 | 1.42 | 0.23 |
| C2 | 38:12:1:1:5 | 15 | 78 | 99 | 8.3 | 6.9 | 6.5 | 1.42 | 0.69 |
| C3 | 25:25:1:1:5 | 15 | 86 | 99 | 8.0 | 7.4 | 7.2 | 1.40 | 0.48 |

^aBall-milling at 30 Hz in a ZrO₂ reactor with one 10 mm ZrO₂ ball. $\eta_{(DCM)} = 0.2 \mu\text{L mg}^{-1}$. ^bDetermined via ¹H NMR spectroscopy. ^c $M_{n,target} = n_{LA}/n_{BnOH} \times M_{LA} + n_{MD}/n_{BnOH} \times M_{MD} + M_{BnOH}$. ^d $M_{n,calc} = n_{LA}/n_{BnOH} \times \text{conv.}(LA) \times M_{LA} + n_{MD}/n_{BnOH} \times \text{conv.}(MD) \times M_{MD} + M_{BnOH}$. ^eDetermined by SEC in THF using PS standards. ^fMolar fraction of MD in precipitated copolymer, determined via ¹H NMR spectroscopy.

completely consumed whereas MD attained high monomer conversion: 80%, 78%, and 86% for C1, C2, and C3, respectively. A similar result was observed for the solution-based DBU/TU-catalyzed copolymerization of LA and MD mixtures, wherein LA polymerized much faster than MD during copolymerization.³⁶ This is attributed to differences in the reactivity of the primary and secondary alcohol end-groups produced by the ring-opening of MD and LA, respectively. Whereas the more reactive primary alcohol is favorable to both LA and MD propagation, the less reactive secondary alcohol is more favorable toward LA homopropagation. Indeed, secondary alcohols are less effective at initiating the ring-opening of MD than primary alcohols.³⁶ Furthermore, differences in ring-strain may equally contribute to these differences in reactivity. Indeed, Finne-Wistrand et al. have demonstrated that 3,6-(dimethyl)morpholine-2,5-dione, whose structure is identical to LA with the exception of the amide bond, has less ring-strain than LA thus leading to the preferential homopropagation of LA.⁵¹

The ¹H and ¹³C NMR spectra of the precipitated copolymers contain all the peaks corresponding to both PLA and PMD repeating units as well as aromatic protons characteristic of the benzyl groups on the copolymer chain-ends (see Figure S6). Comparing the area of the CH₃ proton peak of the PLA units to the CH₂ and CH protons peak of the PMD units, the composition of each copolymer was determined. The molar fraction of MD (m_{MD}) in each copolymer was 0.23, 0.69, and 0.48 for C1, C2, and C3, respectively, close to the MD composition in the feed. Furthermore, all protons composing the PLA and PMD repeating units as well as benzyl end-groups diffuse at one unique diffusion coefficient as observed via DOSY-NMR, suggesting that the resulting polymer chains contain both repeating units (see Figure S7). The molecular weights of the resulting copolymers (8.5, 6.5, and 7.2 kg mol⁻¹ for C1, C2, and C3, respectively) were close to the ones calculated with respect to the individual monomer conversions (7.1, 6.9, and 7.4 kg mol⁻¹ for C1, C2, and C3, respectively). These copolymers are slightly more polydisperse than the PMD homopolymers ($\bar{D} = 1.40\text{--}1.42$), however, their size exclusion chromatograms are unimodal and symmetrical (see Figure S8). Differential scanning calorimetry was performed on the polymers arising from PMD11, C1, C2, C3, and PLA1 (a polylactide (6.9 kg mol⁻¹; $\bar{D} = 1.27$) produced via mechaROP). All materials produced herein are totally amorphous and possess glass transition temperatures (T_g s) of 51.6, 42.3, 43.9, 51.1, and 46.7 °C for PMD11, PLA1, C1, C2, and C3, respectively. The T_g s of the copolymers are comprised between those of PMD and PLA and increase with greater MD proportions (Figure 2). The absence of distinct T_g s corresponding to PMD and PLA moieties suggests that the copolymers integrate both monomers in a random or gradient

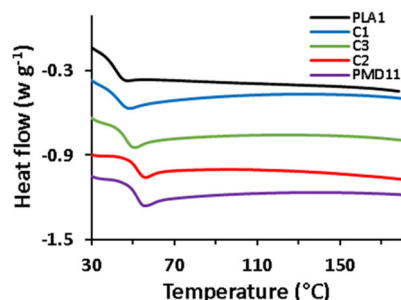


Figure 2. Differential scanning calorimetry thermograms PLA1 (black), C1 (blue), C3 (green), C2 (red), and PMD11 (purple). Exothermal upward.

fashion. Furthermore, the T_g s measured by DSC correspond to the theoretical ones calculated with the Fox equation: 44.4, 48.7, and 46.7 °C for C1, C2, and C3, respectively (see Table S4). In a final exploratory experiment, two homopolymers of PLA and PMD were milled without LAG or catalysts (see Figure S9). Before milling, this mixture of homopolymers possessed two T_g s, whereas the resulting milled polymer displayed one unique T_g (see Table S5 and Figure S10). This suggests that random copolymers could be formed by remarkably simple mechanochemical processes. These types of polyester interchange reactions usually require an organometallic catalyst to proceed, but have also been performed in the catalyst-free ball-milling system.^{52–54} As such, it can be assumed that, in our system, both ROCP and self-catalyzed transesterification reactions contribute to the production of random copolymers.

In this first investigation into the mechaROP of a morpholine-2,5-dione, it was observed that the beneficial effects of a thiourea-cocatalyst on DBU-catalyzed ROPs are operative within ball-milling systems both for MD and LA. Next, using optimized parameters, three copolymers of MD and LA with widely varying proportions of MD were produced. This first probe into mechanochemical ROCPs has demonstrated the impressive potential of ball-milling for the synthesis of copolymers. Indeed, the implementation of these mechaROPs was considerably less demanding and time-consuming, as all reagents were added into the reactor and simply milled. In comparison, for solution-based ROPs, many supplementary factors must be considered: reagent/polymer solubility, flame drying/silanization of glassware, inert atmospheres, viscosity, stirring, sequential reagent additions, solvent reflux, stopper permeability, and so on. Moreover, the product is solid and, therefore, can be very easily collected and precipitated. Finally, the amount of solvent necessary for these mechaROPs is approximately 50× less than that required in solution-based systems.³⁶ In the next step, other catalysts will be investigated to determine those best suited for mechaROPs. The interesting mechanochemical interchange reactions observed herein will

also be investigated as a greener copolymer synthesis route for polyesters.

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Author Contributions

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Notes

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