This is an open access article published under an ACS AuthorChoice License, which permits copying and redistribution of the article or any adaptations for non-commercial purposes.

JACS JOURNAL OF THE AMERICAN CHEMICAL SOCIETY

Article

Cite This: J. Am. Chem. Soc. 2019, 141, 4928−4935

pubs.acs.org/JACS

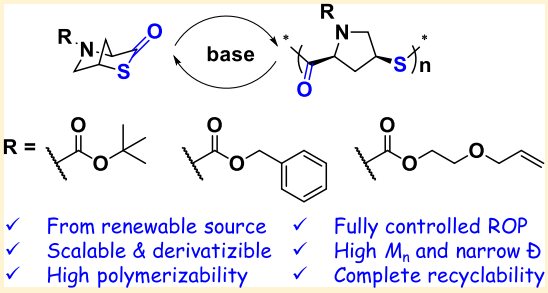
4-Hydroxyproline-Derived Sustainable Polythioesters: Controlled Ring-Opening Polymerization, Complete Recyclability, and Facile Functionalization

Jingsong Yuan, Wei Xiong, Xuhao Zhou, Yi Zhang, Dong Shi, Zichen Li, and Hua Lu*

Beijing National Laboratory for Molecular Sciences, Center for Soft Matter Science and Engineering, Key Laboratory of Polymer Chemistry and Physics of Ministry of Education, College of Chemistry and Molecular Engineering, Peking University, Beijing 100871, People's Republic of China

Supporting Information

ABSTRACT: The sustainable production of chemically recyclable polymers presents a significant opportunity to polymer scientists to tackle the growing environmental and energy problems of current petroleum-based plastics. Despite recent advances, however, there are still pressing needs for an expanded horizon of chemically recyclable polymers. Herein, we introduce a new paradigm of biosourced polythioesters (PTEs) with high polymerizability and complete recyclability under mild and economical conditions. The thiolactone monomers with a high ring strain can be easily prepared in a two-step process from 4-hydroxyproline. Controlled ring-opening polymerizations (ROP) using inexpensive and weak bases afford PTEs with high molar masses (M_n) up to 259 kg mol^{-1} and narrow dispersities generally below 1.15. The properties of PTEs can be readily adjusted by copolymerization and/or pre/post-functionalization on the side chains. Selective and complete depolymerizations of the PTEs in dilute solution at ambient to modest temperatures recycle clean monomers. Density functional theory (DFT) calculation of model reactions provides mechanistic insights and highlights the importance of judicious molecular design. Taken together, the unique ROP/depolymerization chemistry of such PTEs may offer a sustainable solution for creating and manufacturing high-value materials such as optical/photochemical plastics, self-immolative polymers, and degradable biomaterials under situations where recycle and reuse are indispensable.



INTRODUCTION

Polymeric materials play central roles in, and have fundamentally reshaped virtually every aspect of, modern living. However, the evergrowing production, coupled with the extremely poor degradability, of the finite petroleum-based synthetic polymers has raised overarching environmental and economic challenges.[1−5] Over the years, the design of sustainable/green polymers has drawn growing attention,[6−9] which ideally includes but is not limited to the use of renewable feedstock/monomers, synthesis under environment friendly conditions and at low cost, material durability at use, and high recyclability on demand.[10,11] However, complete meeting of all of these criteria has not always been possible in a single polymer.

Many types of polymer including polyester, polycarbonate, polyurethane, polyesteramide, and polyamide have been developed recently on the basis of renewable monomers including furans, vegetable oils, carbon dioxide, and, most often, polysaccharides.[12−19] Among these polymers, polyesters are perhaps the most rigorously explored as recyclable plastics.[20−23] However, high energy inputs such as strong/expensive catalysts and extreme conditions are often required in the monomer−polymer−monomer processing cycle, leading to unsatisfactory depolymerization selectivity.[11,24] One elegant breakthrough in the field recently is the ring-opening polymerization (ROP) of γ-butyrolactone (GBL), a biomass-based and previously considered "non-polymerizable" monomer.[25,26] Importantly, the resultant poly(γ-butyrolactone) (PGBL) can be quantitatively recycled to its monomer via thermolysis or chemical approaches, successfully establishing the circular "monomer−polymer−monomer" cycle. Nevertheless, the ROP requests energy-intensive conditions (e.g., −40 °C), and the resulting PGBL is difficult to process. To increase the polymerizability of GBL, fused bicyclic monomers have been carefully designed to afford polyesters with high molar mass (M_n) at ambient temperature.[8,22]

It is well-known that the introduction of sulfur atoms can lead to drastic changes in optical and thermal properties different from those of regular hydrocarbon-based polymers.[27−33] Therefore, we focus on introducing polythioesters (PTEs), that is, polyester analogues with thioesters in the backbone, as a new paradigm of sustainable polymers. Previously, thioesters have been used in dynamic covalent networks and responsive biomaterials by taking advantage of the intrinsically labile thioester bond.[34−37] We hypothesize that

Received: January 2, 2019
Published: March 20, 2019

Downloaded via 123.116.49.198 on March 27, 2019 at 10:42:44 (UTC).
See https://pubs.acs.org/sharingguidelines for options on how to legitimately share published articles.

Scheme 1

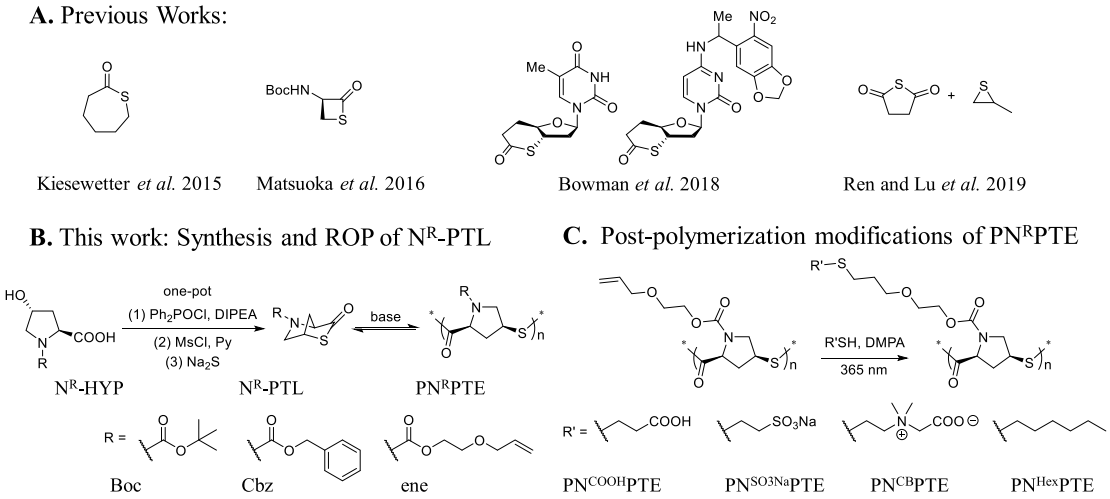


Table 1. Ring-Opening Polymerization Results of N^R-PTL[a]

entry	monomer	base	$[M]_0/[I]_0/[base]_0$	time (min)	M_n^{cal} (kg mol^{-1})[b]	M_n^{obt}(kg mol^{-1})[c]	$Đ$[d]	conv.[e]
1	N^{Boc}-PTL	TEA	25/1/1	40	5.2	6.2	1.07	90%
2	N^{Boc}-PTL	TEA	50/1/1	90	10.3	10.3	1.03	89%
3	N^{Boc}-PTL	TEA	75/1/1	150	15.5	14.8	1.08	90%
4	N^{Boc}-PTL	TEA	100/1/1	270	21.5	20.1	1.10	94%
5	N^{Boc}-PTL	DBU	50/1/1	<1	10.3	10.9	1.25	88%
6	N^{Cbz}-PTL	TEA	25/1/1	40	5.9	6.6	1.11	89%
7	N^{Cbz}-PTL	TEA	50/1/1	90	12.1	14.2	1.09	92%
8	N^{ene}-PTL	TEA	50/1/1	90	11.6	11.2	1.11	90%
9	N^{ene}-PTL	TEA	100/1/1	270	23.4	24.6	1.08	91%
10	N^{ene}-PTL	TEA	150/1/1	480	34.7	38.5	1.13	90%
11	N^{ene}-PTL	TEA	1000/1/5	1440	226	259	1.24	90%
12	N^{ene}-PTL	DBU	1000/1/1	5	226	226	1.32	88%
13	N^{ene}-PTL/N^{Boc}-PTL	TEA	50/50/1/1	90/90	21.9	24.5	1.14	90/90%

[a]All polymerizations were initiated with benzyl mercaptan in $CDCl_3$ in a glovebox at 25 °C, $[N^R\text{-PTL}]_0$ = 2 M. [b]Calculated molar mass based on $[M]_0/[I]_0$ ratio and conversion. [c]Obtained molar mass, determined by SEC equipped with a multi-angle laser light scattering (MALLS) detector. [d]Dispersity, determined by SEC. [e]Monomer conversion, determined by ^{1}H NMR.

PTEs are easier to polymerize and recycle due to the higher susceptibility to nucleophiles and hydrolysis as compared to their polyester analogues. Surprisingly, although thiolactones are often used in polymer synthesis and thioester-containing functional polymers are not rare,[34,35,38−40] PTEs are largely underdeveloped with only a few works published since the 1960s.[41−44] Notable examples of ROP monomers for PTE synthesis include ε-thiocaprolactone (tCL) and cysteine-derived β-thiolactone (Scheme 1A).[43,44] However, those previous attempts can only afford PTEs with broad dispersities ($Đ$) in the range of 1.4−2.4 and unsatisfactory M_n's typically less than 30 kg mol^{-1}. We reason that the uncontrolled ROP is likely a consequence of the rapid intra- and interchain transthioesterification.[37] One approach to achieve controlled ROP is through judicious molecular design of the monomer and polymer structures. For instance, Bowman and co-workers reported the ROP of fused-ring thiolactone monomers (Scheme 1A) for the production of DNA-mimicking PTEs, which showed dynamic and responsive properties, depolymerization capability, and relatively narrow $Đ$ in the range of 1.2−1.3 for the first time.[45] However, the monomer requires sophisticated multiple-step synthesis, and the highest M_n of the PTEs reported was 7.6 kg mol^{-1} with a monomer conversion of 27%. Lu and Ren very recently developed the copolymerization of cyclic thioanhydrides and episulfides (Scheme 1A) for the production of PTEs with modest-to-good control over the M_n and $Đ$ (∼1.23−1.72).[46] In the review process of this Article, an interesting paper by Gutekunst et al. reported the synthesis of PTEs through a radical approach.[47] Despite these advances, there are still pressing needs for more examples of controlled ROPs and recyclable PTEs.

■ RESULTS AND DISCUSSION

To generate recyclable PTEs in a fully controlled manner, the thiolactone monomers must be highly polymerizable (chain growth), and the transthioesterification reactions are expected to be prohibited (chain transfer). The seemingly opposite demands have previously posed significant challenges in molecular design. Here, we report our endeavors in the ROP of *N*-substituted *cis*-4-thia-L-proline thiolactone (N^R-PTL) (Scheme 1B), the postpolymerization functionalization, and the complete recycling of the PTEs. We select the N^R-PTL monomers for a number of reasons. N^R-PTL can be facilely prepared on a more than 1000 kg scale from *trans*-4-hydroxy-L-proline (4-Hyp), an abundant biosourced feedstock.[48−50] Langer et al. examined the use of 4-Hyp for the production

DOI: 10.1021/jacs.9b00031
J. Am. Chem. Soc. 2019, 141, 4928−4935

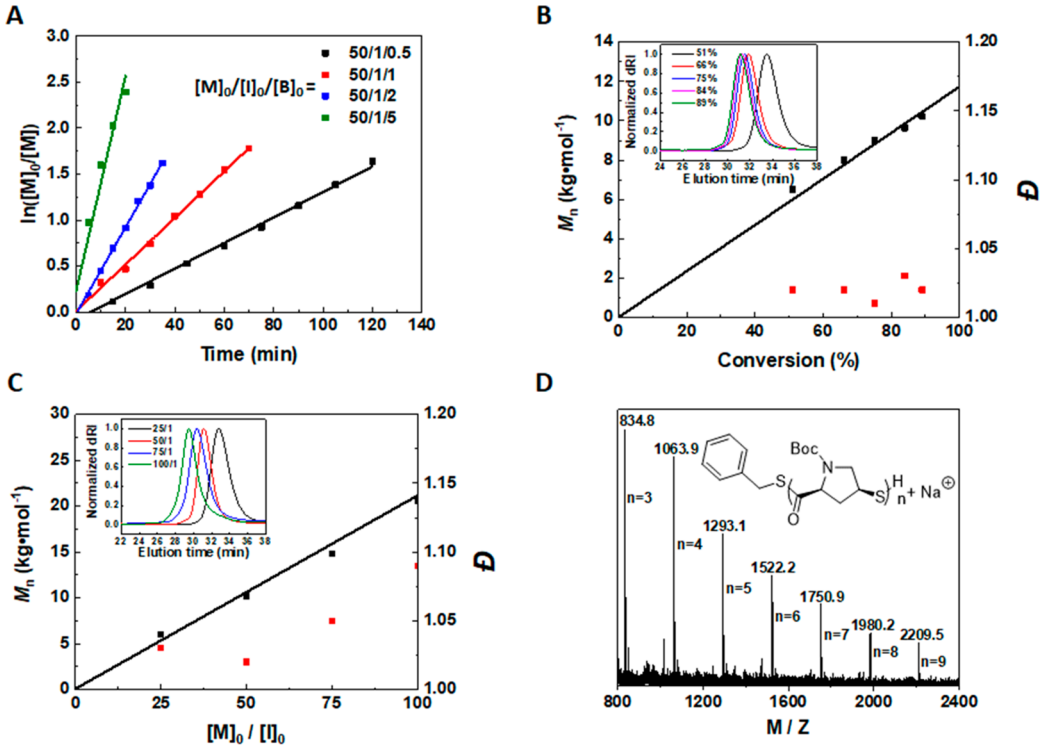


Figure 1. ROP of N^{Boc}-PTL. (A) Kinetic plots of ln([M]$_0$/[M]) versus time with varied TEA equivalents at the [M]$_0$/[I]$_0$ ratio of 50/1. (B) Plots of M_n and $Đ$ as a function of monomer conversion at the [M]$_0$/[I]$_0$ ratio of 50/1. Inset: Overlay of SEC curves at different monomer conversions. (C) Plots of M_n and $Đ$ as a function of the [M]$_0$/[I]$_0$ ratio. Inset: Overlay of SEC curves at different [M]$_0$/[I]$_0$ ratios. (D) MALDI-TOF mass spectrum of P(N^{Boc}PTE)$_{10}$ initiated by benzyl mercaptan and TEA, terminal thiol uncapped.

of polyesters via step growth polymerizations in late 1980s.[51,52] In the pharmaceutical industry, N^{Boc}-PTL has been widely used as a precursor of antibiotics, but its ROP has been considered as a "potentially catastrophic" problem to circumvent rather than an opportunity to pursue.[48] We expect that the bridged bicyclic structure of N^{R}-PTL can offer excellent reactivity due to the high ring strain,[53] making the ROP at room temperature possible and in a way similar to the fused bicyclic GBLs.[8,22] Moreover, we expect that the undesired transthioesterifiation can be minimized due to the steric hindrance of the proline−proline junction in the backbone and the n → π^* orbital interaction between the urethane and thioester carbonyls. Indeed, previous investigations have shown that similar *cis* proline−proline junction thioesters are inert to various nucleophiles including thiols.[54,55] Finally, the R group in the monomer N^{R}-PTL can be easily tuned, allowing the creation of PTE libraries with versatile structures and applications.

Scheme 1B shows the synthesis and chemical structure of three N^{R}-PTL monomers, denoted as N^{Boc}-PTL, N^{Cbz}-PTL, and N^{ene}-PTL, respectively. Briefly, the nitrogen of the bioderived 4-Hyp was tethered with a R group through a urethane bond in the first step. Next, the thiolactone monomers were obtained as white needle crystals (N^{Boc}-PTL and N^{Cbz}-PTL) or a colorless oil (N^{ene}-PTL) by following an established one-pot protocol.[49] The monomers were comprehensively characterized with ^{1}H, ^{13}C NMR, mass spectrometry, and single-crystal X-ray diffraction (Figures S1−S10). Initial attempts of polymerizing N^{Boc}-PTL in high polarity solvents (e.g., acetonitrile, DMF, and NMP) either failed completely or gave uncontrolled polymerizations. Careful analysis of the polymers revealed the coexistence of both linear and small cyclic chains with low M_n's (Figure S11). To our delight, rapid and controlled polymerizations of N^{Boc}-PTL were realized at room temperature in less polar solvents such as chloroform and dichloromethane (DCM) using benzyl mercaptan and triethylamine (TEA) as the initiator and catalyst/base, respectively (entries 1−4, Table 1). ^{1}H NMR probing of the TEA-catalyzed ROP of N^{Boc}-PTL at various temperatures allowed the calculation of the thermodynamic parameters (Figure S12). The change in enthalpy (ΔH_P°) and entropy (ΔS_P°) of polymerization was −15.6 kJ mol^{-1} and −40.4 J mol^{-1} K^{-1}, respectively, which in turn gave a ceiling temperature (T_c) of 112 °C at an initial monomer concentration ([M]$_0$) of 1 M. The high T_c highlighted the outstanding polymerizability of N^{Boc}-PTL, in sharp contrast to GBL with a T_c of −136 °C in the same [M]$_0$.[25]

Kinetic study of the N^{Boc}-PTL ROP showed a clear first-order kinetic character relative to the [M], with the reaction generally reaching more than 88% conversion within hours (Figure 1A). Increasing the base concentration yielded the same first-order kinetic feature but a faster polymerization (Figure 1A). A double logarithm plot of the apparent chain propagation rate constant (k_{app}) versus the concentration of TEA was fit to a straight line with a slope of 0.93 (Figure S13). A linear correlation of the M_n of poly(*N*-Boc 4-thia L-proline thioester) (PN^{Boc}PTE, Figures S14 and S15) with the monomer conversion was observed in Figure 1B, indicating a controlled chain growth polymerization. Next, we studied the N^{Boc}-PTL ROP at varied feeding monomer/initiator ([M]$_0$/[I]$_0$) ratios, quenched the polymerization at ∼90% conversion, and analyzed the resulting PN^{Boc}PTE by size exclusion chromatography (SEC). The obtained M_n of PN^{Boc}PTE matched the theoretical values up to 20.6 kg mol^{-1} calculated from the [M]$_0$/[I]$_0$ ratios (entries 1−4, Table 1 and Figure

DOI: 10.1021/jacs.9b00031
J. Am. Chem. Soc. 2019, 141, 4928−4935

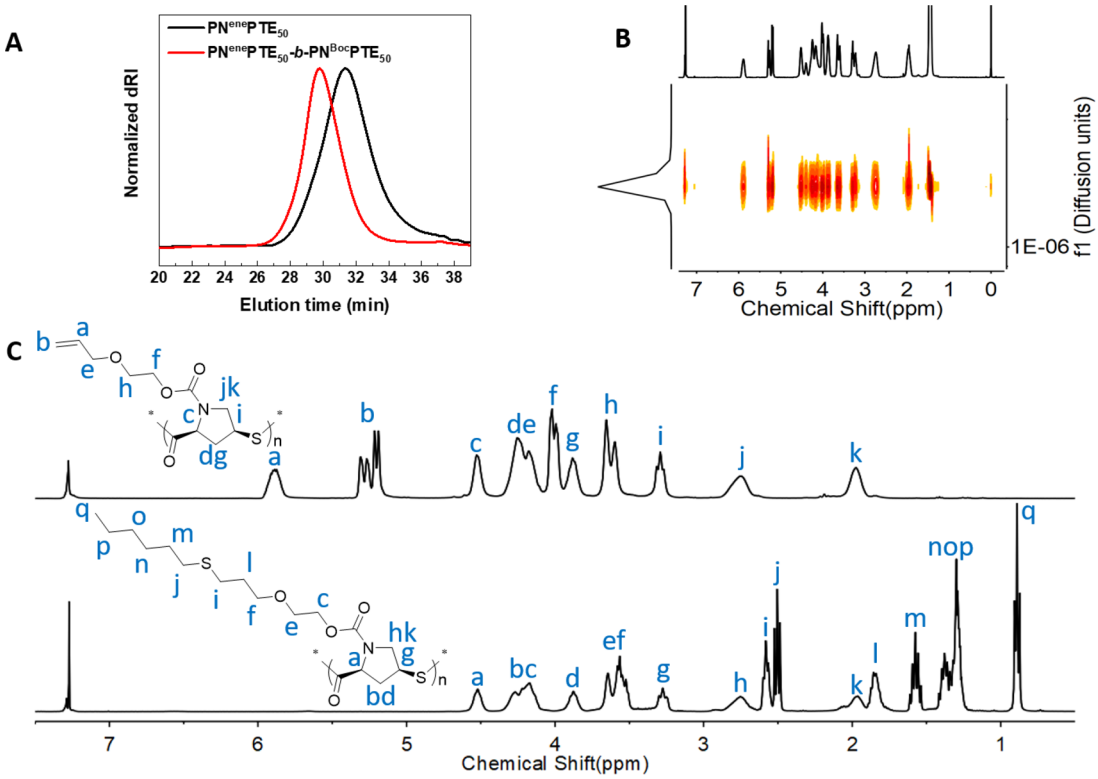


Figure 2. Block copolymerization and postpolymerization functionalization. (A) Overlay of SEC curves of the precursor polymer $PN^{ene}PTE_{50}$ and the block copolymer $PN^{ene}PTE_{50}$-*b*-$PN^{Boc}PTE_{50}$ (entry 12, Table 1). (B) DOSY NMR spectrum of the block copolymer $PN^{ene}PTE_{50}$-*b*-$PN^{Boc}PTE_{50}$. (C) ^{1}H NMR spectra of $PN^{ene}PTE_{50}$ before (top) and after (bottom) the "thiol−ene" modification with hexanethiol in $CDCl_3$.

1C). All polymers exhibited monomodal peaks and narrow $Đ$ below 1.10, unprecedented in previous PTEs (entries 1−4, Table 1 and Figure 1C). Switching the catalyst from TEA to stronger bases such as 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) gave significantly faster polymerizations. Indeed, the DBU-catalyzed ROP of N^{Boc}-PTL was so fast that the monomer reached ∼90% conversion instantaneously (less than 10 s), making it impossible to accurately monitor the kinetics. The DBU-mediated ROP afforded $PN^{Boc}PTE$ with a M_n of 12.9 kg mol^{-1} (expected M_n 10.3 kg mol^{-1}) and a slightly broader $Đ$ of 1.25 at the feeding $[M]_0/[I]_0/[B]_0$ ratio of 50/1/1 (entry 5, Table 1). MALDI-TOF mass spectrometry of $PN^{Boc}PTE$ showed only one set of molecular ion peaks with the same spacing of 229 Da, corresponding to the M_n of the repeating unit N^{Boc}-PTL (Figure 1D). Careful analysis of the peaks revealed that all of the polymers exclusively bear the ($PhCH_2S$−/−SH) end groups at the termini. The excellent terminal thiol reactivity and livingness of the polymerization were evidenced by the highly efficient capping using iodoacetamide, which gave peaks exclusively corresponding to $PN^{Boc}PTE$ or $PN^{Cbz}PTE$ bearing ($PhCH_2S$−/−CH_2CONH_2) end groups (Figures S16 and S17). Notably, the ROPs in large (100−500 mg) and small (20−50 mg) scales all gave similar results in M_n and $Đ$.

Next, we explored the monomer scope. Both N^{Cbz}-PTL and N^{ene}-PTL can be effectively polymerized using the aforementioned methods under similar conditions (entries 6−10, Table 1), affording poly(*N*-carboxybenzyl 4-thia L-proline thioester) ($PN^{Cbz}PTE$, Figure S18) and poly(*N*-(2-(allyloxy)-ethylcarbamate) 4-thia L-proline thioester) ($PN^{ene}PTE$, Figures S19 and S20) with well-controlled M_n close to the theoretical values and narrow $Đ$ (<1.15). Of note, the highest M_n of $PN^{ene}PTE$ we obtained using TEA as the base was 259 kg mol^{-1} at a M/I ratio of 1000/1 (entry 11, Table 1). The ROP of N^{ene}-PTL at the same M/I ratio using DBU as the base gave a polymer M_n of 226 kg mol^{-1} within 5 min (entry 12, Table 1). We also tested the copolymerizability of N^R-PTL monomer. Sequential addition of N^{Boc}-PTL and N^{ene}-PTL afforded a block copolymer as shown by the SEC (entry 13, Table 1 and Figure 2A) and DOSY NMR characterizations (Figure 2B). More importantly, the side chain allyl group of $PN^{ene}PTE$ can be modified easily with various thiols under UV irradiation, yielding libraries of PTE with functionalities including carboxylic acid, sulfonate, zwitterion, and alkyl groups (Scheme 1C and Figures S21−S24). Taking the hexanethiol-modified $PN^{ene}PTE$ as an example, the complete disappearance of the double bond peaks (5.15, 5.33, and 5.89 ppm) in ^{1}H NMR spectrum indicated a more than 95% grafting efficiency (Figure 2C). The unimodal and narrow distributed SEC curve of $PN^{ene}PTE$ after thiol−ene modification confirmed the polymer integrity (Figure S25). The tolerance of the backbone PTEs to radicals and the excellent copolymerizability were truly remarkable, which greatly facilitated the generation of chemically diverse PTE-based polymers.

The thermal properties of PN^RPTE were measured by thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). $PN^{ene}PTE$s (11.0 kg mol^{-1}) with or without capping of the terminal thiol both showed a 5% weight loss decomposition temperature (T_d) ∼198−199 °C (Figure S26 and Table S1). The glass transition temperatures (T_g) of the aforementioned $PN^{ene}PTE$s were measured to be ∼32−37 °C (Figure S27 and Table S1). $PN^{Boc}PTE$ (10.0 kg mol^{-1}) and $PN^{Cbz}PTE$ (12.0 kg mol^{-1}) were found to have a $T_d \approx 204$ and

DOI: 10.1021/jacs.9b00031
J. Am. Chem. Soc. 2019, 141, 4928−4935

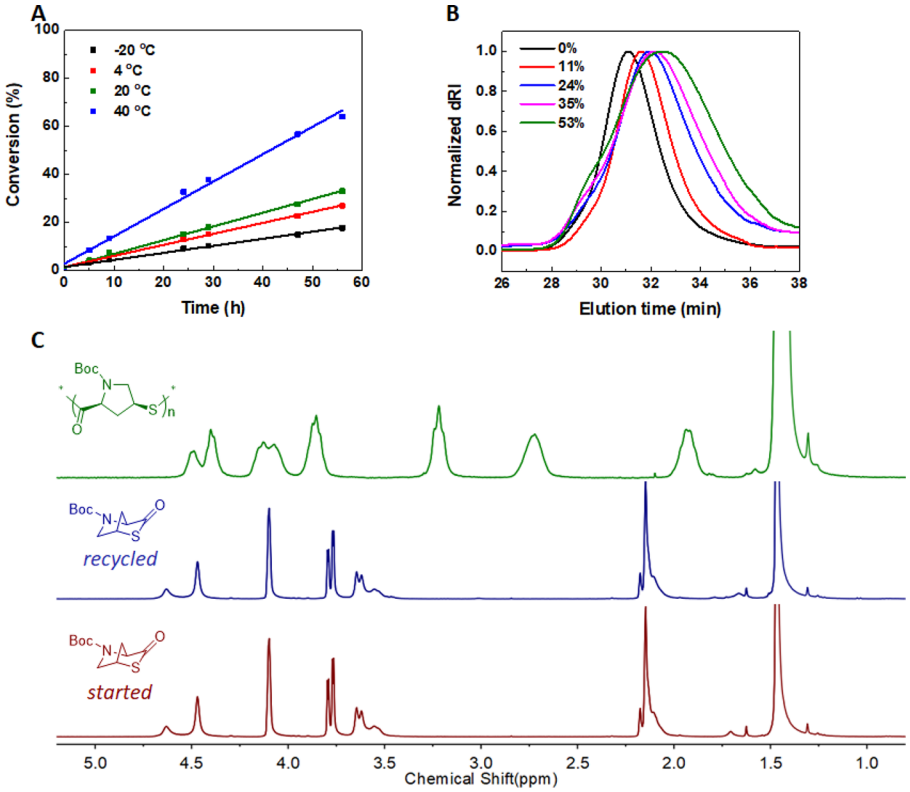


Figure 3. Depolymerization of $PN^{Boc}PTE_{50}$. (A) Kinetic plots of the depolymerization conversion versus time at different temperatures (with 4.6 equiv of TEA relative to thiols). (B) Overlay of the SEC curves at different depolymerization conversions (4.6 equiv of TEA, 20 °C). (C) Overlay of the ^{1}H NMR spectra of $PN^{Boc}PTE_{50}$ (top), recycled N^{Boc}-PTL after treating the polymer with 0.046 equiv of DBU at 50 °C for 2 min (middle), and the started monomer N^{Boc}-PTL for comparison (bottom). All experiments were conducted in $CDCl_3$.

196 °C, respectively. The T_g for $PN^{Cbz}PTE$ was 67 °C, whereas no obvious T_g was detected for $PN^{Boc}PTE$. The lower T_g of $PN^{ene}PTEs$ relative to $PN^{Cbz}PTEs$ could be a reason for the more flexible 2-(allyloxy)ethyl side chain. None of the polymer showed a melting-transition temperature (T_m) in the DSC measurement.

To test the recyclability, $PN^{Boc}PTE$ bearing a terminal thiol group was dissolved in $CDCl_3$ at 10 mg/mL with 4.6 equiv of TEA relative to the number of thiols. All depolymerization attempts underwent smoothly following a zero-order kinetic character, with a temperature-dependent rate constant (Figure 3A and Table S2). SEC analysis of the depolymerization process showed the gradual shift of unimodal peaks to the late elution time (Figure 3B). When a catalytic amount (0.046 equiv relative to the number of thiols) of a stronger base DBU was used, a quantitative regeneration of clean monomer was realized within 2 min at 50 °C as confirmed by ^{1}H NMR (Figure 3C). Overall, the conditions for recycling the PTE polymers were significantly milder than those for polyesters and polycarbonates, which typically required higher temperature and/or stronger catalysts.[8] The almost instantaneous depolymerization (less than 2 min) of our PTEs also indicated an easier process than most other recyclable polymers. Interestingly, $PN^{Boc}PTE$ showed no degradation without base up to 5 days heating at 50 °C, regardless of small molecular thiols (Figure S28). Moreover, $PN^{Boc}PTE$ capped with iodoacetaminde remained stable against thiol and TEA (Figure S29). Together, these experiments once again highlighted the robustness of the PTE backbone under normal conditions. The results also suggested that the depolymerization reaction took place in a domino fashion without random chain−chain scission or macrocyclization. Initial attempts on the thermolysis of $PN^{Boc}PTE$ at 160 °C under high vacuum (to prevent oxidation) and with a condenser (for monomer sublimation) gave a ∼79% recovery of the monomer N^{Boc}-PTL in white crystal form (Figure S30). Further optimization of the thermolysis conditions is still undergoing in our laboratory.

To better understand the ROP and depolymerization processes, we conducted DFT calculations to illustrate the energy barriers for the chain growth and the potential interchain transthioesterification steps (Figure 4A and methods in the Supporting Information). For clarity and simplicity purposes, *N*-acetyl was used as the side chain in the model reactions, and a dimer was used in the chain transfer step. The exothermic chain growth reaction had a net free energy decrease of 7.9 kcal mol^{-1} in DCM (INT_1 to INT_3). When the terminal thiol was deprotonated, the energy barrier for the chain growth was ∼6.8 kcal mol^{-1} (Figure 4B, INT_1 to TS_1). Investigation of the model transthioesterification reaction (INT_1 to 2-INT_3) in Figure 4B indicated an energy barrier ∼11.1 kcal mol^{-1}. The 4.3 kcal mol^{-1} difference in the energy barrier between the chain propagation and transfer implied a ∼2000-fold rate difference at room temperature. Considering the greater steric hindrance in the real chain transfer reaction, the rate difference in chain propagation and transfer could be even pronounced. Together, the DFT calculation explained the high polymerizability of N^R-PTL, the excellent control in M_n, and the narrow $Đ$.

In conclusion, we present here a new paradigm of sustainable polymers from renewable resources. The synthesis of the 4-hydroxyproline-derived bicyclic thiolactone monomers is straightforward and well-established in industry. The

DOI: 10.1021/jacs.9b00031
J. Am. Chem. Soc. 2019, 141, 4928−4935

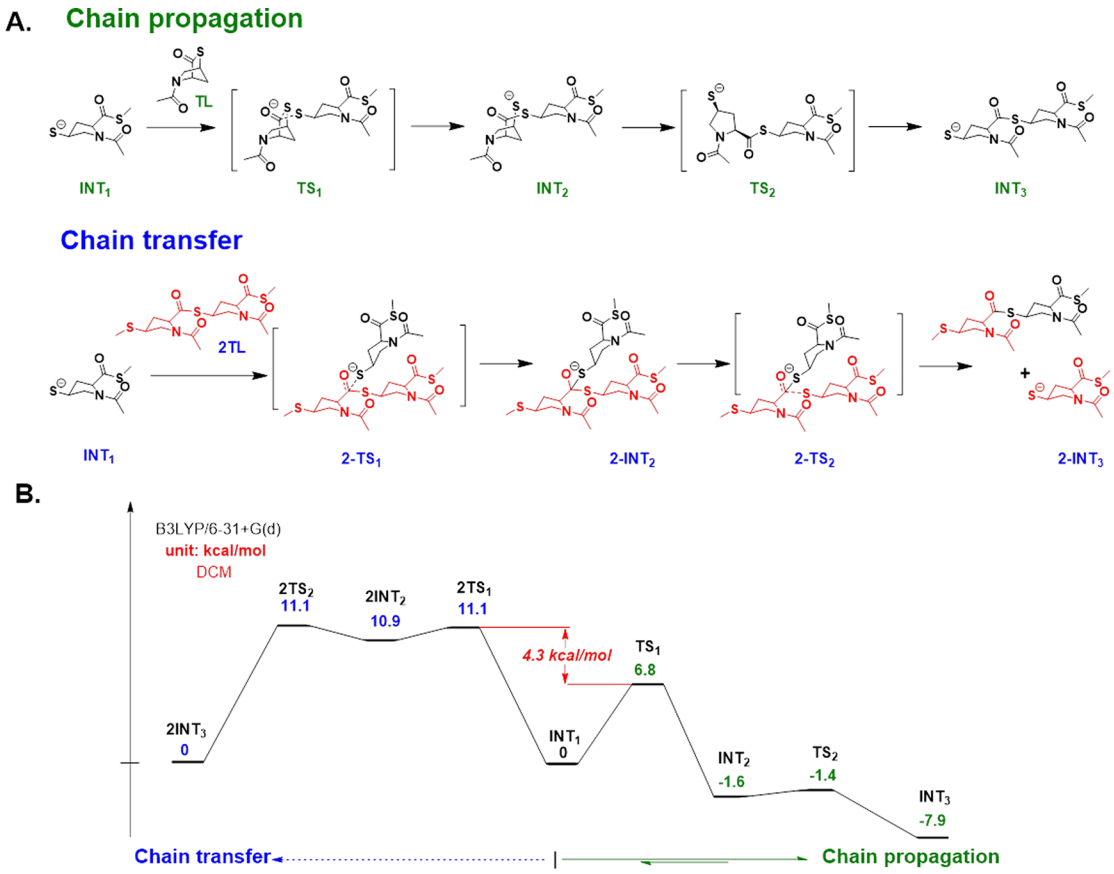


Figure 4. Mechanism investigation by DFT calculation. (A) Proposed chain propagation and transfer intermediates (INT) and transition states (TS) in the ROP of N^R-PTL in DCM. (B) Calculated free energy of each INT and TS.

monomers are highly polymerizable, allowing the facile generation of various PTEs under mild conditions. The properties of the PTEs can be conveniently fine-tuned with strategies such as copolymerization and postpolymerization modification. The resultant functionalized PTEs are characterized by their stability under most base-free conditions, as well as their ability to undergo highly selective and complete depolymerization in dilute alkaline solutions. Although further improvement, such as cost reduction and more efficient thermolysis, would be necessary for the commercialization of these PTEs, their unique ROP/depolymerization chemistry provides a sustainable method for creating and manufacturing high-value materials such as optical/photochemical plastics, self-immolative polymers,[56−60] and degradable biomaterials that can be easily recycled or reused.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/jacs.9b00031.

Experimental details, ^{1}H and ^{13}C NMR spectra, MALDI-TOF mass spectra, SEC curves, and TGA and DSC curves (PDF)

X-ray crystallographic data (CIF)

X-ray crystallographic data (CIF)

■ AUTHOR INFORMATION

Corresponding Author

*chemhualu@pku.edu.cn

ORCID

Zichen Li: 0000-0002-0746-9050

Hua Lu: 0000-0003-2180-3091

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (21722401). We thank Prof. Suwei Dong for inspiring discussions and Prof. Zhi-Xiang Yu for advice on DFT calculations.

■ REFERENCES

(1) Zhu, Y. Q.; Romain, C.; Williams, C. K. Sustainable polymers from renewable resources. *Nature* **2016**, *540* (7633), 354−362.

(2) Albertsson, A. C.; Hakkarainen, M. Designed to degrade Suitably designed degradable polymers can play a role in reducing plastic waste. *Science* **2017**, *358* (6365), 872−873.

(3) Garcia, J. M.; Robertson, M. L. The future of plastics recycling Chemical advances are increasing the proportion of polymer waste that can be recycled. *Science* **2017**, *358* (6365), 870−872.

(4) Hillmyer, M. A. The promise of plastics from plants Plant-derived feedstocks are increasingly competitive in plastics production. *Science* **2017**, *358* (6365), 868−870.

(5) Tang, X.; Chen, E. Y. X. Toward Infinitely Recyclable Plastics Derived from Renewable Cyclic Esters. *Chem.* **2019**, *5* (2), 284−312.

(6) Garcia, J. M.; Jones, G. O.; Virwani, K.; McCloskey, B. D.; Boday, D. J.; ter Huurne, G. M.; Horn, H. W.; Coady, D. J.; Bintaleb, A. M.; Alabdulrahman, A. M. S.; Alsewailem, F.; Almegren, H. A. A.; Hedrick, J. L. Recyclable, Strong Thermosets and Organogels via

DOI: 10.1021/jacs.9b00031
J. Am. Chem. Soc. 2019, 141, 4928−4935

Paraformaldehyde Condensation with Diamines. *Science* **2014**, *344* (6185), 732−735.
(7) Fortman, D. J.; Brutman, J. P.; De Hoe, G. X.; Snyder, R. L.; Dichtel, W. R.; Hillmyer, M. A. Approaches to Sustainable and Continually Recyclable Cross-Linked Polymers. *ACS Sustainable Chem. Eng.* **2018**, *6* (9), 11145−11159.
(8) 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) Lu, X. B.; Liu, Y.; Zhou, H. Learning Nature: Recyclable Monomers and Polymers. *Chem. - Eur. J.* **2018**, *24* (44), 11255−11266.
(10) Tang, X.; Chen, E. Y. Chemical synthesis of perfectly isotactic and high melting bacterial poly(3-hydroxybutyrate) from bio-sourced racemic cyclic diolide. *Nat. Commun.* **2018**, *9* (1), 2345.
(11) Zhang, X. Y.; Fevre, M.; Jones, G. O.; Waymouth, R. M. Catalysis as an Enabling Science for Sustainable Polymers. *Chem. Rev.* **2018**, *118* (2), 839−885.
(12) Song, Y.; Ji, X.; Dong, M.; Li, R.; Lin, Y. N.; Wang, H.; Wooley, K. L. Advancing the Development of Highly-Functionalizable Glucose-Based Polycarbonates by Tuning of the Glass Transition Temperature. *J. Am. Chem. Soc.* **2018**, *140* (47), 16053−16057.
(13) Gandini, A.; Lacerda, T. M.; Carvalho, A. J. F.; Trovatti, E. Progress of Polymers from Renewable Resources: Furans, Vegetable Oils, and Polysaccharides. *Chem. Rev.* **2016**, *116* (3), 1637−1669.
(14) Galbis, J. A.; Garcia-Martin, M. D.; de Paz, M. V.; Galbis, E. Synthetic Polymers from Sugar-Based Monomers. *Chem. Rev.* **2016**, *116* (3), 1600−1636.
(15) Delidovich, I.; Hausoul, P. J. C.; Deng, L.; Pfutzenreuter, R.; Rose, M.; Palkovits, R. Alternative Monomers Based on Lignocellulose and Their Use for Polymer Production. *Chem. Rev.* **2016**, *116* (3), 1540−1599.
(16) Liu, Y.; Zhou, H.; Guo, J. Z.; Ren, W. M.; Lu, X. B. Completely Recyclable Monomers and Polycarbonate: Approach to Sustainable Polymers. *Angew. Chem., Int. Ed.* **2017**, *56* (17), 4862−4866.
(17) Zhang, J. Y.; Li, T. Q.; Mannion, A. M.; Schneiderman, D. K.; Hillmyer, M. A.; Bates, F. S. Tough and Sustainable Graft Block Copolymer Thermoplastics. *ACS Macro Lett.* **2016**, *5* (3), 407−412.
(18) Felder, S. E.; Redding, M. J.; Noel, A.; Grayson, S. M.; Wooley, K. L. Organocatalyzed ROP of a Glucopyranoside Derived Five-Membered Cyclic Carbonate. *Macromolecules* **2018**, *51* (5), 1787−1797.
(19) Xu, S.; Lamm, M. E.; Rahman, M. A.; Zhang, X.; Zhu, T.; Zhao, Z.; Tang, C. Renewable atom-efficient polyesters and thermosetting resins derived from high oleic soybean oil. *Green Chem.* **2018**, *20* (5), 1106−1113.
(20) Watts, A.; Kurokawa, N.; Hillmyer, M. A. Strong, Resilient, and Sustainable Aliphatic Polyester Thermoplastic Elastomers. *Biomacromolecules* **2017**, *18* (6), 1845−1854.
(21) De Hoe, G. X.; Zumstein, M. T.; Tiegs, B. J.; Brutman, J. P.; McNeill, K.; Sander, M.; Coates, G. W.; Hillmyer, M. A. Sustainable Polyester Elastomers from Lactones: Synthesis, Properties, and Enzymatic Hydrolyzability. *J. Am. Chem. Soc.* **2018**, *140* (3), 963−973.
(22) Zhu, J. B.; Chen, E. Y. X. Living Coordination Polymerization of a Six-Five Bicyclic Lactone to Produce Completely Recyclable Polyester. *Angew. Chem., Int. Ed.* **2018**, *57* (38), 12558−12562.
(23) MacDonald, J. P.; Shaver, M. P. An aromatic/aliphatic polyester prepared via ring-opening polymerisation and its remarkably selective and cyclable depolymerisation to monomer. *Polym. Chem.* **2016**, *7* (3), 553−559.
(24) Jehanno, C.; Pérez-Madrigal, M. M.; Demarteau, J.; Sardon, H.; Dove, A. P. Organocatalysis for depolymerisation. *Polym. Chem.* **2019**, *10* (2), 172−186.
(25) Hong, M.; Chen, E. Y. X. Completely recyclable biopolymers with linear and cyclic topologies via ring-opening polymerization of gamma-butyrolactone. *Nat. Chem.* **2016**, *8* (1), 42−49.
(26) Zhao, N.; Ren, C.; Li, H.; Li, Y.; Liu, S.; Li, Z. Selective Ring-Opening Polymerization of Non-Strained gamma-Butyrolactone Catalyzed by A Cyclic Trimeric Phosphazene Base. *Angew. Chem., Int. Ed.* **2017**, *56* (42), 12987−12990.
(27) Lv, A.; Cui, Y.; Du, F. S.; Li, Z. C. Thermally Degradable Polyesters with Tunable Degradation Temperatures via Postpolymerization Modification and Intramolecular Cyclization. *Macromolecules* **2016**, *49* (22), 8449−8458.
(28) Griebel, J. J.; Glass, R. S.; Char, K.; Pyun, J. Polymerizations with elemental sulfur: A novel route to high sulfur content polymers for sustainability, energy and defense. *Prog. Polym. Sci.* **2016**, *58*, 90−125.
(29) Luo, M.; Zhang, X. H.; Darensbourg, D. J. Poly(monothiocarbonate)s from the Alternating and Regioselective Copolymerization of Carbonyl Sulfide with Epoxides. *Acc. Chem. Res.* **2016**, *49* (10), 2209−2219.
(30) Kausar, A.; Zulfiqar, S.; Sarwar, M. I. Recent Developments in Sulfur-Containing Polymers. *Polym. Rev.* **2014**, *54* (2), 185−267.
(31) Tian, T.; Hu, R. R.; Tang, B. Z. Room Temperature One-Step Conversion from Elemental Sulfur to Functional Polythioureas through Catalyst-Free Multicomponent Polymerizations. *J. Am. Chem. Soc.* **2018**, *140* (19), 6156−6163.
(32) Li, W.; Wu, X.; Zhao, Z.; Qin, A.; Hu, R.; Tang, B. Z. Catalyst-Free, Atom-Economic, Multicomponent Polymerizations of Aromatic Diynes, Elemental Sulfur, and Aliphatic Diamines toward Luminescent Polythioamides. *Macromolecules* **2015**, *48* (21), 7747−7754.
(33) Higashihara, T.; Ueda, M. Recent Progress in High Refractive Index Polymers. *Macromolecules* **2015**, *48* (7), 1915−1929.
(34) Konieczynska, M. D.; Villa-Camacho, J. C.; Ghobril, C.; Perez-Viloria, M.; Tevis, K. M.; Blessing, W. A.; Nazarian, A.; Rodriguez, E. K.; Grinstaff, M. W. On-Demand Dissolution of a Dendritic Hydrogel-based Dressing for Second-Degree Burn Wounds through Thiol-Thioester Exchange Reaction. *Angew. Chem., Int. Ed.* **2016**, *55* (34), 9984−9987.
(35) Ghobril, C.; Charoen, K.; Rodriguez, E. K.; Nazarian, A.; Grinstaff, M. W. A dendritic thioester hydrogel based on thiol-thioester exchange as a dissolvable sealant system for wound closure. *Angew. Chem., Int. Ed.* **2013**, *52* (52), 14070−14074.
(36) Bowman, C. N.; Kloxin, C. J. Covalent Adaptable Networks: Reversible Bond Structures Incorporated in Polymer Networks. *Angew. Chem., Int. Ed.* **2012**, *51* (18), 4272−4274.
(37) Worrell, B. T.; Mavila, S.; Wang, C.; Kontour, T. M.; Lim, C. H.; McBride, M. K.; Musgrave, C. B.; Shoemaker, R.; Bowman, C. N. A user's guide to the thiol-thioester exchange in organic media: scope, limitations, and applications in material science. *Polym. Chem.* **2018**, *9* (36), 4523−4534.
(38) Aksakal, S.; Aksakal, R.; Becer, C. R. Thioester functional polymers. *Polym. Chem.* **2018**, *9* (36), 4507−4516.
(39) Espeel, P.; Carrette, L. L. G.; Bury, K.; Capenberghs, S.; Martins, J. C.; Du Prez, F. E.; Madder, A. Multifunctionalized Sequence-Defined Oligomers from a Single Building Block. *Angew. Chem., Int. Ed.* **2013**, *52* (50), 13261−13264.
(40) Espeel, P.; Goethals, F.; Du Prez, F. E. One-Pot Multistep Reactions Based on Thiolactones: Extending the Realm of Thiol-Ene Chemistry in Polymer Synthesis. *J. Am. Chem. Soc.* **2011**, *133* (6), 1678−1681.
(41) Overberg, C. G.; Weise, J. K. Anionic Ring-Opening Polymerization of Thiolactones. *J. Am. Chem. Soc.* **1968**, *90* (13), 3533−3537.
(42) Kato, M.; Toshima, K.; Matsumura, S. Enzymatic synthesis of polythioester by the ring-opening polymerization of cyclic thioester. *Biomacromolecules* **2007**, *8* (11), 3590−3596.
(43) Bannin, T. J.; Kiesewetter, M. K. Poly(thioester) by Organocatalytic Ring-Opening Polymerization. *Macromolecules* **2015**, *48* (16), 5481−5486.
(44) Suzuki, M.; Makimura, K.; Matsuoka, S. Thiol-Mediated Controlled Ring-Opening Polymerization of Cysteine-Derived beta-Thiolactone and Unique Features of Product Polythioester. *Biomacromolecules* **2016**, *17* (3), 1135−1141.
(45) Mavila, S.; Worrell, B. T.; Culver, H. R.; Goldman, T. M.; Wang, C.; Lim, C. H.; Domaille, D. W.; Pattanayak, S.; McBride, M.

DOI: 10.1021/jacs.9b00031
J. Am. Chem. Soc. 2019, 141, 4928−4935

K.; Musgrave, C. B.; Bowman, C. N. Dynamic and Responsive DNA-like Polymers. *J. Am. Chem. Soc.* **2018**, *140* (42), 13594−13598.
(46) Yue, T. J.; Zhang, M. C.; Gu, G. G.; Wang, L. Y.; Ren, W. M.; Lu, X. B. Precise Synthesis of Poly(thioester)s with Diverse Structures by Copolymerization of Cyclic Thioanhydrides and Episulfides Mediated by Organic Ammonium Salts. *Angew. Chem., Int. Ed.* **2019**, *58* (2), 618−623.
(47) Smith, R. A.; Fu, G.; McAteer, O.; Xu, M.; Gutekunst, W. R. Radical Approach to Thioester-Containing Polymers. *J. Am. Chem. Soc.* **2019**, *141* (4), 1446−1451.
(48) Abbas, S.; Ferris, L.; Norton, A. K.; Powell, L.; Robinson, G. E.; Siedlecki, P.; Southworth, R. J.; Stark, A.; Williams, E. G. Application of an enantiomerically pure bicyclic thiolactone in the synthesis of a farnesyl transferase inhibitor. *Org. Process Res. Dev.* **2008**, *12* (2), 202−212.
(49) Brands, K. M. J.; Jobson, R. B.; Conrad, K. M.; Williams, J. M.; Pipik, B.; Cameron, M.; Davies, A. J.; Houghton, P. G.; Ashwood, M. S.; Cottrell, I. F.; Reamer, R. A.; Kennedy, D. J.; Dolling, U. H.; Reider, P. J. Efficient one-pot synthesis of the 2-aminocarbonylpyrrolidin-4-ylthio-containing side chain of the new broad-spectrum carbapenem antibiotic ertapenem. *J. Org. Chem.* **2002**, *67* (14), 4771−4776.
(50) Brands, K. M. J.; Marchesini, G.; Williams, J. M.; Dolling, U. H.; Reider, P. J. An expedient one-pot synthesis for protected 2-thia-5-azabicyclo[2.2.1]heptan-3-ones. Versatile intermediates in the synthesis of carbapenem sidechains. *Tetrahedron Lett.* **1996**, *37* (17), 2919−2922.
(51) Kwon, H. Y. L. R. Pseudopoly (amino acids): A Study of the Synthesis and Characterization of Poly(*trans*-4-hydroxy-*N*-acyl-$_L$-proline esters). *Macromolecules* **1989**, *22*, 3250−3255.
(52) Kohn, J. L. R. Polymerization Reactions Involving the Side Chains of α-$_L$-Amino Acids. *J. Am. Chem. Soc.* **1987**, *109*, 817−820.
(53) Gui, Y.; Qiu, L. Q.; Li, Y. H.; Li, H. X.; Dong, S. W. Internal Activation of Peptidyl Prolyl Thioesters in Native Chemical Ligation. *J. Am. Chem. Soc.* **2016**, *138* (14), 4890−4899.
(54) Sayers, J.; Karpati, P. M. T.; Mitchell, N. J.; Goldys, A. M.; Kwong, S. M.; Firth, N.; Chan, B.; Payne, R. J. Construction of Challenging Proline-Proline Junctions via Diselenide-Selenoester Ligation Chemistry. *J. Am. Chem. Soc.* **2018**, *140* (41), 13327−13334.
(55) Pollock, S. B.; Kent, S. B. H. An investigation into the origin of the dramatically reduced reactivity of peptide-prolyl-thioesters in native chemical ligation. *Chem. Commun.* **2011**, *47* (8), 2342−2344.
(56) Wang, W. X.; Alexander, C. Self-immolative polymers. *Angew. Chem., Int. Ed.* **2008**, *47* (41), 7804−7806.
(57) Esser-Kahn, A. P.; Sottos, N. R.; White, S. R.; Moore, J. S. Programmable Microcapsules from Self-Immolative Polymers. *J. Am. Chem. Soc.* **2010**, *132* (30), 10266−10268.
(58) Chen, E. K. Y.; McBride, R. A.; Gillies, E. R. Self-Immolative Polymers Containing Rapidly Cyclizing Spacers: Toward Rapid Depolymerization Rates. *Macromolecules* **2012**, *45* (18), 7364−7374.
(59) Liu, G. H.; Zhang, G. F.; Hu, J. M.; Wang, X. R.; Zhu, M. Q.; Liu, S. Y. Hyperbranched Self-Immolative Polymers (hSIPs) for Programmed Payload Delivery and Ultrasensitive Detection. *J. Am. Chem. Soc.* **2015**, *137* (36), 11645−11655.
(60) Gnaim, S.; Shabat, D. Self-Immolative Chemiluminescence Polymers: Innate Assimilation of Chemiexcitation in a Domino-like Depolymerization. *J. Am. Chem. Soc.* **2017**, *139* (29), 10002−10008.

DOI: 10.1021/jacs.9b00031
J. Am. Chem. Soc. 2019, 141, 4928−4935