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Synthesis, Functionalization, and Controlled Degradation of High Molecular Weight Polyester from Itaconic Acid via ADMET Polymerization

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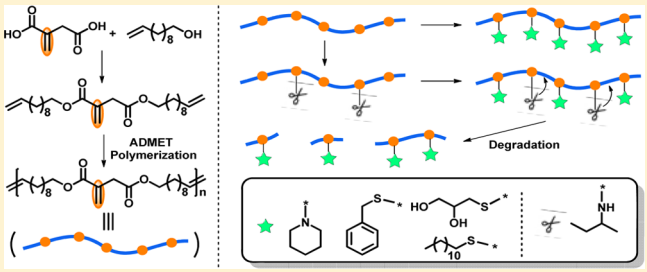
Supporting Information



ABSTRACT: We report a facile strategy for the synthesis, functionalization, and controlled degradation of high molecular weight polyesters based on itaconic acid (IA) and 10-undecenol. A diene monomer, di(10-undecenyl) itaconate (DUI), was synthesized from IA and 10-undecenol by esterification reaction. The acyclic diene metathesis (ADMET) polymerization of DUI was conducted with Grubbs first-generation catalyst (G-I) to afford high molecular weight polyesters (PEIA: **P1** and **P2**). Modification of **P1** with three mercaptans (3-mercapto-1,2-propanediol (MP), benzyl mercaptan (BM), and dodecyl mercaptan (DM)) and piperidine (PI) via Michael addition reaction with the itaconate vinyl groups was performed. Quantitative postpolymerization modifications with no degradation of the polyesters were achieved for all the three mercaptans and PI as revealed by NMR and GPC characterizations. One-pot sequential modification of **P1** with MP and PI was also successfully conducted. Thermal properties of the modified polyesters were studied by thermal gravimetric analysis (TGA) and differential scanning calorimetry (DSC). All the modified polyesters are semicrystalline with variable glass transition and melting temperatures which are affected by the modified side groups. Based on a detailed model reaction study, controlled modification of the itaconate vinyl groups with primary amines (*sec*-butylamine and 3-pentanamine) without intramolecular cyclization was achieved. Thus, *sec*-butylamine was used to modify **P1** to generate a secondary amine functionalized polyester (**P1-BA/DM**) which was stable at low temperature but undergone self-degradation in solid or solution via intramolecular cyclization with the formation of a five-membered lactam at elevated temperatures. This is a new kind of self-degradable polyester with controllable degradation rates.

INTRODUCTION

Because of the limited supply of fossil resources and the environmental problems such as the greenhouse effect caused by the consumption of nonrenewable resources, it has gained great interest to synthesize polymers from renewable resources.[1−11] In this context, many kinds of raw materials from renewable resources such as plant oils, rosins, terpenes, sugars, and so on have been investigated as building blocks of polymeric materials.[12] Among them, itaconic acid (IA) produced by the fermentation of *Aspergillus terreus* from sugar is a promising diacid containing an active 1,1-disubstituted vinyl group.[13−15] Because of its green synthetic procedure and great potential as a sustainable platform chemical and a building block for the production of polymers, IA has been selected as one of the "top 12" bio-based building block molecules by the U.S. Department of Energy.[16,17] Former studies using IA as a starting material for polymeric materials mainly focused on two directions. One is the radical copolymerization of itaconate esters to prepare vinyl copolymers,[18−21] and the other is the condensation polymerization of IA with diols to form polyesters.[22−25] However, for the latter one, only very low molecular weight polyesters were obtained due to the cross-linking caused by the itaconate vinyl groups at high temperature and in high vacuum. Moderate molecular weight polyesters were obtained only when IA was copolymerized with other diacid in a low molar content.[22] These polyesters are generally used to form thermosets by cross-linking.[22,24]

Aliphatic polyesters have attracted widespread interest in recent years owing to the growing demand for biodegradable and environmentally benign polymers.[7,8,26−28] The most widely studied aliphatic polyesters are poly(lactic acid), poly(glycolic acid), and poly(ε-caprolactone) for their important applications in biomedical fields.[29−31] Long-chain aliphatic polyester is another kind of very important polyesters due to its great potential as elastomers, packaging films, and so on.[7,8] These long-chain aliphatic polyesters are generally synthesized by stepwise polymerization of long-chain monomers[32−35] or ring-opening polymerization of large ring lactones.[7,36−41] Recently,

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synthesis of these polyesters from renewable resources has been an expanding area both in academy and industry.[42] The starting materials are generally long-chain aliphatic acids, alcohols, or aldehydes from plant oils, with 10-undecenol from castor oil as the widely used one.[6,8,34,42−44]

To meet different applications, the properties of aliphatic polyesters, e.g., hydrophilicity, degradability, and thermal properties, always need to be tuned.[3,27,45] One of the most efficient methods is the postmodification of side-chain-functionalized polyesters[3,27,45] which are conventionally synthesized by ring-opening polymerization of functionalized lactones[29,45−47] or condensation polymerization of monomers with functional side groups.[48,49] Though many kinds of side-chain-functionalized polyesters have been obtained through the above-mentioned methods, there are still several limits, such as complex synthesis of monomers and protection−deprotection of the functional groups.[50] Therefore, it is of great interest to develop facile synthetic strategies for side-chain-functionalized polyesters. In this context, it is exciting to notice that polyesters based on IA (PEIA) are easily accessed platforms for postpolymerization modification, since the itaconate vinyl groups of PEIA can be simply modified through Michael addition reaction with mercaptans and amines. Postpolymerization modification of polyesters with similar vinyl groups synthesized via the Baylis−Hillman reaction has been reported.[50,51] However, the molecular weights of the polymers are low, the synthetic procedure is complicated, and the monomers are limited and nonrenewable. Moreover, compared with the vinyl groups generated by the Baylis−Hillman reaction, the itaconate vinyl groups have distinct properties. After modification of PEIA with suitable primary amine via Michael addition reaction, the introduced secondary amino groups can react intramolecularly with one itaconate ester group to form a five-membered lactam, leading to the broken of one ester bond simultaneously. It is thus expected that polyesters like PEIAs may undergo self-degradation via intramolecular cyclization after being modified. Similar works on degradation of polyesters and poly(ester amide)s via pendant amine-induced intramolecular cyclization have been reported recently.[52−54] However, the polymer synthesis in these works is rather complicated and time-consuming.

Acyclic diene metathesis (ADMET) polymerization is the condensation polymerization of diene monomers via olefin metathesis reaction catalyzed by Grubbs catalysts.[55−59] It has the advantages of high tolerance to many functional groups, mild polymerization condition, and efficient conversion of the double bonds. Because of these outstanding features, it has already been widely used in many fields such as synthesis of vinyl copolymers with regular sequence,[55−64] polymers from renewable resources,[33−35,58,65−69] and poly(thienylene vinylene)s.[70,71] According to the results reported by Grubbs et al., the itaconate vinyl groups would not participate in the olefin metathesis reaction catalyzed by the Grubbs first-generation catalyst (G-I) due to its electron deficiency and large steric hindrance.[72,73] Considering the mild condition of ADMET polymerization, we hypothesize that high molecular weight PEIA could be obtained through the ADMET polymerization of IA-based diene monomers.

Herein, we developed a facile strategy to synthesize high molecular weight PEIA from IA and 10-undecenol via ADMET polymerization and to regulate the properties of PEIA by postpolymerization modification of the itaconate vinyl groups. First, IA was transferred to a diene monomer, di(10-undecenyl) itaconate (DUI), through esterification reaction with another renewable resource, 10-undecenol. Then, high molecular weight PEIA was obtained by the ADMET polymerization of DUI. Efficient modification of the itaconate vinyl groups in PEIA via Michael addition reaction with three mercaptans (3-mercapto-1,2-propanediol (MP), benzyl mercaptan (BM), and dodecyl mercaptan (DM)) and piperidine (PI) was conducted. Furthermore, *sec*-butylamine was used to modify a PEIA, and the resultant secondary amine functionalized PEIA can undergo self-degradation via intramolecular cyclization with the formation of a five-membered lactam. Thus, this synthetic methodology provides a novel strategy toward high molecular weight PEIA with tunable self-degradable property.

■ EXPERIMENTAL SECTION

Materials. All reagents were used as received unless otherwise stated. 10-Undecenol (99%) was purchased from TCI (Shanghai). Itaconic acid (IA, 99%), 3-mercapto-1,2-propanediol (MP, 90+%), benzyl mercaptan (BM, 99%), dibutyl itaconate (98%), *sec*-butylamine (98%), 3-pentanamine (98%), and *tert*-pentylamine (98%) were obtained from Alfa Aesar. G-I was received from Sigma-Aldrich. The following reagents were purchased from Beijing Chem. Reagent Co., Ltd.: piperidine (PI, 97%), hydroquinone (99%), dodecyl mercaptan (DM, 98%), *p*-toluenesulfonic acid (97%), and triethylamine (TEA, >99%). All the solvents were analytical grade and used without further purification.

Measurements and Characterizations. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker ARX-400 spectrometer. The samples were dissolved in $CDCl_3$ with tetramethylsilane (TMS) as the internal reference. Electrospray ionization mass spectroscopy (ESI-MS) characterizations were performed on a Bruker APEX-IV Fourier transform mass spectrometer in the positive ion mode. Molecular weights and polydispersity index (PDI) were measured by gel permeation chromatograph (GPC), which is equipped with a Waters 2414 refractive index detector, a Waters 1525 binary HPLC pump, and three Waters Styragel columns (1×10^4, 1×10^3, and 500 Å pore sizes). Tetrahydrofuran (THF) was used as the eluent at a flow rate of 1 mL/min, and the column oven was set at 35 °C. Molecular weights and PDI were calculated with a Breeze 3.30 software using polystyrene as the standard. Fourier transform infrared (FTIR) spectra were recorded on a Bruker Vector-22 Fourier transform infrared spectrometer in KBr disks. Thermal gravimetric analysis (TGA) was conducted on a Q600-SDT thermogravimetric analyzer (TA Co., Ltd.) at a heating rate of 10 °C/min under a nitrogen atmosphere of 100 mL/min. Differential scanning calorimetry (DSC) was performed on a Q100 differential scanning calorimeter at a heating rate of 10 °C/min under a nitrogen atmosphere of 50 mL/min. Data of the endothermic curve were recorded from the second scan and analyzed with a TA Universal Analysis software.

Synthesis of DUI.[74] IA (3.90 g, 30 mmol), 10-undecenol (10.22 g, 60 mmol), *p*-toluenesulfonic acid (0.456 g, 2.65×10^{-3} mmol), hydroquinone (0.29 g, 2.68×10^{-3} mmol), and toluene (45 mL) were transferred into a 100 mL round-bottom flask fitted with a Dean−Stark trap. The mixture was refluxed under vigorous stirring until no more water was collected (about 3 h). Then, the reaction solution was cooled down to room temperature and washed with water for three times. The organic layer was dried and concentrated by rotary evaporation. The obtained crude product was purified by silica column chromatography (petroleum ether/ethyl acetate = 12/1) to afford the final product as a colorless oil in 85% yield. ^{1}H NMR (400 MHz, $CDCl_3$), δ (TMS, ppm): 6.31 (s, 1H), 5.81 (m, 2H), 5.68 (s, 1H), 4.96 (m, 4H), 4.15 (m, 2H), 4.08 (m, 2H), 3.33 (s, 2H), 2.04 (m, 6.9 Hz, 4H), 1.77−1.55 (m, 4H), 1.46−1.21 (m, 24H). ^{13}C NMR (101 MHz, $CDCl_3$), δ (TMS, ppm): 170.76 (s), 166.22 (s), 139.15 (s), 134.19 (s), 128.04 (s), 114.15 (s), 65.18 (s), 65.08 (s), 37.83 (s), 33.81 (s), 29.47 (s), 29.41 (s), 29.24 (d), 29.11 (s), 28.93 (s), 28.57 (d). ESI-MS: calcd for $C_{27}H_{46}O_4$ $[M + Na]^+$ 457.34; found 457.33.

ADMET Polymerization. *Synthesis of P1.* Monomer DUI (869.3 mg, 2 mmol), G-I (8.2 mg, 10 μmol), and CH_2Cl_2 (0.5 mL) were sequentially transferred into a 25 mL Schlenk flask, which was equipped with a reflux condenser. The mixture was heated in an oil bath set at 40 °C. A continuous nitrogen flow was provided to remove the generated ethylene. CH_2Cl_2 was evaporated, and the mixture became semisolid within several hours. The polymerization was continued for 10 h. Then, a large excess of ethyl vinyl was added to quench the reaction. The mixture was concentrated and precipitated into methanol (60 mL). Finally, an off-white solid was obtained after centrifugation and vacuum dryness for 0.5 h in 86% yield.

Synthesis of P2. Polymerization of DUI was first conducted for 10 h in the same way as for the synthesis of **P1**. Then, another portion of CH_2Cl_2 (1 mL) was added, and the polymerization was continued for another 24 h. After that, the mixture was treated similarly as that for **P1** to afford the final product **P2** as an off-white solid in 89% yield.

Postmodification of P1 with Mercaptans. Three mercaptans (MP, BM, and DM) were used for the postmodification of **P1**, and the procedures were essentially the same. Take the postmodification with BM as an example. Polymer **P1** (101.7 mg, 0.25 mmol itaconate vinyl groups), THF (3 mL), methanol (2 mL), and BM (465.8 mg, 3.75 mmol) were sequentially transferred into a 10 mL round-bottom flask. The mixture was stirred at 25 °C for 20 h and then precipitated into methanol (30 mL). A white semisolid (**P1-BM**) was obtained after centrifugation and vacuum dryness in 92% yield.

Modification of P1 with PI. Polymer **P1** (101.7 mg, 0.25 mmol itaconate vinyl groups), THF (3 mL), and PI (319.3 mg, 3.75 mmol) were sequentially transferred into a 10 mL round-bottom flask. The mixture was stirred at 25 °C for 20 h and then precipitated into methanol (30 mL). A light-yellow semisolid (**P1-PI**) was obtained after centrifugation and vacuum dryness in 93% yield.

One-Pot Sequential Modification of P1 with MP and PI. Polymer **P1** (101.7 mg, 0.25 mmol itaconate vinyl groups), THF (3 mL), methanol (2 mL), and MP (81.2 mg, 0.75 mmol) were sequentially transferred into a 10 mL round-bottom flask. The mixture was stirred at 25 °C for 12 h. A small portion of the reaction solution (0.5 mL) was precipitated into methanol to afford the partially modified polyester (**P1-MP′**) for ^{1}H NMR measurement. Then, PI (255.6 mg, 3.00 mmol) was added to the remaining mixture, and the reaction was continued for another 3 h. The final product (**P1-MP/PI**) was obtained as a white semisolid after precipitation into methanol (30 mL), centrifugation, and vacuum dryness in 93% yield.

Model Reaction of *sec*-Butylamine with Dibutyl Itaconate in THF. *sec*-Butylamine (14.6 mg, 0.2 mmol) and dibutyl itaconate (48.5 mg, 0.2 mmol) were dissolved in THF-d_8 (0.5 mL) and then transferred into a NMR tube which was cooled in a 0 °C ice water bath. The NMR tube was taken for ^{1}H NMR measurements at the scheduled times.

The reaction of *sec*-butylamine with dibutyl itaconate in THF at 37 °C was conducted in a similar way.

Model Reaction of *sec*-Butylamine with Dibutyl Itaconate in THF/CH_3OH (v/v = 3/2). *sec*-Butylamine (73.1 mg, 1.0 mmol), dibutyl itaconate (242.3 mg, 1.0 mmol), THF (1.5 mL), and CH_3OH (1 mL) were transferred into a 10 mL round-bottom flask which was cooled in a 0 °C ice water bath with stirring. A small portion of the reaction mixture (0.3 mL) was taken out periodically. The solvent and *sec*-butylamine were evaporated under vacuum, and the residual was used for ^{1}H NMR measurement in $CDCl_3$.

Model reactions of 3-pentanamine and *tert*-pentylamine with dibutyl itaconate in THF/CH_3OH (v/v = 3/2) were conducted in a similar way.

Synthesis of Secondary Amine Functionalized PEIA (P1-BA/DM). Polymer **P1** (203.4 mg, 0.5 mmol itaconate vinyl groups), THF (6 mL), methanol (4 mL), and *sec*-butylamine (548.6 mg, 7.5 mmol) were sequentially transferred into a 10 mL round-bottom flask. The mixture was stirred at 0 °C for 14 h. A small portion of the reaction solution (0.5 mL) was precipitated into methanol to afford **P1-BA**. Meanwhile, DM (1062.6 mg, 5.25 mmol) was added to the remaining reaction mixture. The reaction was continued for another 1.5 h. The final product (**P1-BA/DM**) was obtained as an off-white semisolid after precipitation into methanol (30 mL), centrifugation, and vacuum dryness (0 °C, 3 h) in 92% yield. This polymer was usually stored at −20 °C in a refrigerator.

To obtain the hydrochloride salt of the polymer, the polymer solution was precipitated into an acidic methanol containing hydrochloride; this polymer is stable at room temperature for at least 2 months.

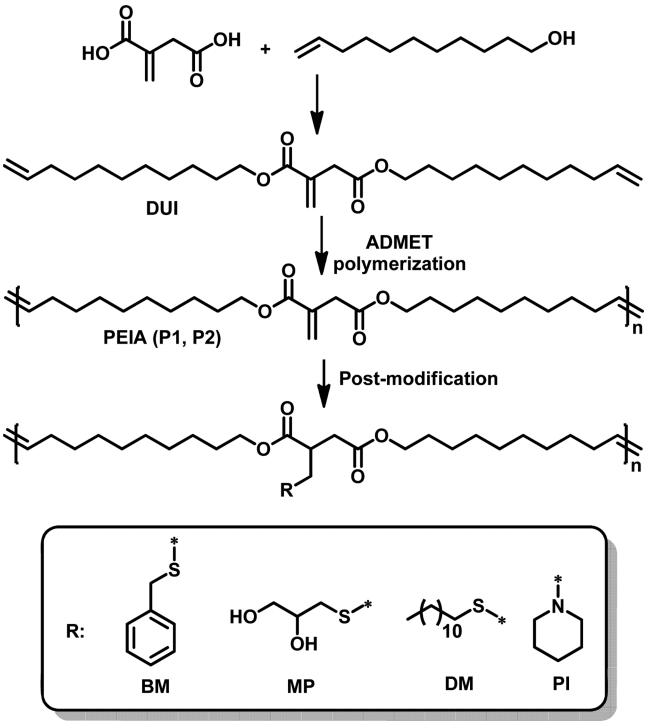
Degradation Study of P1-BA/DM in Bulk. Polymer **P1-BA/DM** (100 mg) was put into a small glass bottle which was heated in a 37 °C water bath. After prescribed times, a small portion of the product (8 mg every time) was taken out for ^{1}H NMR and GPC measurements. For the degradation in bulk at 150 °C, the polymer sample, **P1-BA/DM** (8 mg) was put in a crucible and heated under nitrogen for the scheduled times using the Q600-SDT thermogravimetric analyzer. The remaining sample was used for ^{1}H NMR and GPC measurements.

Degradation Study of P1-BA/DM in CD_2Cl_2 and THF-d_8. Take the degradation of **P1-BA/DM** in CD_2Cl_2 as an example. Polymer **P1-BA/DM** (5 mg) was dissolved in CD_2Cl_2 (0.5 mL) and then transferred into a NMR tube. The sealed NMR tube was heated in a 37 °C water bath, and the ^{1}H NMR spectrum was measured at the scheduled times. Degradation study of **P1-BA/DM** in THF-d_8 was conducted in a similar way.

RESULTS AND DISCUSSION

Monomer Synthesis. Monomer DUI was synthesized according to the procedures reported before.[74] Hydroquinone was added to the reaction mixture to inhibit cross-linking of the itaconate vinyl groups. ESI-MS, ^{1}H NMR, and ^{13}C NMR spectra confirmed the monomer structure (Scheme 1, Figure 1, and Figure S1).

Scheme 1. Synthesis and Functionalization of PEIA



ADMET Polymerization. Grubbs et al. have reported several examples of olefin cross-metathesis reaction between 1,1-disubstituted vinyl groups and 1-substituted vinyl groups.[72,73] According to their results, this kind of olefin cross-metathesis reaction did not occur when G-I was used as the catalyst due to its relatively lower reactivity than those of

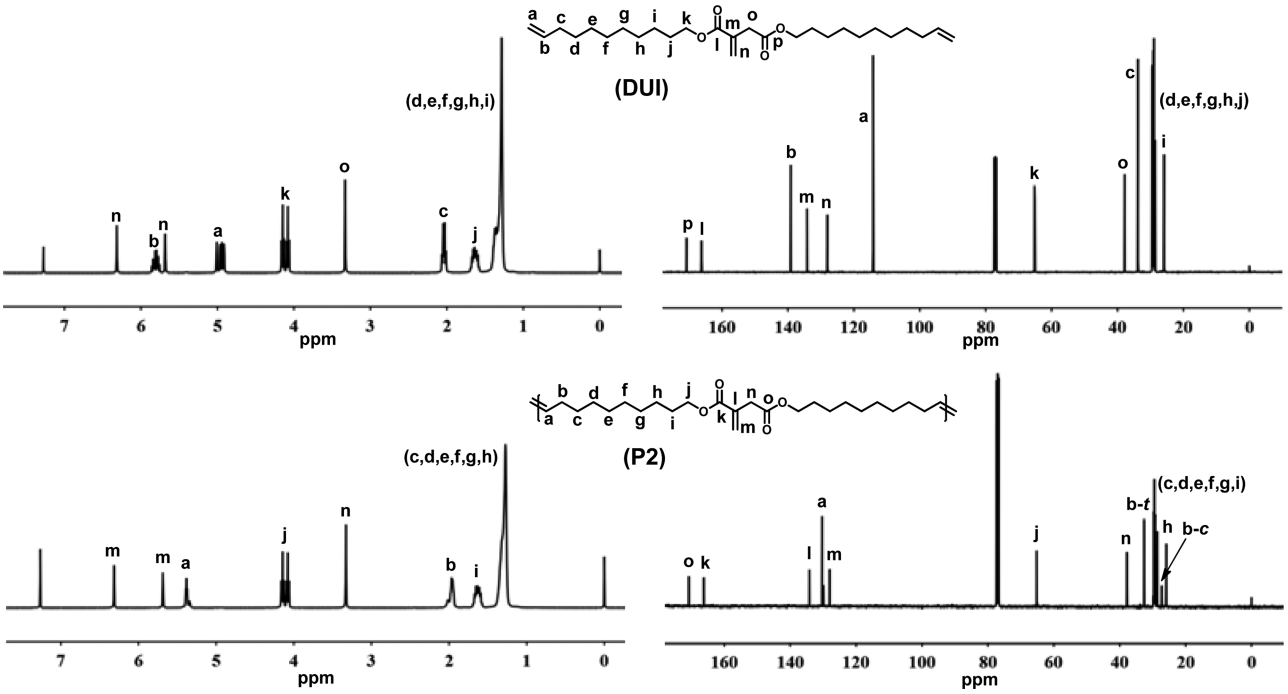


Figure 1. ^{1}H and ^{13}C NMR spectra of DUI and **P2** in $CDCl_3$.

Table 1. Molecular Weight and Thermal Data of Polyester Samples

polymer	M_n[a] (Da)	PDI[a]	T_g[b] (°C)	T_m[b] (°C)	T_c[b] (°C)	T_d[c] (°C)	ΔH_m[b] (J/g)
P1	23400	1.75					
P2	44000	1.46					
P1-BM	29900	1.46	−47.0	−3.7	−21.0	350.0	20.1
P1-PI	19000	1.69	−50.6	−10.8	−30.2	245.0, 368.0	25.9
P1-MP	33400	1.49	−30.9	31.1	18.0	328.0	24.9
P1-DM	26500	1.84	−15.4	6.4	−1.6	337.8	23.5
P1-MP/PI	22500	1.42	−44.5	5.7	−10.9	210.0, 355.2	17.5
P1-BA	19900	1.65					
P1-BA/DM	22000	1.55					

[a]Determined by GPC with THF as eluent (1 mL/min, 35 °C) using polystyrene calibration. [b]Determined by DSC (scan rate: 10 °C/min). Values were recorded from second scan data. [c]Determined by TGA (scan rate: 10 °C/min). T_d was defined as the temperature at 5% weight loss.

the other Grubbs catalysts. Compared with the 1,1-disubstituted vinyl groups that have been investigated by Grubbs et al., the itaconate vinyl groups possess even larger steric hindrance. Thus, it is reasonable to hypothesize that olefin cross-metathesis reaction between the itaconate vinyl groups and the terminal vinyl groups of DUI would not occur with G-I as the catalyst. This is the main reason why G-I was chosen as the catalyst in this work. Furthermore, G-I also has the advantage of causing much less olefin isomerization compared with other Grubbs catalysts.[66,75]

ADMET polymerization of DUI was performed using G-I as the catalyst at 40 °C in CH_2Cl_2. The polymerization was quenched after 10 h because the system was very viscous and could not be stirred any more. A PEIA sample (**P1**) was obtained after precipitation in methanol. GPC measurement revealed a M_n of 23 400 Da (Table 1 and Figure S2). To further increase the molecular weight, CH_2Cl_2 (1 mL) was added into the system when the mixture became very viscous after 10 h. In this way, the mixture can be stirred again and the metathesis reaction was continued. After another 24 h polymerization with good stirring, a PEIA sample (**P2**) with an even higher M_n (44 000 Da) was obtained (Table 1 and Figure S2). This was attributed to the stepwise nature of the ADMET polymerization so that the molecular weight can be apparently increased by increasing the reaction time. We also tried the ADMET polymerization in bulk for 3 days; however, cross-linking occurred. Both **P1** and **P2** were stable in the solid state at 0 °C, but cross-linking occurred when they were kept at room temperature for a long time. To avoid possible cross-linking, we stored **P1** and **P2** in CH_2Cl_2 solution.

Polyesters (**P1** and **P2**) were characterized by ^{1}H NMR, ^{13}C NMR (Figure 1 and Figure S3), and MALDI-TOF-MS (Figure 2). Take **P2** as an example. The ^{1}H NMR signals at 5.69, 6.31, and 3.33 ppm attributed to the itaconate vinyl groups and the methylene groups adjacent to the itaconate vinyl groups were maintained in the ^{1}H NMR spectrum of **P2**, demonstrating that the itaconate vinyl groups did not participate in the ADMET polymerization and no cross-linking occurred. The terminal olefin signals at 5.81 and 4.96 ppm completely disappeared while the internal olefin signals at 5.37 ppm were visible, indicating the formation of high molecular weight polyesters. All the signals of ^{1}H NMR and ^{13}C NMR spectra were consistent with the expected structure of **P2**. Moreover, the MALDI-TOF-MS spectrum of **P1** displays two series of peaks,

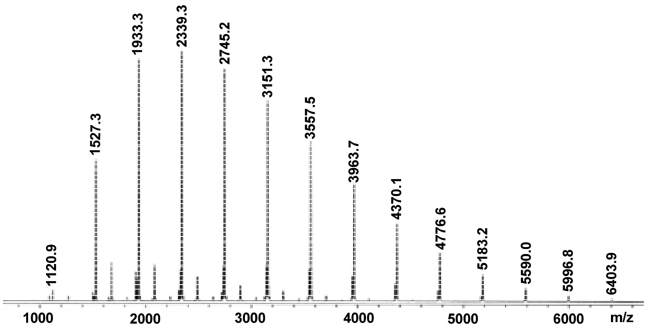


Figure 2. MALDI-TOF-MS spectrum of **P1**.

both separated by intervals of 406 Da, which is consistent with the molar mass of the repeating unit of **P1** (406.3 Da). The appearance of two series of peaks was due to the side reactions happened to the terminal olefins connected with G-I.[76] The molecular weight measured by MALDI-TOF-MS is much lower than that measured by GPC owing to the mass discrimination effect of MALDI-TOF-MS.[77,78] In conclusion, high molecular weight PEIA was obtained by the ADMET polymerization of DUI, and its structure was clearly confirmed.

Postpolymerization Modification. Michael addition reactions of mercaptans or amines with vinyl groups of (meth)acrylates have been widely used in polymer science due to their mild conditions and high efficiency.[50,79−82] Reaction conditions such as solvent, catalyst, and reactant reactivity have been intensively studied.[83−85] Generally, Michael addition reactions are favored in highly polar solvents. Mercaptans as more nucleophilic reactants exhibit higher reactivity than primary amines. For amines, secondary cyclic aliphatic amines like morpholine and **PI** are more reactive than primary amines and other secondary amines due to their smaller steric hindrance and higher nucleophilicity. Therefore, we chose **PI** and three mercaptans (DM, MP, and BM) for the modification of **P1** through Michael addition reaction.

We first carried out the modification of **P1** with DM in THF/CH_3OH (v/v = 3/2) at room temperature. The mixed solvent was chosen because THF is a good solvent for **P1** while CH_3OH is a highly polar solvent. The molar ratio of [mercaptan]/[TEA]/[itaconate vinyl groups] was 15/15/1. The corresponding product **P1-DM** was obtained after 20 h and characterized by ^{1}H NMR, ^{13}C NMR (Figure 3), and GPC (Figure S4). ^{1}H NMR signals at 5.69 and 6.31 ppm due to the itaconate vinyl groups completely disappeared; meanwhile, signals of the methylene groups adjacent to the itaconate vinyl groups shifted from 3.33 to 2.52−2.81 ppm. Collectively, these results suggested the quantitative modification of the itaconate vinyl groups. The ^{13}C NMR spectrum further confirmed the structure of **P1-DM**. The M_n value of **P1-DM** (26 500 Da) measured by GPC was slightly higher than that of **P1**, which could be ascribed to the addition of new components to **P1** and one more precipitation process. When the modification was conducted with the same molar ratio in THF at room temperature for 20 h, the modification ratio of the itaconate vinyl groups was only 30%, which was calculated based on the area integration ratio of the ^{1}H NMR signals attributed to the methylene groups (4.06−4.16 ppm) and the residual itaconate vinyl groups (5.69 and 6.31 ppm). When the molar ratio of [mercaptan]/[TEA]/[itaconate vinyl groups] was lowered to 3/3/1, the reaction became much slower with only 30% of the itaconate vinyl groups being modified in the mixed solvent after 20 h. Therefore, modifications of **P1** with MP and BM were conducted in the same mixed solvent with a reactant molar ratio of 15/15/1. Again, the corresponding products, **P1-MP** and **P1-BM** were confirmed by ^{1}H NMR, ^{13}C NMR (Figure S5), and GPC (Figure S4).

In the case of the modification with **PI**, the Michael addition reaction can be autocatalyzed; thus, no other organic base was needed. The reactant molar ratio was also 15/1. Quantitative modification was achieved in THF after 20 h, indicating a much higher reactivity of PI than that of DM. Structure of **P1-PI** was also confirmed by ^{1}H NMR, ^{13}C NMR (Figure 3), and GPC (Figure S4).

On the basis of the large difference in reactivity between **PI** and mercaptans toward Michael addition reactions, we carried out a one-pot sequential modification of **P1** (Scheme 2). First, modification with MP was performed using a molar ratio of 3/3/1 in the same mixed solvent for 15 h (offering **P1-MP′** with a

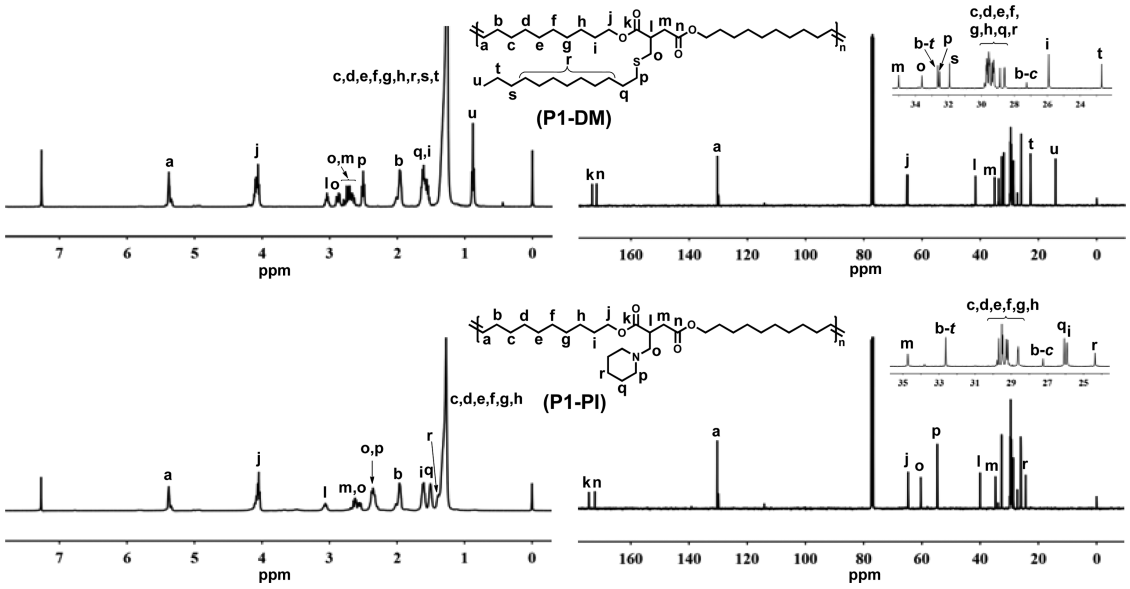
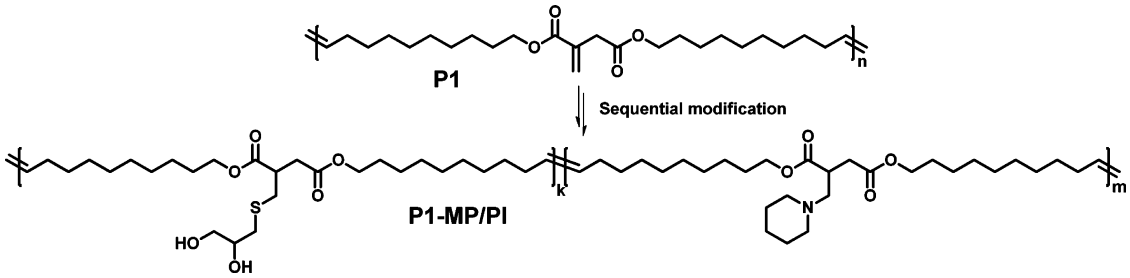
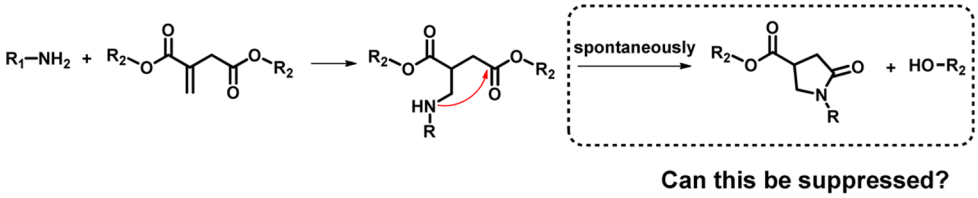


Figure 3. ^{1}H and ^{13}C NMR spectra of **P1-DM** and **P1-PI** in $CDCl_3$.

Scheme 2. Sequential Modification of P1 with MP and PI



Scheme 3. Reaction of Primary Amine with Itaconate To Form a Five-Membered Lactam



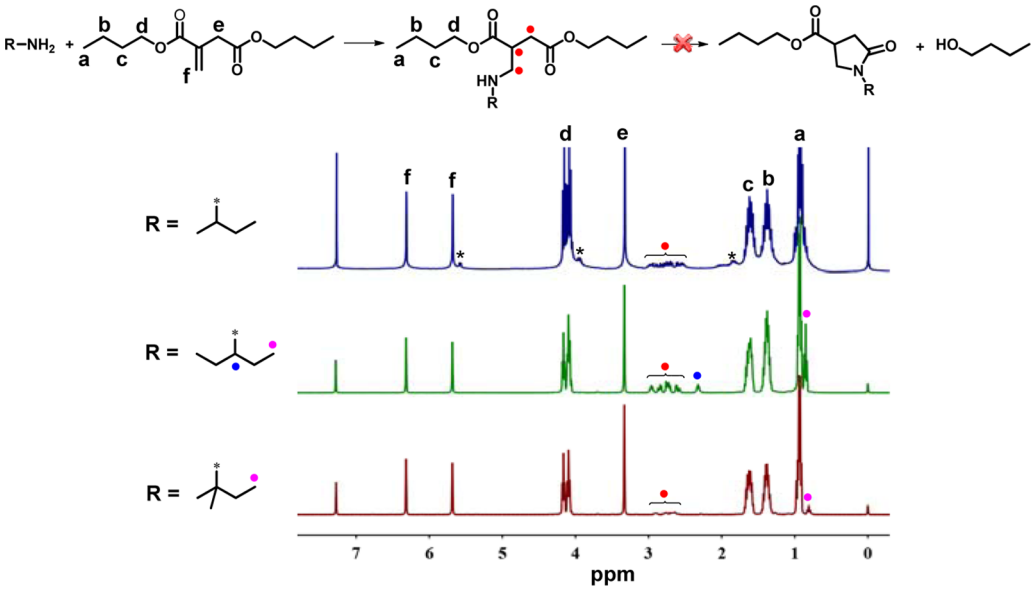


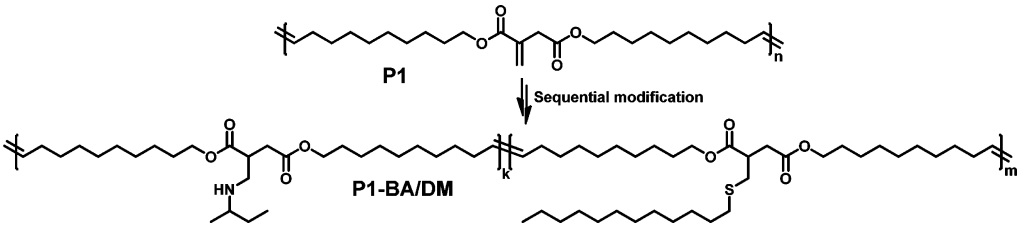
Figure 4. Model reactions of primary amines with dibutyl itaconate in THF/CH_3OH = 3/2 at 0 °C and the ^{1}H NMR spectra of the corresponding products (*: signals due to the side reaction of *sec*-butylamine).

modification ratio of 31%, Figure S6); then 12 equiv of PI was added into the mixture. The reaction was continued for another 3 h. Quantitative modification of the remaining itaconate vinyl groups was demonstrated by the ^{1}H NMR spectrum of the product **P1-MP/PI** (Figure S7). The modification ratio of **P1-MP/PI** by MP was 32%, which was calculated based on the area integration ratio of the signals at 3.55 ppm (MP) and 2.35 ppm (PI). This was almost identical to that of **P1-MP′**, thus indicating that almost no MP participated in the Michael addition reaction after PI was added. The above results demonstrated that this one-pot sequential postpolymerization modification procedure can be used for the synthesis of polyester with prescribed modification ratios of mercaptans and secondary cyclic aliphatic amines.

Thermal Properties of the Modified Polyesters. For **P1** and **P2**, cross-linking occurred at high temperature. Thus, it is impossible to investigate their thermal properties. Thermal stabilities of all the modified polyesters were examined by TGA. All the TGA curves are shown in Figure S8, and the corresponding T_ds are summarized in Table 1. Polyesters modified by three mercaptans (**P1-MP**, **P1-DM**, and **P1-BM**) displayed decomposition temperatures between 320 and 350 °C attributed to the pyrolysis of the polyester backbones. For **P1-PI** and **P1-MP/PI**, their TGA curves displayed a two-stage weight loss. The first stage covering a temperature range from 200 to 300 °C was caused by the loss of **PI**. This was confirmed by the fact that the percentages weight loss of the first stage (17.0% and 11.1% for **P1-PI** and **P1-MP/PI**, respectively) were in good agreement with the calculated **PI** contents (17.3% and 11.4% for **P1-PI** and **P1-MP/PI**, respectively). Temperatures of the second stage were slightly higher than the decomposition temperatures of **P1-MP**, **P1-DM**, and **P1-BM.** Cross-linking of the polymers after the loss of PI may account for this.

Glass transition and melting behavior of the modified polyesters were investigated by DSC (Table 1 and Figure S8). As shown in the DSC traces, all these modified polyesters

Scheme 4. Synthesis of a Secondary Amine Functionalized PEIA



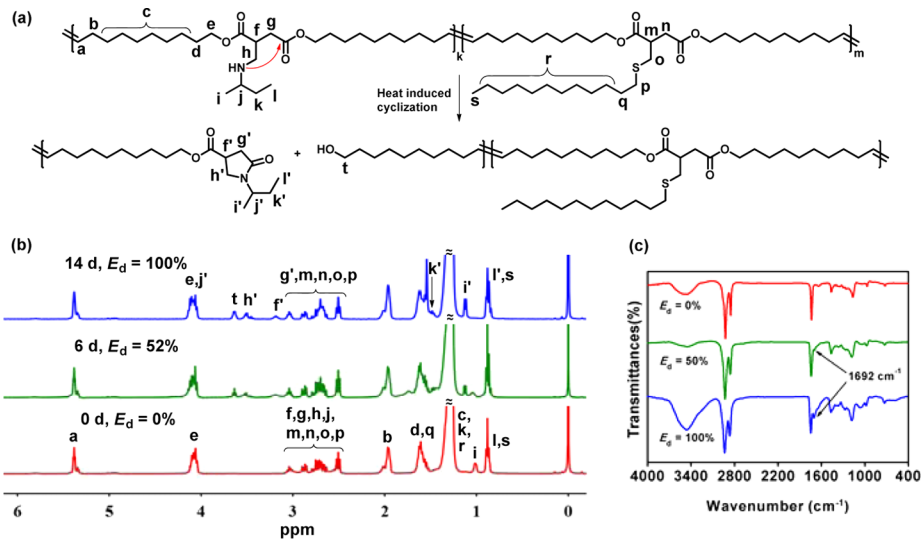


Figure 5. (a) Degradation mechanism of **P1-BA/DM**. (b) ^{1}H NMR and (c) FTIR spectra of **P1-BA/DM** and its degradation products at 37 °C in bulk.

are semicrystalline with T_gs ranging from −50 to −15 °C and T_ms ranging from −10.8 to 31.1 °C. The T_ms of these modified polyesters are much lower than those of the reported unsaturated polyesters with similar backbone but without any side groups (around 70 °C) mainly due to the introduced side groups.[86,87] Another reason is probably the asymmetry of the repeating unit. Generally, polyesters with more rigid side groups had lower melting temperatures, since these rigid groups may disrupt the backbone packing. The T_m of **P1-MP** is much higher than those of the others, probably because hydrogen bond among the hydroxyl groups facilitated the crystallization of the polymer main chain.

Synthesis and Degradation of the Secondary Amine Functionalized PEIA. It is reported that when a primary amine was used for the Michael addition reaction with itaconates, the newly generated secondary amine could undergo spontaneous intramolecular cyclization to form a five-membered lactam as shown in Scheme 3.[88−90]

Similarly, we proposed that postmodification of PEIA with primary amines will lead to the degradation of the polyester via intrachain cyclization. Therefore, it is natural to ask whether this procedure can be a controllable process, meaning that the intramolecular cyclization does not happen under certain postpolymerization modification conditions, but can be activated by changing to other conditions. If it works, this would be a novel methodology to transform PEIA into a new type of polyesters with controllable degradability. In this context, the work reported by Valentin et al. inspired us.[89] When they used isopropylamine instead of ethylamine for the Michael addition reaction with dimethyl itaconate in methanol at 0 °C, an open-chain adduct was obtained in an equal molar amount to the intramolecular cyclization product, indicating that a highly sterically hindered amine can suppress the intramolecular cyclization at low temperature. Furthermore, shorter reaction time and less polar solvent may further inhibit the intramolecular cyclization.

We first carried out model Michael addition reactions of commercially available dibutyl itaconate with *sec*-butylamine, 3-pentanamine, and *tert*-pentylamine. These three primary amines all have larger steric hindrance than isopropylamine (Figure 4). The reactions in THF and mixed solvent (THF/CH_3OH (v/v = 3/2)) at different temperatures were investigated. The molar ratio of the primary amine to dibutyl itaconate was fixed at 1/1. The reaction was monitored by ^{1}H NMR spectroscopy.

The modification ratio of the itaconate vinyl groups was calculated based on the area integration ratio of the ^{1}H NMR signals attributed to the methylene groups (1.65 ppm) and the residual itaconate vinyl groups (6.3 ppm). For *sec*-butylamine, almost no reaction occurred in THF at 0 °C after 36 h. Raising the temperature to 30 °C led to a 10% modification ratio after 36 h (Figure S9). Meanwhile, no signals in the ^{1}H NMR spectrum due to the intramolecular cyclization were observed. Extending the reaction time to 5 days resulted in a modification ratio of 60%, but intramolecular cyclization also occurred due to the high temperature and long time (Figure S9). In the mixed solvent, the modification ratio of dibutyl itaconate with *sec*-butylamine was increased to 30% without intramolecular cyclization at 0 °C after 16 h (Figure 4). Further increasing the reaction time to 40 h led to a higher modification ratio (50%) together with minimal unwanted intramolecular cyclization (Figure S10). Model reactions of 3-pentanamine and *tert*-

pentylamine were also conducted in the mixed solvent at 0 °C. For 3-pentanamine, a modification ratio of 31% can be achieved without intramolecular cyclization after 64 h (Figure 4). Further increasing the reaction time also led to detectable intramolecular cyclization (Figure S11). In the case of *tert*-pentylamine, a modification ratio of only 10% was achieved in 64 h (Figure 4), indicating a much lower reactivity of *tert*-pentylamine than those of 3-pentanamine and *sec*-butylamine due to its much larger steric hindrance. Collectively, it can be concluded that controlled modification of the itaconate vinyl groups with *sec*-butylamine and 3-pentanamine without intramolecular cyclization can be realized in THF/CH_3OH (v/v = 3/2) at 0 °C when the modification ratio of the itaconate vinyl groups was limited to about 30%.

Based on the above results, modification of **P1** with *sec*-butylamine was conducted in THF/CH_3OH (v/v = 3/2) at 0 °C (Scheme 4). Since the itaconate vinyl groups in the polymer backbone may be less reactive than that in small molecules, 15 equiv of *sec*-butylamine was used. The modified polyesters obtained by precipitation were characterized by ^{1}H NMR (Figure 5, Figures S12 and S14) and GPC (Figure S13). The modification ratio of the itaconate vinyl groups was determined based on the area integration ratio of ^{1}H NMR signals attributed to the methyl groups close to the secondary amino group (0.99 ppm) and the C═C bonds in the backbone (5.32−5.41 ppm) (Figure S12). A modification ratio of 29% was achieved after 14 h (the corresponding polyester was denoted as **P1-BA**). The M_n measured by GPC was 19 900 Da (Figure S13), which was slightly lower than that of **P1**, probably due to the change of hydrodynamic radius. When the reaction time was increased to 60 h, the modification ratio was increased to 60% (**P1-BA′**) (Figure S14). However, a notable intramolecular cyclization occurred as evidenced by both ^{1}H NMR spectrum and GPC measurement (M_n decreased to 8000 Da) (Figure S13). Therefore, to avoid any intramolecular cyclization, the reaction time was fixed at 14 h. The remaining itaconate vinyl groups of **P1-BA** was further modified by adding 15 equiv of DM into the reaction mixture and continuing the reaction for 1.5 h at 0 °C in one pot. For this sequentially modified polyester, **P1-BA/DM**, the peaks at 5.69 and 6.31 ppm in the ^{1}H NMR spectrum disappeared (Figure 5b), demonstrating a complete modification of all the remaining itaconate vinyl groups with DM within 1.5 h. Though most of the ^{1}H NMR signals related to the modification with *sec*-butylamine and DM overlapped at 2.49−3.00, 1.24−1.38, and 0.86 ppm, signals at 0.99 ppm attributed to the methyl group close to the secondary amine groups demonstrated the successful modification with *sec*-butylamine. In addition, owing to the much higher reactivity of DM than that of *sec*-butylamine, **P1-BA/DM** displayed a similar modification ratio (30%) by *sec*-butylamine to that of **P1-BA** (29%). More importantly, no signals due to intramolecular cyclization appeared. The M_n of **P1-BA/DM** (22 000 Da) was higher than that of **P1-BA** attributed to the addition of DM. Therefore, it can be concluded that spontaneous intramolecular cyclization was successfully suppressed by modifying **P1** with *sec*-butylamine in THF/CH_3OH (v/v = 3/2) at 0 °C. The resulting **P1-BA/DM** as a secondary amine functionalized PEIA is stable in its hydrochloride form and will show unique self-degradable properties in its free base form.

The self-degradation behavior of **P1-BA/DM** in bulk and solution was then investigated. The degradation process was monitored by ^{1}H NMR, GPC, and FTIR measurements (Figure 5 and Figures S15−S21). Take the degradation of **P1-BA/DM** at 37 °C in bulk as an example. Figure 5 shows the ^{1}H NMR and FTIR spectra of **P1-BA/DM** and its degradation products. The methyl signal at 0.99 ppm gradually shifted to 1.11 ppm; signals attributed to the newly generated five-membered lactam were observed at 1.48, 3.19, and 3.50 ppm. In addition, a triplet peak attributed to the methylene groups adjacent to the hydroxyl groups appeared at 3.64 ppm. The cyclization percentage of the amino groups calculated by the area integration ratio of peak i and i′ was defined as the extent of degradation (E_d). Formation of the five-membered lactam was further confirmed by FTIR measurement. Peaks at 1692 cm^{-1} in the FTIR spectrum (Figure 5c) was assigned to the C═O stretching vibration of the five-membered lactam.[89] The M_n of **P1-BA/DM** gradually decreased to about 3000 Da (Figure S16). Because of the random degradation, the M_n dramatically decreased from 22 000 to 15 500 Da even when the E_d was 26%. A low molecular weight (about 600 Da) peak was observed in most of the GPC traces (Figures S16 and S20) because the cyclization occurred in the random direction due to the asymmetric repeating units. It should be pointed out that no degradation of **P1-BA/DM** occurred at −20 °C within 2 weeks, while the E_d was 5% after 2 weeks at 0 °C (Figure S21). As expected, the bulk degradation was completed within 2 h at 150 °C (Figures S19 and S20).

The degradation of **P1-BA/DM** in CH_2Cl_2 and THF was also monitored by ^{1}H NMR at 37 °C. The degradation mechanism was identical to that in bulk but with higher degradation rates. To compare the degradation rates under different conditions, the kinetics of degradation is shown in Figure 6. Complete degradation of **P1-BA/DM** in bulk, CH_2Cl_2, and THF took 14, 11, and 6 days, respectively. The degradation in solution was faster than that in bulk due to the easier movement of the polymer chains in solution at the same temperature. The degradation in THF was faster than that in CH_2Cl_2, as THF is more polar than CH_2Cl_2.

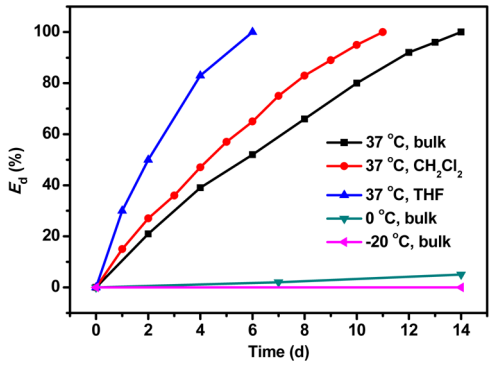


Figure 6. Kinetics of **P1-BA/DM** degradation under various conditions.

■ CONCLUSION

We have demonstrated a facile strategy for the synthesis and functionalization of high molecular weight PEIA. This approach has several features. First, the two monomers, IA and 10-undecenol, are entirely derived from renewable resources. Second, the itaconate vinyl groups can tolerate the ADMET polymerization and are preserved in the resulting PEIAs. Third, the itaconate vinyl groups in the PEIA can be selectively modified by Michael addition reactions with three mercaptans

and PI. Sequential modification with PI and MP is also successful due to their large difference in reactivity. The modified polyesters are semicrystalline polymers with distinctive T_ms, and those with more rigid side groups possess lower T_ms. Finally, a new type of secondary amine functionalized polyester is synthesized using *sec*-butylamine as a suitable sterically hindered primary amine for the Michael addition reaction. This polymer is stable at low temperature but exhibits controlled self-degradation behavior by intramolecular cyclization at high temperature. The degradation in solution is faster than that in bulk; highly polar solvent can accelerate the intramolecular cyclization. This new kind of self-degradable polyester may find potential applications in biomedical fields. Therefore, this work not only provides a facile strategy toward high molecular weight PEIA from renewable resources but also shows the importance of postpolymerization modification to tune the thermal property, degradation of the polyesters.

■ ASSOCIATED CONTENT

Supporting Information

NMR and IR spectra, GPC traces, and TGA curves. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Gross, R. A.; Kalra, B. *Science* **2002**, *297*, 803−807.
(2) Gandini, A. *Macromolecules* **2008**, *41*, 9491−9504.
(3) Williams, C. K. *Chem. Soc. Rev.* **2007**, *36*, 1573−1580.
(4) Williams, C. K.; Hillmyer, M. A. *Polym. Rev.* **2008**, *48*, 1−10.
(5) Nair, L. S.; Laurencin, C. T. *Prog. Polym. Sci.* **2007**, *32*, 762−798.
(6) Biermann, U.; Bornscheuer, U.; Meier, M. A. R.; Metzger, J. O.; Schäfer, H. J. *Angew. Chem., Int. Ed.* **2011**, *50*, 3854−3871.
(7) Hillmyer, M. A.; Tolman, W. B. *Acc. Chem. Res.* **2014**, *47*, 2390−2396.
(8) Maisonneuve, L.; Lebarbe, T.; Grau, E.; Cramail, H. *Polym. Chem.* **2013**, *4*, 5472−5517.
(9) Miller, S. A. *ACS Macro Lett.* **2013**, *2*, 550−554.
(10) Tschan, M. J. L.; Brule, E.; Haquette, P.; Thomas, C. M. *Polym. Chem.* **2012**, *3*, 836−851.
(11) Yao, K.; Tang, C. *Macromolecules* **2013**, *46*, 1689−1712.
(12) Belgacem, M. N.; Gandini, A. *Monomers, Polymers and Composites from Renewable Resources*; Elsevier: Amsterdam, 2008.
(13) Pfeifer, V. F.; Vojnovich, C.; Heger, E. N. *Ind. Eng. Chem.* **1952**, *44*, 2975−2980.
(14) Horitsu, H.; Takahashi, Y.; Tsuda, J.; Kawai, K.; Kawano, Y. *J. Appl. Microbiol. Biotechnol.* **1983**, *18*, 358−360.
(15) Okabe, M.; Lies, D.; Kanamasa, S.; Park, E. Y. *Appl. Microbiol. Biotechnol.* **2009**, *84*, 597−606.
(16) Orts, W. J.; Holtman, K. M.; Seiber, J. N. *J. Agric. Food. Chem.* **2008**, *56*, 3892−3899.
(17) Wang, R.; Ma, J.; Zhou, X.; Wang, Z.; Kang, H.; Zhang, L.; Hua, K. C.; Kulig, J. *Macromolecules* **2012**, *45*, 6830−6839.
(18) Arrighi, V.; Mcewen, I. J.; Holmes, P. F. *Macromolecules* **2004**, *37*, 6210−6218.
(19) Arrighi, V.; Triolo, A.; Mcewen, I. J.; Holmes, P.; Triolo, R.; Amenitsch, H. *Macromolecules* **2000**, *33*, 4989−4991.
(20) Cowie, J. M. G.; Henshall, S. A. E.; Mcewen, I. J.; Velickovic, J. *Polymer* **1977**, *18*, 612−616.
(21) Satoh, K.; Lee, D. H.; Nagai, K.; Kamigaito, M. *Macromol. Rapid Commun.* **2014**, *35*, 161−167.
(22) Barrett, D. G.; Merkel, T. J.; Luft, J. C.; Yousaf, M. N. *Macromolecules* **2010**, *43*, 9660−9667.
(23) Naves, A. F.; Fernandes, H. T. C.; Immich, A. P. S.; Catalani, L. H. *J. Polym. Sci., Part A: Polym. Chem.* **2013**, *51*, 3881−3891.
(24) Goerz, O.; Ritter, H. *Polym. Int.* **2013**, *62*, 709−712.
(25) Ma, S.; Liu, X.; Jiang, Y.; Tang, Z.; Zhang, C.; Zhu, J. *Green Chem.* **2013**, *15*, 245−254.
(26) Vert, M. *Biomacromolecules* **2005**, *6*, 538−546.
(27) Seyednejad, H.; Ghassemi, A. H.; Van Nostrum, C. F.; Vermonden, T.; Hennink, W. E. *J. Controlled Release* **2011**, *152*, 168−176.
(28) Coulembier, O.; Degee, P.; Hedrick, J. L.; Dubois, P. *Prog. Polym. Sci.* **2006**, *31*, 723−747.
(29) Albertsson, A. C.; Varma, I. K. *Biomacromolecules* **2003**, *4*, 1466−1486.
(30) Place, E. S.; George, J. H.; Williams, C. K.; Stevens, M. M. *Chem. Soc. Rev.* **2009**, *38*, 1139−1151.
(31) Uhrich, K. E.; Cannizzaro, S. M.; Langer, R. S.; Shakesheff, K. M. *Chem. Rev.* **1999**, *99*, 3181−3198.
(32) Quinzler, D.; Mecking, S. *Angew. Chem., Int. Ed.* **2010**, *49*, 4306−4308.
(33) Ortmann, P.; Mecking, S. *Macromolecules* **2013**, *46*, 7213−7218.
(34) Montero De Espinosa, L.; Meier, M. A. R. *Chem. Commun.* **2011**, *47*, 1908−1910.
(35) Warwel, S.; Tillack, J.; Demes, C.; Kunz, M. *Macromol. Chem. Phys.* **2001**, *202*, 1114−1121.
(36) van der Meulen, I.; Gubbels, E.; Huijser, S.; Sablong, R.; Koning, C. E.; Heise, A.; Duchateau, R. *Macromolecules* **2011**, *44*, 4301−4305.
(37) Bouyahyi, M.; Pepels, M. P. F.; Heise, A.; Duchateau, R. *Macromolecules* **2012**, *45*, 3356−3366.
(38) Pepels, M. P. F.; Bouyahyi, M.; Heise, A.; Duchateau, R. *Macromolecules* **2013**, *46*, 4324−4334.
(39) Peng, Y.; Decatur, J.; Meier, M. A. R.; Gross, R. A. *Macromolecules* **2013**, *46*, 3293−3300.
(40) Bouyahyi, M.; Duchateau, R. *Macromolecules* **2014**, *47*, 517−524.
(41) Pascual, A.; Sardon, H.; Veloso, A.; Ruipérez, F.; Mecerreyes, D. *ACS Macro Lett.* **2014**, *3*, 849−853.
(42) Vilela, C.; Sousa, A. F.; Fonseca, A. C.; Serra, A. C.; Coelho, J. F. J.; Freire, C. S. R.; Silvestre, A. J. D. *Polym. Chem.* **2014**, *5*, 3119−3141.
(43) Chikkali, S.; Mecking, S. *Angew. Chem., Int. Ed.* **2012**, *51*, 5802−5808.
(44) Tueruenc, O.; De Espinosa, L. M.; Meier, M. A. R. *Macromol. Rapid Commun.* **2011**, *32*, 1357−1361.
(45) Pounder, R. J.; Dove, A. P. *Polym. Chem.* **2010**, *1*, 260−271.
(46) Jérôme, C.; Lecomte, P. *Adv. Drug Delivery Rev.* **2008**, *60*, 1056−1076.
(47) Lecomte, P.; Riva, R.; Jerome, C.; Jerome, R. *Macromol. Rapid Commun.* **2008**, *29*, 982−997.
(48) Albertsson, A. C.; Varma, I. K. *Adv. Polym. Sci.* **2002**, *157*, 1−40.
(49) Metzke, M.; Bai, J. Z.; Guan, Z. B. *J. Am. Chem. Soc.* **2003**, *125*, 7760−7761.
(50) Ji, S.; Bruchmann, B.; Klok, H. A. *Macromolecules* **2011**, *44*, 5218−5226.
(51) Peng, C.; Joy, A. *Macromolecules* **2014**, *47*, 1258−1268.
(52) Mejia, J. S.; Gillies, E. R. *Polym. Chem.* **2013**, *4*, 1969−1982.
(53) Lux, C. D. G.; Almutairi, A. *ACS Macro Lett.* **2013**, *2*, 432−435.
(54) Lux, C. D. G.; Olejniczak, J.; Fomina, N.; Viger, M. L.; Almutairi, A. *J. Polym. Sci., Part A: Polym. Chem.* **2013**, *51*, 3783−3790.
(55) Opper, K. L.; Wagener, K. B. *J. Polym. Sci., Part A: Polym. Chem.* **2011**, *49*, 821−831.

(56) Atallah, P.; Wagener, K. B.; Schulz, M. D. *Macromolecules* **2013**, *46*, 4735−4741.
(57) Lindmark-Hamberg, M.; Wagener, K. B. *Macromolecules* **1987**, *20*, 2949−2951.
(58) Mutlu, H.; De Espinosa, L. M.; Meier, M. A. R. *Chem. Soc. Rev.* **2011**, *40*, 1404−1445.
(59) Baughman, T. W.; Wagener, K. B. *Adv. Polym. Sci.* **2005**, *176*, 1−42.
(60) Li, Z. L.; Li, L.; Deng, X. X.; Lv, A.; Wang, C. H.; Du, F. S.; Li, Z. C. *J. Polym. Sci., Part A: Polym. Chem.* **2013**, *51*, 2900−2909.
(61) Li, Z. L.; Li, L.; Deng, X. X.; Zhang, L. J.; Dong, B. T.; Du, F. S.; Li, Z. C. *Macromolecules* **2012**, *45*, 4590−4598.
(62) Li, Z. L.; Li, L.; Du, F. S.; Li, Z. C. *Chin. J. Polym. Sci.* **2013**, *31*, 355−362.
(63) Li, Z. L.; Lv, A.; Li, L.; Deng, X. X.; Zhang, L. J.; Du, F. S.; Li, Z. C. *Polymer* **2013**, *54*, 3841−3849.
(64) Li, Z. L.; Lv, A.; Du, F. S.; Li, Z. C. *Macromolecules* **2014**, *47*, 5942−5951.
(65) Rybak, A.; Meier, M. A. R. *Green Chem.* **2007**, *9*, 1356−1361.
(66) Fokou, P. A.; Meier, M. A. R. *J. Am. Chem. Soc.* **2009**, *131*, 1664−1665.
(67) Stempfle, F.; Ortmann, P.; Mecking, S. *Macromol. Rapid Commun.* **2013**, *34*, 47−50.
(68) Kreye, O.; Toth, T.; Meier, M. A. R. *J. Am. Chem. Soc.* **2011**, *133*, 1790−1792.
(69) Ortmann, P.; Heckler, I.; Mecking, S. *Green Chem.* **2014**, *16*, 1816−1827.
(70) Qin, Y.; Hillmyer, M. A. *Macromolecules* **2009**, *42*, 6429−6432.
(71) Speros, J. C.; Paulsen, B. D.; White, S. P.; Wu, Y.; Jackson, E. A.; Slowinski, B. S.; Frisbie, C. D.; Hillmyer, M. A. *Macromolecules* **2012**, *45*, 2190−2199.
(72) Chatterjee, A. K.; Choi, T. L.; Sanders, D. P.; Grubbs, R. H. *J. Am. Chem. Soc.* **2003**, *125*, 11360−11370.
(73) Chatterjee, A. K.; Grubbs, R. H. *Org. Lett.* **1999**, *1*, 1751−1753.
(74) Abramova, N.; Bratov, A.; Ipatov, A.; Levichev, S.; Aris, A.; Rodriguez, E. M. *Talanta* **2013**, *113*, 31−35.
(75) Petkovska, V. I.; Hopkins, T. E.; Powell, D. H.; Wagener, K. B. *Macromolecules* **2005**, *38*, 5878−5885.
(76) Ulman, M.; Grubbs, R. H. *J. Org. Chem.* **1999**, *64*, 7202−7207.
(77) Schriemer, D. C.; Li, L. *Anal. Chem.* **1997**, *69*, 4169−4175.
(78) Schriemer, D. C.; Li, L. *Anal. Chem.* **1997**, *69*, 4176−4183.
(79) Mather, B. D.; Viswanathan, K.; Miller, K. M.; Long, T. E. *Prog. Polym. Sci.* **2006**, *31*, 487−531.
(80) Ma, X.; Tang, J.; Shen, Y.; Fan, M.; Tang, H.; Radosz, M. *J. Am. Chem. Soc.* **2009**, *131*, 14795−14803.
(81) Song, C. C.; Ji, R.; Du, F. S.; Li, Z. C. *Macromolecules* **2013**, *46*, 8416−8425.
(82) Nair, D. P.; Podgorski, M.; Chatani, S.; Gong, T.; Xi, W.; Fenoli, C. R.; Bowman, C. N. *Chem. Mater.* **2014**, *26*, 724−744.
(83) Wu, D. C.; Liu, Y.; He, C. B.; Chung, T. S.; Goh, S. T. *Macromolecules* **2004**, *37*, 6763−6770.
(84) Li, G. Z.; Randev, R. K.; Soeriyadi, A. H.; Rees, G.; Boyer, C.; Tong, Z.; Davis, T. P.; Becer, C. R.; Haddleton, D. M. *Polym. Chem.* **2010**, *1*, 1196−1204.
(85) Chan, J. W.; Hoyle, C. E.; Lowe, A. B.; Bowman, M. *Macromolecules* **2010**, *43*, 6381−6388.
(86) Bauch, C. G.; Wagener, K. B.; Boncella, J. M. *Makromol. Chem., Rapid Commun.* **1991**, *12*, 413−417.
(87) Warwel, S.; Tillack, J.; Demes, C.; Kunz, M. *Macromol. Chem. Phys.* **2001**, *202*, 1114−1121.
(88) Culbertson, T. P.; Domagala, J. M.; Nichols, J. B.; Priebe, S.; Skeean, R. W. *J. Med. Chem.* **1987**, *30*, 1711−1715.
(89) Felluga, F.; Pitacco, G.; Prodan, M.; Pricl, S.; Visintin, M.; Valentin, E. *Tetrahedron: Asymmetry* **2001**, *12*, 3241−3249.
(90) Kenda, B. M.; Matagne, A. C.; Talaga, P. E.; Pasau, P. M.; Differding, E.; Lallemand, B. I.; Frycia, A. M.; Moureau, F. G.; Klitgaard, H. V.; Gillard, M. R.; Fuks, B.; Michel, P. *J. Med. Chem.* **2004**, *47*, 530−549.