

Polymer Chemistry

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Defining Alternating Sequences in Polyurethanes: Sequence-Controlled Photo-Degradation in Step Polymerization

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Abstract

Programmable degradation is an important functionality for sustainable polymer materials; however, in conventional step polymerization of AA and BB type monomers, polymer sequence itself has long lacked a clear and actionable definition. Polymers synthesized from AA and BB type monomers enable the incorporation of functional units directly into the polymer main chain, while inevitably featuring AA–BB connectivity; yet the concept of an “alternating” sequence has remained ambiguous. To address this fundamental limitation, we redefine sequence control in step polymerization by focusing on the connectivity unit rather than monomer composition. Using polyurethane as a representative model polymer, an AB-type monomer framework combined with dimeric species enables the explicit definition and practical implementation of (partially) alternating sequences. Incorporation of a photo-degradable monomer unit directly into the polymer backbone reveals pronounced sequence-dependent photo-degradability via main chain scission, which is drastically enhanced in alternating polymers, while thermal properties are likewise strongly influenced by polymer sequence. This work establishes polymer sequence as an additional and actionable design parameter in polyurethane as an example of step polymerization and provides a conceptual framework potentially applicable beyond polyurethanes to a broad range of AA/BB-based polymers. The utility of this framework for functional material development is demonstrated through sequence-controlled photo-degradation on the polymer main chain, offering a promising strategy toward sustainable polymer design.

Introduction

Controlling polymer sequence is a fundamental challenge in polymer synthesis, essential both for

understanding polymer primary structures and for enabling precise material design through tuning of properties such as degradability, recyclability, and mechanical performance. ^[1-30] Accordingly, extensive efforts have been devoted to achieve increasingly sophisticated sequence control across diverse polymer classes. However, these developments have been concentrated on chain polymerization processes, such as vinyl polymerization, where the concept of sequence is inherently well-defined, and functional units are typically incorporated on polymer side chain.

In contrast, step polymerization — despite its central importance in both academic and industrial polymer chemistry — has received limited attention from the perspective of sequence definition and control. Yet, many technologically relevant polymers, including polyesters, polyamides, polycarbonates, and polyurethanes (PUs), are synthesized via step-growth mechanisms. In these systems, typical polymers prepared from AA- and BB-type monomers inevitably exhibit AA–BB connectivity along the backbone. As a result, the concept of polymer sequence itself—and in particular the meaning of an “alternating” sequence—remains ambiguous. This conceptual ambiguity has hindered systematic investigations of sequence–property relationships in polymers obtained by step polymerization, in sharp contrast to the well-established framework available for chain polymerizations. While various advanced polymerization methods based on step polymerization have been developed, these approaches have largely focused on molecular weight control, leaving polymer sequence inherently ambiguous. ^[31-37] Because functional units are incorporated into the polymer main chain, sequence control in step polymerization provides a powerful tool for designing backbone-functional materials such as degradable polymers.



PU serves as a representative and industrially significant example of this issue. [38-56] Conventionally, PUs are synthesized via highly efficient polyaddition reactions between diols and di-isocyanates (**Figure 1A**), allowing broad compositional flexibility and facile tuning of material properties ranging from soft elastomers to rigid coatings. Owing to their practical utility, most PU research has focused on formulation-driven material development rather than on precise control of polymer primary structure. Nevertheless, it is evident that the positioning of urethane bonds and comonomer units along the polymer backbone critically influences thermal, mechanical, and functional properties, underscoring the importance of sequence control. However, conventional AA/BB-type polyaddition intrinsically lacks a framework to define or implement distinct sequence motifs, such as alternating arrangements, within PU backbones (**Figure 1A**).

To address sequence control beyond conventional step polymerizations, alternative PU production strategies have been explored. These include (i) ring-opening polymerization (ROP) of cyclic urethane monomers via chain-growth mechanisms and (ii) iterative one-by-one monomer addition to produce sequence-defined oligomers or polymers. [57-68] While these approaches have successfully enabled advanced structural control, they are associated with substantial synthetic cost and limited practicality. ROP approaches require multistep cyclic monomer synthesis and offer restricted structural diversity, whereas iterative synthesis suffers from high workload and typically limits accessible molecular weights around a few thousand g/mol or less. Consequently, a practical, scalable method that allows systematic sequence definition and control within the step polymerization framework remains highly desirable.

Recently, we introduced a facile PU synthesis strategy based on AB-type monomers, which provides a new platform to address this long-standing issue. [69-73] In this approach, monomers bearing both acylazide and alcohol functionalities undergo heat-induced Curtius rearrangement to generate isocyanates *in situ*, triggering self-polyaddition between the isocyanate and alcohol groups (**Figure 1B**). Because the acylazide functionality is inert toward alcohols prior to the Curtius rearrangement, polymerization is effectively gated, enabling controlled step polymerization from AB-type building blocks. Importantly, this strategy establishes a clear definition of polymer sequence in PUs, enabling the construction of diverse polymer architectures, including block, statistic (random), grafted, and alternating polymers (**Figure 1C**). The synthetic accessibility of AB-type monomers, readily derived from a diverse molecular pool of carboxylic acid

species bearing alcohol groups, further allows flexible molecular design and broad monomer scope.

Using this framework, we have demonstrated that copolymerization behavior is strongly influenced by monomer reactivity, leading to statistical sequence distributions in certain systems. As expected, monomers featuring primary alcohol groups afford PUs more rapidly than those bearing secondary alcohol groups, resulting in statistical rather than completely random sequence distributions during copolymerization. [69-73] Moreover, this approach has enabled the preparation of functional PU materials with advanced primary structure control including photo-degradable polymers. While earlier studies have reported PU synthesis from acyl azide-alcohol monomers, these efforts largely focused on homopolymer formation for bio-based materials or dendrimer synthesis, rather than on sequence definition or copolymerization. [74-77] Consequently, systematic implementation of alternating sequences within step polymerized PU backbones has remained unexplored.

Establishing a well-defined alternating sequence is particularly important for elucidating sequence-property relationships in step polymerizations. To clearly evaluate the impact of sequence control, alternating monomer pairs should ideally exhibit distinct chemical or physical characteristics that enable unambiguous structural and property differentiation. In this context, we previously developed a photo-degradable PU monomer **M1** featuring an *o*-nitrobenzyl alcohol (*o*-NBA) unit, which displayed a certain homo-diad preference during copolymerization (**Figure 2A**). [72] This uneven monomer distribution led to inefficient photo-degradation due to the formation of locally concentrated photo-cleavable segments. Introducing an alternating sequence represents a rational strategy to homogenize the distribution of photo-degradable units and thereby enhance degradation efficiency. Furthermore, alternating incorporation of rigid **M1** units with flexible comonomers, such as **M2** bearing a 2-ethylhexyl side chain, is expected to significantly influence the thermomechanical properties of the resulting polymers (**Figure 2B**). [73]

In this study, we define and implement alternating sequences within a step polymerization framework using polyurethane as a representative model system to achieve advanced photo-degradability control. While our previous statistical sequence system demonstrated that sequence could be discussed in AB-type polyurethane synthesis, it did not allow the explicit implementation of alternating connectivity; this limitation is addressed in this work through a dimer-based strategy. Such explicit alternating control is essential for examining sequence-property



relationships without ambiguity arising from statistical sequence distributions. A newly designed dimeric monomer **M3** is employed to introduce alternating connectivity in combination with AB-type monomers **M1/M2** (Figure 2B). The resulting polymers are systematically analyzed in terms of photo-degradability and thermal properties to elucidate the effects of the sequence control. As shown in this study, by redefining the connectivity unit through a combination of AB-type

monomers and a dimeric species, step polymerization is transformed from a process with an ambiguous sequence definition into a sequence-definable one. This work therefore establishes a conceptual and synthetic framework for defining and implementing alternating sequences in step polymerization, while sequence-dependent properties are examined as validation of its chemical and functional significance.

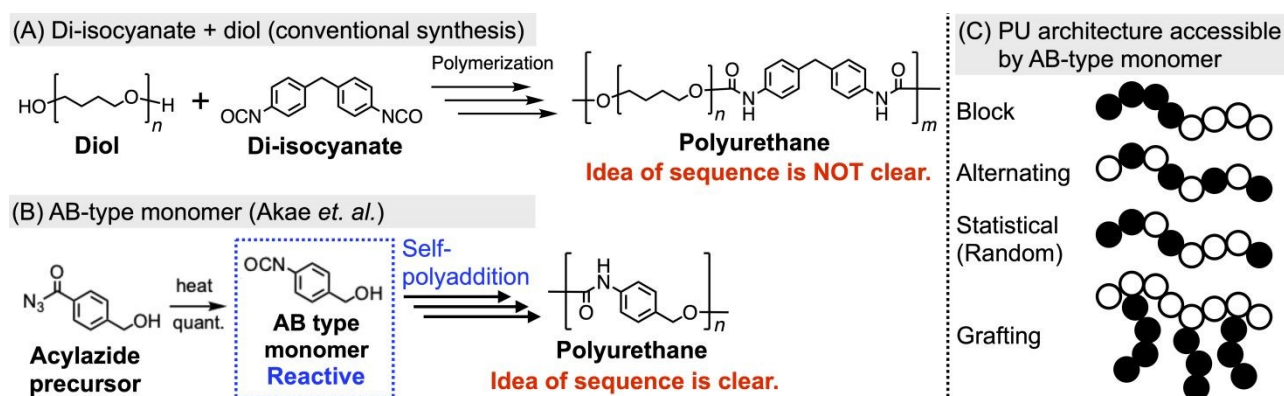


Figure 1. General concept of this work as illustrated using PU as a model system; (A) PU synthesis by the conventional method; (B) PU synthesis based on the AB-type monomer featuring both acylazide and alcohol groups; ^[69-73] (C) PU architectures accessible by AB-type monomer.

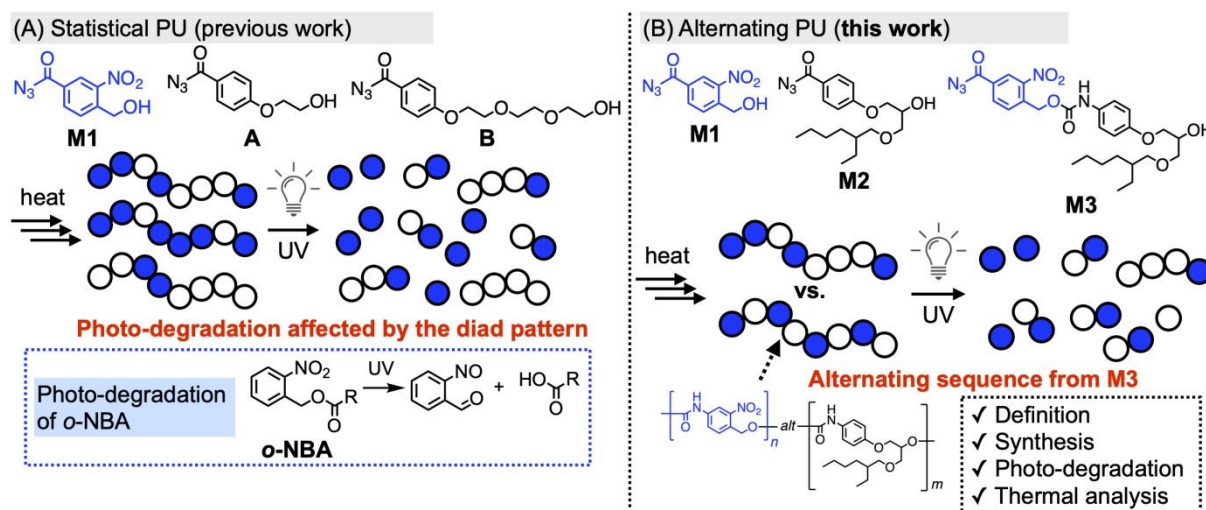


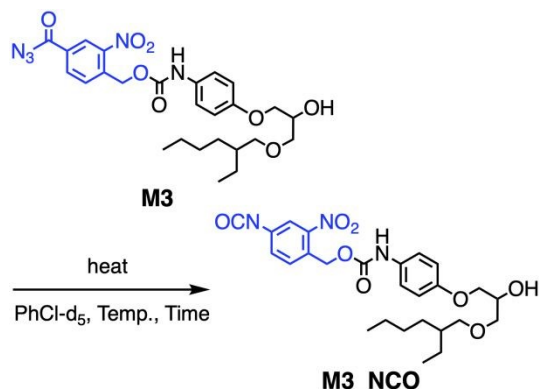
Figure 2. Conceptual overview of PU sequence control using photo-degradable monomer **M1** on (A) previous work showing statistical sequence distribution; ^[72] (B) this work enabling alternating sequence incorporation.



Results and Discussion

M1-M3 were all synthesized by following previously reported standard synthesis including the final step to convert a carboxylic acid group to an acylazide group by diphenyl phosphoryl azide (DPPA).^[69-73,78-83] Newly synthesized **M3** was obtained as a solid at room temperature as same as **M1**, while **M2** is liquid. According to previous results, liquid monomers typically show good polymerizability under bulk condition, while solid ones often need some solvent on the polymerization for supplying enough fluidity to the reaction mixture, but this issue is affected by the T_g/T_m of the corresponding polymers. Since polymerization behavior of **M1** and **M2** were already investigated by previous studies, that of **M3** is firstly evaluated.

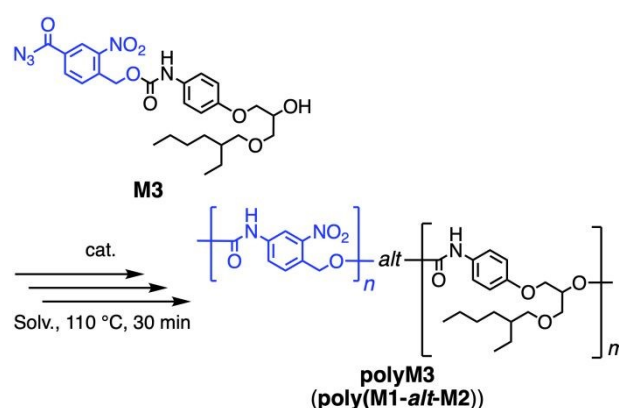
The kinetic analysis of the Curtius rearrangement of **M3** was studied by following previous reports (**Scheme 1**).^[69-73,83-86] Namely, **M3** was dissolved in PhCl-d₅ at 0.020 M concentration, and heated at 100 °C to induce the Curtius rearrangement. ¹H NMR measurement was conducted after 5, 10, and 15 min heat to estimate the time-course of the spectral integration for calculating the kinetic constant. The results are summarized in ESI, and obtained kinetic values are consistent with previous reports.^[69-73] Namely, the Curtius rearrangement reaches a quantitative conversion within 60 min at 100 °C, and 30 min at 110 °C, which will be used for the setup of polymerization condition.



Scheme 1. Curtius rearrangement of **M3**.

Next, to get the insight about the polymerization behavior of **M3**, its homopolymerization was conducted under standard four reaction conditions (**Scheme 2**, **Table 1**). Namely, the polymerization was carried out at 110 °C for 30 min under bulk or DMF (1.0 M) solvent, and under the existence of the dibutyltin di-laurate (DBTDL) catalyst or not, which was subsequently purified by the precipitation to cold MeOH. The SEC

profiles of products showed unimodal signals, while their ¹H NMR spectra clearly indicated the successful formation of **polyM3** (**Figure 4**, **5A**, and **5B**).^[83] Namely, ¹H NMR signals of the polymer became broader than the respective monomer signals, and each peak shift before and after the polymerization was consistent with previous reports,^[69-73] while the generation of the new urethane signal ϵ_1 at 10.4 ppm clearly indicated the occurrence of the polymerization. Comparing investigated four conditions (**Table 1**), the polymerization under bulk with the catalyst afforded the highest yield and the highest molecular weight (**polyM3a**, 59%, $M_n = 11$ kDa, $D = 1.6$), while other reaction conditions also successfully provided the desired polymer. Since the effective copolymerization condition among **M1/M2/M3** would depend on the comonomer combination, the observed applicability of **M3** on various polymerization conditions is useful. Although the polymerization under DMF solution condition without the catalyst resulted in low yield (27%), the corresponding homopolymerization of **M2** only afforded a trace amount of **polyM2**,^[73] suggesting the higher reactivity of **M3** than **M2**, and/or the lower solubility in precipitation solvent (cold MeOH) of **polyM3** framework than **polyM2**. Since **polyM3** is the equivalent structure to **poly(M1-*alt*-M2)**, PU featuring the alternating sequence was successfully synthesized by the step polymerization. For a clarification, “alternating sequence” means in this manuscript the strict alternating connection of **M1** and **M2** units provided by the dimeric monomer **M3**, distinguishing it from the inherent repeating unit alternation in traditional AA/BB polymerization.



Scheme 2. Homopolymerization of **M3**.

Table 1. Reaction condition of the homopolymerization of **M3** by **Scheme 2**.



Polymer	Solv.	DBTDL (cat.)	Yield [%]	M_n^a [kDa]	M_w^a [kDa]	\bar{D}^a
polyM3a	Bulk	O	59	11	18	1.6
polyM3b	Bulk	X	49	9.6	16	1.7
polyM3c	DMF	O	52	9.2	15	1.8
polyM3d	DMF	X	27	7.8	12	1.5

^a Calculated by SEC (eluent; DMAc, flow rate; 0.5 mL / min, 50 °C)

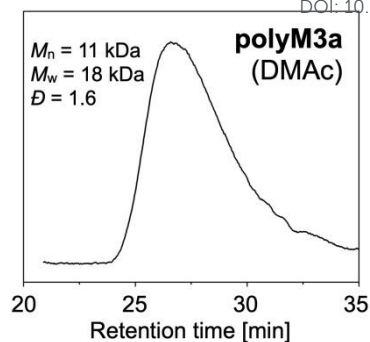


Figure 4. SEC profile of **polyM3a** (eluent; DMAc, flow rate; 0.5 mL / min, 50 °C).

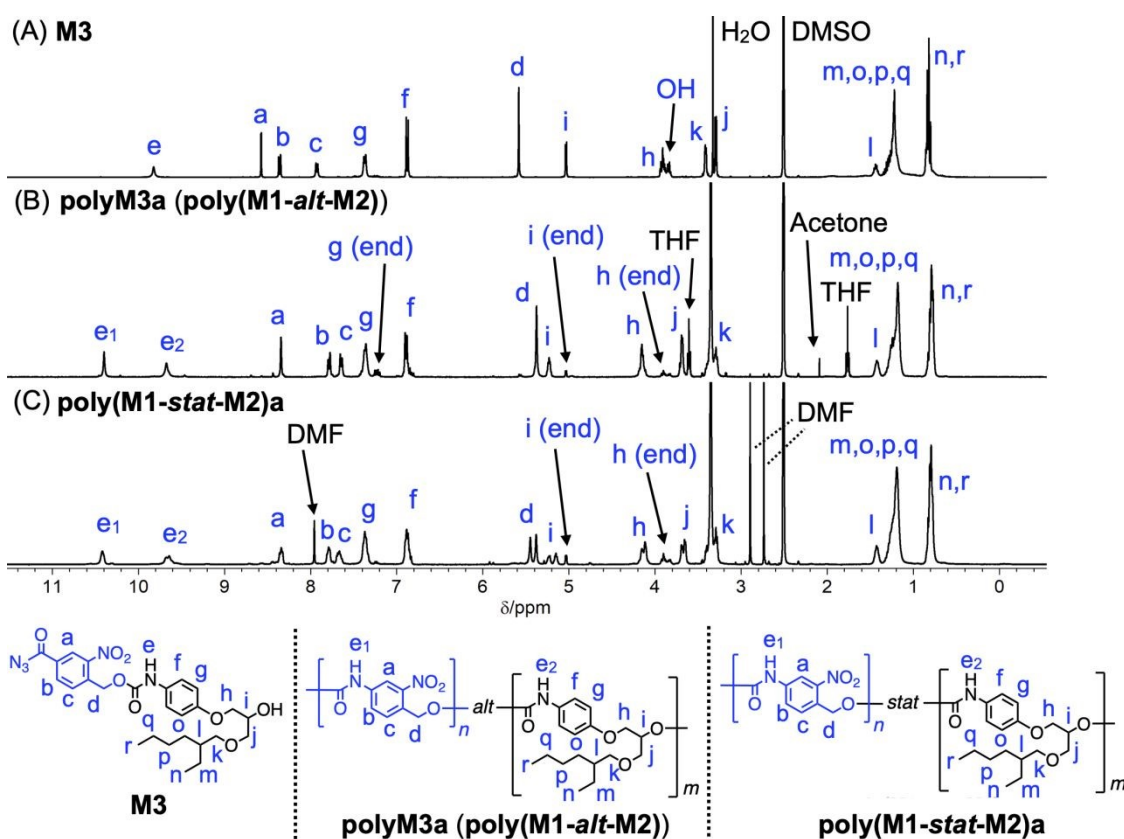
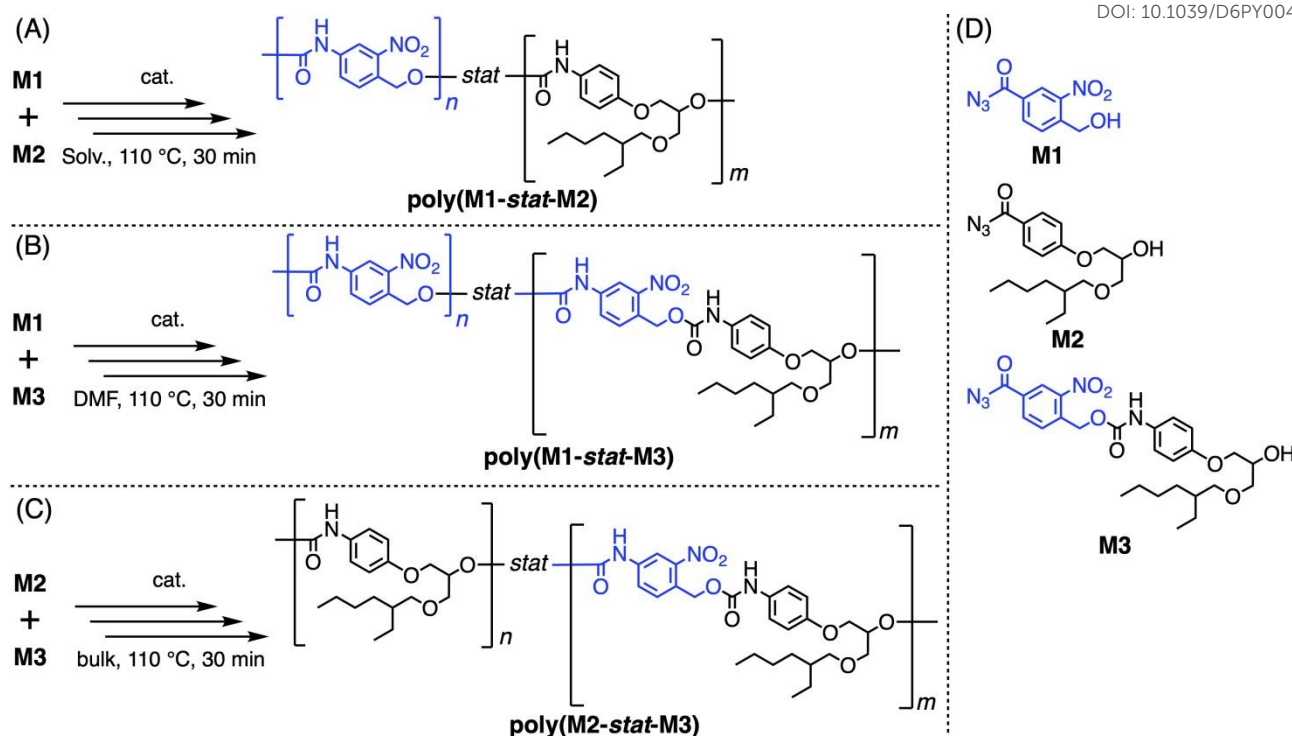


Figure 5. ^1H NMR spectra of (A) **M3**; (B) **polyM3a (poly(M1-*alt*-M2))**; (C) **poly(M1-*stat*-M2)a** (400 MHz, 298 K, DMSO-d_6).





Scheme 3. Copolymerization of (A) **M1/M2**; (B) **M1/M3**; (C) **M2/M3**. (D) Chemical structures of **M1-M3**.

Table 2. Copolymerization shown by **Scheme 3**.

Polymer	Monomer feed ratio	M1/M2 unit feed ratio	Solv.	Composition ^a M1/M2	Yield [%]	M_n^b [kDa]	M_w^b [kDa]	D^b
poly(M1-stat-M2)a	M1/M2 = 1/1	1/1	DMF	49/51	65	8.6	12	1.3
poly(M1-stat-M2)b	M1/M2 = 4/1	4/1	DMF	70/30	77	8.0	15	1.9
poly(M1-stat-M2)c	M1/M2 = 1/4	1/4	bulk	22/78	29	6.0	10	1.7
poly(M1-stat-M2)d	M1/M2 = 1/1	1/1	bulk	49/51	67	13	17	1.4
poly(M1-stat-M3)	M1/M3 = 3/1	4/1	DMF	72/28	97	8.2	15	1.8
poly(M2-stat-M3)	M2/M3 = 3/1	1/4	bulk	24/76	55	9.3	13	1.4

^a Calculated by ¹H NMR spectra. ^b Calculated by SEC (eluent; DMAc, flow rate; 0.5 mL / min, 50 °C).

To study the sequence-property control on various **M1/M2** feed ratios, copolymerization of **M1**, **M2**, and **M3** were conducted (**Scheme 3**, **Table 2**). Here, **M1/M2** feed ratio is set as 1/1, 4/1, and 1/4, and the alternating sequence was partially integrated by copolymerization with **M3** (**Scheme 3B** and **3C**). In case of high **M1** content, the DMF solution condition was applied to proceed polymerization effectively, while the bulk condition was applied for high **M2** content, considering the preferable polymerization condition of **M1** and **M2**.^[65-69] When **M1/M2** is 1/1, both the solution and the bulk conditions were applied (**poly(M1-stat-M2)a**, and **poly(M1-stat-M2)d**). As a result, all the copolymers

were successfully synthesized in moderate to high yields as confirmed by each unimodal SEC signals with the M_n value around 6-13 kDa.^[83] All the ¹H NMR signals of the copolymer were clearly assigned in a similar manner to **polyM3**, which also indicated the successful polymer synthesis (**Figure 5C**).^[83] Interestingly, certain differences were observed in ¹H NMR signals between the alternating polymer **polyM3** and **M1/M2** = 1/1 statistical copolymer **poly(M1-stat-M2)a**. (**Figure 5B**, **5C**). In general, the statistical copolymer showed broader peaks than the alternating copolymer, which indicated more diverse chemical status of corresponding signals on the former. This

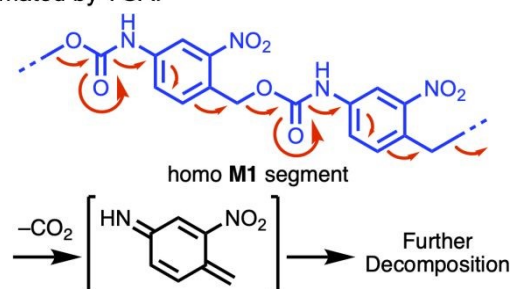


broadening effect is consistent considering the existence of various sequence patterns on the statistical copolymer, while the alternating one has only a single pattern. Moreover, multiple aliphatic signals near urethane bonds showed two signals on the statistical copolymer, while only single signals on the alternating copolymer, e.g. the benzyl proton of **M1** unit *d* at 5.4 ppm and alkyl signals *h* at 4.2 ppm, *i* at 5.2 ppm, and *j* at 3.7 ppm of **M2** unit. These equally split signals in the statistical copolymer are attributed to two different local diad environments, depending on whether the corresponding repeating unit is next to **M1** or **M2**, which is also consistent with the previous observation on other PUs from AB-type monomers. [69-73] In contrast, the alternating copolymer provides only a single local sequence environment, resulting in one corresponding signal for each resonance. Thus, the sequence effect, statistical vs. alternating, was clearly observed on NMR measurement. Compositions of obtained copolymers were calculated by ¹H NMR analyses and approximately following the feed ratio as summarized in **Table 2**. [83] Meanwhile, further detailed analysis of diad or triad patterns based on NMR was difficult, because the difference from them could not be clearly detected in our current system. Although the homopolymerization of **M1** did not proceed effectively under bulk condition, its copolymerization with **M2** certainly worked at **M1/M2** ratio = 1/1 or 1/4, suggesting **M2** unit provides sufficient fluidity for the effective reaction progress during the polymerization. Including homopolymer **polyM3** (= **poly(M1-*alt*-M2)**) in addition to these copolymers, PUs having multiple **M1/M2** compositions were successfully synthesized featuring a certain degree of the alternating sequence, which has been difficult to achieve by other existing synthetic methods.

Table 3. Thermal parameters of polymers. The values of **polyM1** and **polyM2** are cited by previous reports. [72,73]

Polymer	Monomer feed ratio	M1/M2 unit feed ratio	T_g^b [°C]	T_{d5}^c [°C]
polyM1	-	-	ND ^a	141
polyM2	-	-	42	272
polyM3a	-	1/1	78	245
poly(M1-<i>stat</i>-M2)a	M1/M2 = 1/1	1/1	66	210
poly(M1-<i>stat</i>-M2)b	M1/M2 = 4/1	4/1	107	144
poly(M1-<i>stat</i>-M2)c	M1/M2 = 1/4	1/4	56	237
poly(M1-<i>stat</i>-M2)d	M1/M2 = 1/1	1/1	78	246
poly(M1-<i>stat</i>-M3)	M1/M3 = 3/1	4/1	87	147
poly(M1-<i>stat</i>-M3)	M2/M3 = 3/1	1/4	40	238

^a Not detected; ^b Estimated by DSC (2nd heating); ^c Estimated by TGA.



Scheme 4. Thermal degradation of **M1** segment.

Next, thermal properties of obtained polymers were analyzed by DSC and TGA measurement (**Table 3**). [83] As previously observed, **polyM1** has a thermal self-immolative nature by the conjugative depolymerization path including decarboxylation step (**Scheme 4**), [80,82,87-89] leading the lower T_{d5} values of copolymers containing high **M1** content (around 145 °C) than the ones with high **M2** content (around 240 °C). Considering high T_{d5} values of **M1/M2** = 1/1 copolymers, the thermal degradation of **polyM1** segment does not proceed effectively in these copolymers, probably because **M2** unit stops the conjugative degradation path. Owing to the higher rigidity of **M1** unit than **M2**, copolymers bearing the higher **M1** content generally showed the higher T_g values, while certain differences were observed according to the sequence. A clear T_g difference was observed on **M1/M2** = 4/1 samples, **poly(M1-*stat*-M2)b** and **poly(M1-*stat*-M3)** (107 °C and 87 °C). On the latter, the soft **M2** unit always locates next to **M1** unit by the alternating sequence, would effectively reduce the packing of the local homo **M1** segment, while the generation of certain amount of homo **M1** or **M2** segments were inevitable on the former, which could induce easier homo segment packing to increase T_g value (**Figure 6**). A similar T_g difference was observed on **M1/M2** = 1/4 samples, **poly(M1-*stat*-M2)c**



and **poly(M2-stat-M3)** (56 °C and 40 °C), which can be explained in the same manner. Namely, the dimer integration induced the distribution of the hard **M1** unit always next the soft **M2** unit, while the generation of a certain content of homo **M1/M2** was inevitable on the copolymerization without the dimer **M3**, which caused the trend of easier packing by local homo polymer segments to increase T_g value. In these cases, the partial alternating sequence (**M3** unit) introduction significantly reduced the packing nature of the local polymer segments compared with the corresponding statistical copolymers, resulting in the decrease of T_g values. Meanwhile, the reason for the difference in T_g values on **M1/M2** = 1/1 statistical polymers (**poly(M1-stat-M2)a** and **poly(M1-stat-M2)d**) was not completely clear, but could have been influenced by the sequence formation process during the polymerization. Namely, the bulk condition on **poly(M1-stat-M2)d** reduced the fluidity of the polymerization mixture during the copolymerization, which would have caused the local homo **M1/M2** segment formation, while DMF solution condition on **poly(M1-stat-M2)a** induced more homogeneous distribution of **M1/M2** unit on the polymer framework. The resulting sequence difference would

have caused the different T_g values. Interestingly, **poly(M1-stat-M3)** having 20% hard **M1** content showed the slightly lower T_g value than the 100% soft segment homopolymer **polyM2** (40 °C and 42 °C respectively). This suggested that the small content of **M1** on the former disturbed the effective packing of the aliphatic side chain moieties of entire **polyM2** framework to reduce T_g , and this effect would work more dominantly than the increase of the rigidity by the introduction of hard **M1** unit. Considering the above discussion about the polymer sequence, the implementation of the alternating sequence was clearly proved to affect the thermal properties on polymer derived from step polymerization (PU in this case), underscoring the importance of the “sequence” as a parameter to control the basic properties on polymer obtained by step polymerization. Moreover, the pronounced sequence dependence observed in thermal properties indicates that the sequence effect is not limited to photo-cleavable systems, although photo-degradability was chosen in this work as a particularly clear model response.

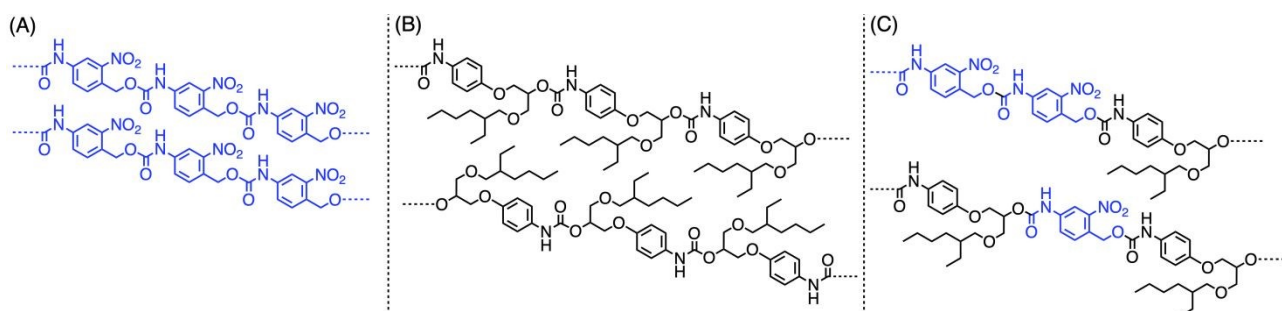
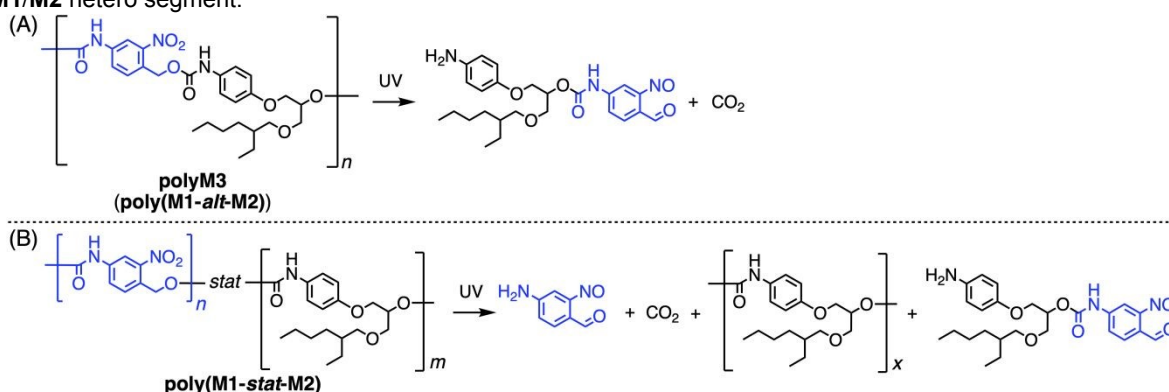


Figure 6. Schematics of the plausible local polymer packing structure of (A) homo **M1** segment; (B) homo **M2** segment; (C) **M1/M2** hetero segment.



Scheme 5. Photo-degradation of (A) **polyM3 (poly(M1-alt-M2))**; (B) **poly(M1-stat-M2)**.



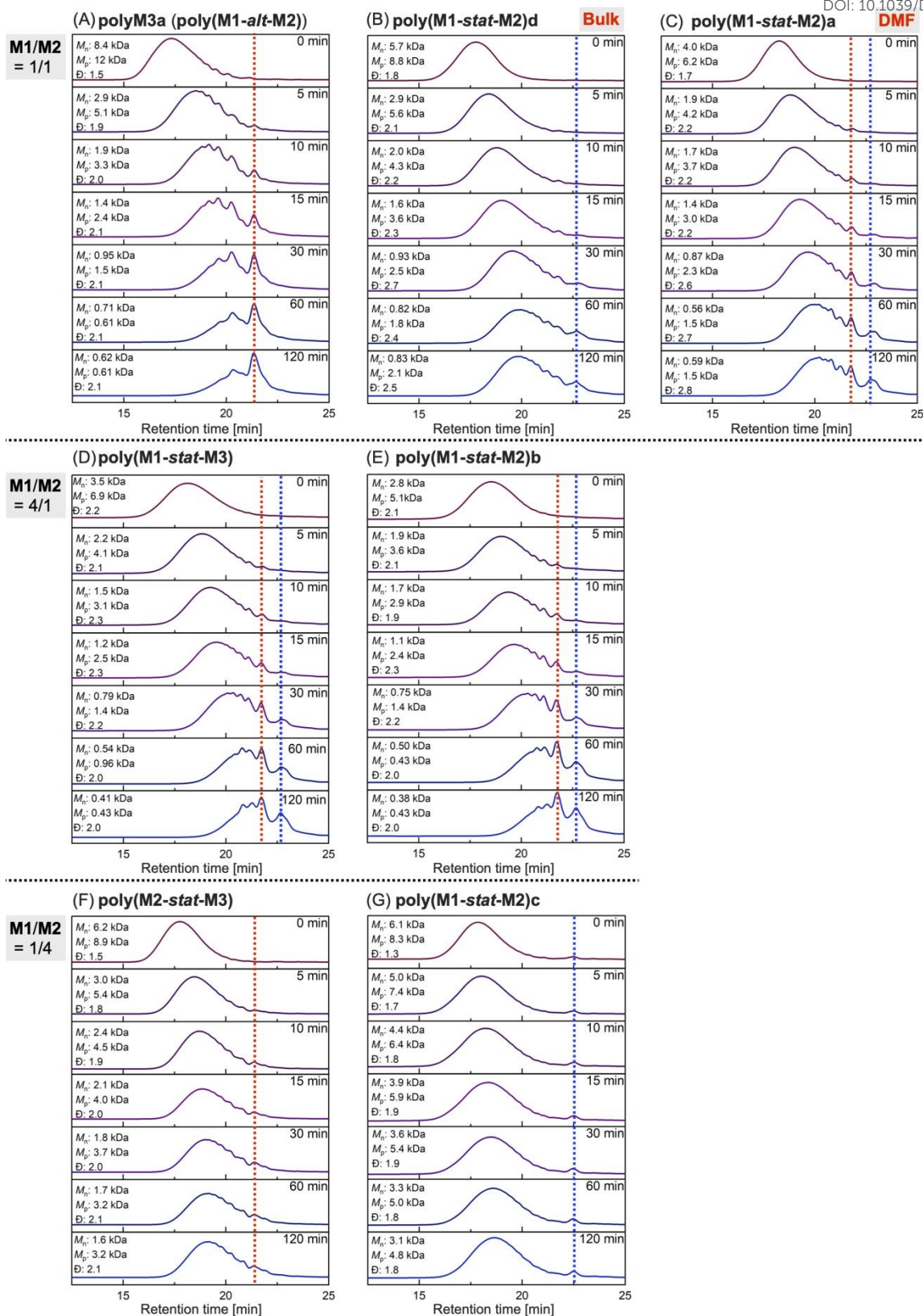
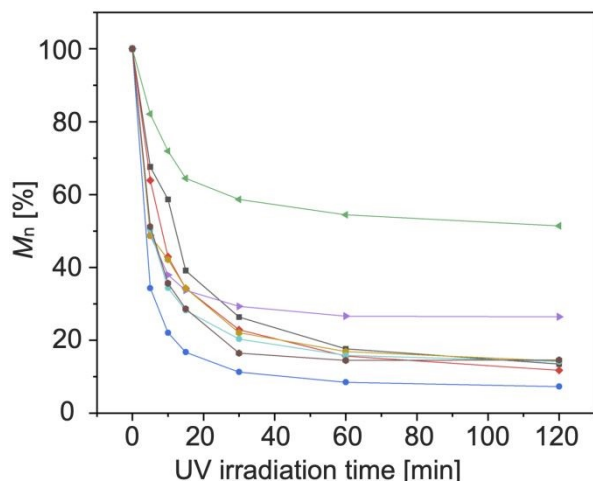


Figure 7. Time course of SEC profiles of (A) polyM3a; (B) poly(M1-*stat*-M2)d; (C) poly(M1-*stat*-M2)a; (D) poly(M1-*stat*-M3); (E) poly(M1-*stat*-M2)b; (F) poly(M2-*stat*-M3); (G) poly(M1-*stat*-M2)c (UV irradiation after 0, 5, 10, 15, 30, 60, and 120 min; eluent; THF, flow rate; 1.0 mL/min, 25 °C). Red dot line indicates the dimeric fragment generation, while blue one does the monomeric fragment.





	M1/M2 unit ratio	M_n [kDa]
—●— polyM3a	1/1	8.4
—●— polyM3c	1/1	5.2
—●— poly(M1-stat-M2)a	1/1	4.0
—●— poly(M1-stat-M2)d	1/1	5.7
—●— poly(M1-stat-M3)	4/1	3.5
—●— poly(M1-stat-M2)b	4/1	2.8
—●— poly(M2-stat-M3)	1/4	6.2
—●— poly(M1-stat-M2)c	1/4	6.1

Figure 8. Plot of M_n [%] vs UV irradiation time of copolymers. The column of M_n shows the initial M_n before UV irradiation (eluent; THF, flow rate; 1.0 mL/min, 25 °C)

Next, photo-degradability of copolymers were investigated to evaluate the effect of their sequences on it by following the previous report (Figure 7 and 8, Scheme 5).^[72] Namely, each copolymer was dissolved in THF or DMAc in diluted condition (1 mg/mL), and 365 nm light was irradiated to induce the photo-cleavage reaction of *o*-NBA framework on **M1** unit, which was traced by the SEC measurement after 0, 5, 10, 15, 30, 60, and 120 min of the light irradiation and summarized as the time-course M_n plot (Figure 8). Here, the result of THF system is discussed, because the result of DMAc indicated the similar trend, and the former showed sharper SEC signals to be clearly detected.^[83] First, all the samples showed clear decrease of the molecular weight even after 5 min irradiation, and the continuous irradiation induced the further decrease to be mostly completed within one hour, while the control test of the UV irradiation on polyM2 did not change its SEC profile at all even after several hours, clearly indicated the occurrence of the photo-degradation on **M1** unit.^[83] The general trend of the photo-degradability is consistent with the previous report,^[72] meaning copolymers bearing high **M1** content are likely to show more

intensive photo-degradability, while certain effects by the sequence was clearly observed as discussed as followings.

Comparing polyM3a and polyM3c, which are both featuring the alternating sequence poly(M1-*alt*-M2), the former showed more intensive degradation than the latter. Since both polymers have the same sequence/composition, this difference would be caused by the molecular weight difference. In this method, the minimum unit after the photo-degradation is the monomeric unit from **M1** ($M_w \sim 150$ Da) or the dimeric unit from **M2-M1** diad ($M_w \sim 470$ Da), meaning the size of the initial polymer certainly affects the percentage of the M_n decrease when they are around 10 kDa or less. Thus, the initially bigger polyM3a ($M_n = 8.4$ kDa) showed more decrease of the percentage of M_n from the beginning to the complete degradation than polyM3c ($M_n = 5.2$ kDa). It also affects the more intensive degradation of polyM3a than the copolymers bearing 80% **M1** content (poly(M1-*stat*-M3) and poly(M1-*stat*-M2)b). In this case, the high **M1** content increases the photo-degradability of polymers, but it also caused the lower molecular weight of the resulting polymer, possibly because of the high rigidity of **M1** unit,^[72] which could cause the low fluidity during the polymerization to disturb the propagation reaction. The effect of the molecular weight would be more dominant than the high content of **M1** unit, would have induced the highest photo-degradability of polyM3a on this measurement. Except polyM3a, copolymers bearing more than 50% **M1** content showed similar trend on the time-course of the M_n decrease regardless of their sequence or **M1** content, suggesting these parameters do not significantly influence their photo-degradability, possibly because they are already highly photo-degradable. Meanwhile, a large photo-degradability difference was observed on copolymers bearing 20% **M1** content (poly(M2-*stat*-M3) and poly(M1-*stat*-M2)c), the smallest **M1** content in this work. Both degraded less than the others, but poly(M2-*stat*-M3) (~45% decrease of M_n) was further less than poly(M1-*stat*-M2)c (~70% decrease of M_n), which was associated with the sequence difference. Namely, the alternating sequence from **M3** induces more homogeneous distribution of photo-degradable **M1** unit to the entire polymer chain, while **M1/M2** statistical polymer without **M3** includes inevitable local homo **M1** and **M2** polymer segments, which decrease the photo-degradability owing to the non-photo-degradable homo **M2** segment. When **M1** content is higher than 50%, this effect would not be dominant, but it causes significant influence on the low



M1 content copolymers, resulted in the drastic photo-degradability difference between partially alternating polymer and complete statistical polymer. This “alternating vs. statistical” sequence dependent photo-degradability was firstly observed by the implementation of sequence definition/control on the polymer derived from step polymerization (PU in this case), supporting its importance.

Meanwhile, SEC profiles showed further dependence of the resulting residues from the photo-degradation on the sequence (**Figure 7**). According to the photo-degradation of **polyM3a**, the SEC intensity around 21.5 min (red dot line on **Figure 7A**) increased, suggesting the formation of dimeric fragments after the alternating polymer framework cleavage. The peaks on the same retention time were also observed on other polymers containing alternating sequence (**Figure 7D** and **7F**). On the other hand, copolymers made from **M1** shows the SEC peak increase around 22.5 min in proportion to the UV irradiation time (blue dot lines on **Figure 7**), which would be derived from the monomeric fragment after the photo-degradation of homo **M1** segment. Statistical polymers without **M3** integration also showed peaks from dimeric fragments around 21.5 min, suggesting the existence of various sequence patterns there including homo **M1** segment and other hetero segment types. Comparing two copolymers featuring 20% **M1** content, the one with the alternating sequence showed intense dimeric fragment peak on the residue (**Figure 7F**), while the one without the alternating sequence did the intense monomeric fragment peak (**Figure 7G**), highlighting the sequential difference and the homo **M1** segment formation on **poly(M1-stat-M2)c**, which induced its more decreased photo-degradability and the higher T_g than the partially alternating sequenced counterpart **poly(M2-stat-M3)**. Finally, comparing two statistical copolymers featuring **M1/M2** = 1/1 content, the one made in DMF solution polymerization showed more intensive dimeric peak (**Figure 7C**) than the one made in the bulk (**Figure 7B**), while both showed monomeric fragment peaks. This difference is probably because the solvent increased the fluidity on the reaction mixture to induce more homogeneous polymerization system, while the bulk condition could cause the local aggregation of the homo polymer segments, resulting in the monomeric fragment generation by the photo-degradation and the higher T_g from their higher packing preference. Further spectroscopic analysis of the degradation products would provide deeper mechanistic insight into this system, but such analysis was experimentally difficult

for the present degraded samples owing to the low product amount in diluted solution. Therefore, the degradation mechanism proposed here remains partly speculative and should be interpreted with appropriate caution. A more detailed structural elucidation of the degradation products will be the subject of future study.

Considering the above, thermal properties and photo-degradability of **M1/M2** copolymers were consistently associated with their polymer sequence, which was clearly controlled by the (partial) integration of the alternating sequence. The detailed analysis indicated a certain level of sequence-property control through the polymerization condition (bulk vs. solution), which could supportively contribute to the polymer design. In the end, this work successfully demonstrated the definition of alternating sequence on polymer derived from step polymerization conventionally featuring only AA-BB-type connectivity by the combination of AB-type monomer framework and the dimeric species, and the property analysis of redefined polymers suggested that polymer sequence acts as an independent design parameter in step polymerization, giving rise to pronounced sequence-property divergence (**Figure 9**).



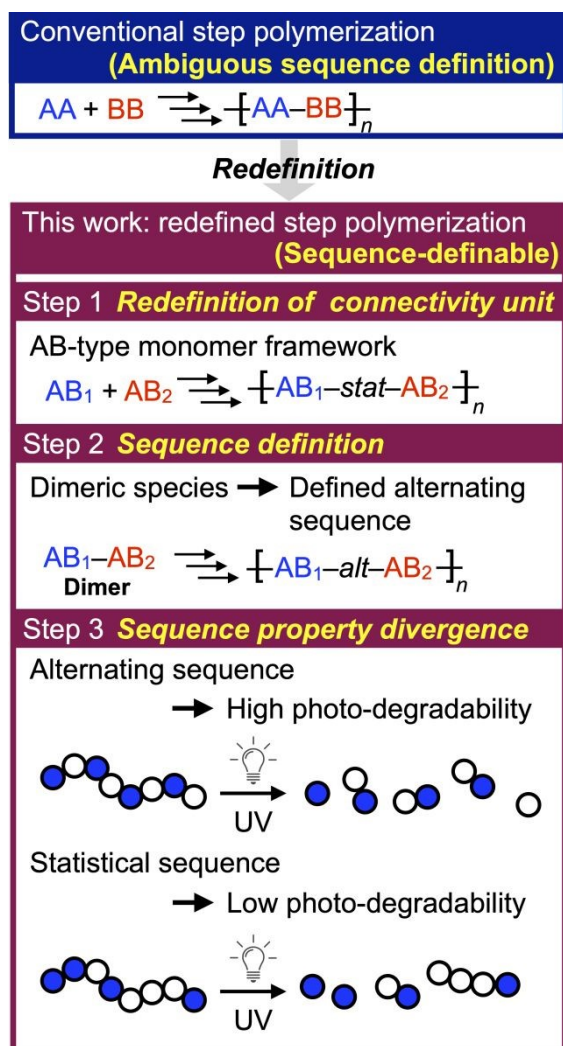


Figure 9. Sequence definition on polymer derived from step polymerization demonstrated in this work, highlighting the resulting sequence–property divergence for photo-degradation control.

Conclusion

In this work, we addressed a fundamental yet ambiguous question in step polymerization by defining what constitutes an alternating sequence in polymers synthesized from AA and BB type monomers. An AB-type monomer framework enabled explicit sequence definition, while a dimer-based strategy allowed the practical implementation of alternating connectivity. Using polyurethane as a model system, we demonstrated that defined alternating sequences give rise to pronounced sequence–property relationships, as reflected in thermal properties and photo-degradability, enabling programmable material degradation. The main contribution of this study is the establishment of a conceptual and synthetic basis for alternating sequences in step polymerization, while the observed

sequence-dependent properties confirm the practical relevance of this framework. This study establishes polymer sequence as an additional and actionable design parameter in polyurethane as a model system for step polymerization, beyond conventional monomer and composition design. The framework demonstrated in this work would potentially be applicable to other step polymerization systems. By enabling the controlled incorporation of the functional unit into the polymer main chain rather than the side chain, this method provides a complementary tool for contributing to functional/sustainable material development other than well-studied chain polymerization.

Supporting Information

General methods, chemical synthesis, property analysis of synthesized compounds, kinetic analysis, and spectra of synthesized compounds

Author contributions

X. K.: data curation, formal analysis, investigation, visualization; J. R.-B.: data curation, investigation; T. C.: data curation; P. T.: resources, writing – review & editing; Y. A. conceptualization, formal analysis, funding acquisition, methodology, project administration, resources, supervision, validation, visualization, writing – original draft, writing – review & editing.

Acknowledgements

This work was supported by JSPS KAKENHI (Japan) grant number JP20J00360 (Y.A.), JP21K14672 (Y.A.), and JP22KJ1489 (Y.A.). The authors acknowledge financial support from the Helmholtz Association.

Conflicts of interest

The authors declare no conflict of interest.

References

- [1] J. F. Lutz, M. Ouchi, D. R. Liu, and M. Sawamoto, "Sequence-Controlled Polymers," *Science* 341 (2013): 1238149.
- [2] S. L. Perry and C. E. Sing, "100th Anniversary of Macromolecular Science Viewpoint: Opportunities in the Physics of Sequence-Defined Polymers," *ACS Macro Letters* 9 (2020): 216–225.
- [3] Q. Shia, Z. Denga, M. Houa, X. Hua, S. Liu, "Engineering precise sequence-defined polymers for advanced functions," *Progress in Polymer Science* 141 (2023): 101677.
- [4] M. A. R. Meier, C. Barner-Kowollik, "A New Class of Materials: Sequence-Defined Macromolecules and Their Emerging Applications," *Advanced Materials* 31 (2019): 1806027.
- [5] Z. Gan, J. Liu, Z. Xu, S. Jia, X.-H. Dong, "Precision polymers: advances in synthesis, structural engineering, and functional optimization," *Progress in Polymer Science* 170 (2025): 102030.
- [6] L. D. Thai, J. A. Kammerer, D. Golberg, H. Mutlu, C. Barner-Kowollik, "Sequence-defined main-chain photoswitching macromolecules with odd-even effect-controlled properties," *Chem* 11 (2025): 102341.



- [7] H. S. Wang, M. Agrachev, H. Kim, N. P. Truong, T.-L. Choi, G. Jeschke, A. Anastasaki, "Visible Light-Triggered Depolymerization of Commercial Polymethacrylates," *Science* 387 (2025): 874–880.
- [8] L. Cederholm, P. Olsen, M. Hakkarainen, and K. Odelius, "Design for Recycling: Polyester- and Polycarbonate-Based A–B–A Block Copolymers and Their Recyclability Back to Monomers," *Macromolecules* 56 (2023): 3641–3649.
- [9] Y. Takahashi, A. Kanazawa, and S. Aoshima, "3-Alkoxyphthalides as Nonhomopolymerizable, Highly Reactive Comonomers for ABC Pseudo-Periodic Terpolymers and Degradable Polymers via Cationic co- and Terpolymerizations With Oxiranes and/or Vinyl Ethers," *Macromolecules* 56 (2023): 4198–4207.
- [10] M. Uchiyama, Y. Murakami, K. Satoh, M. Kamigaito, "Synthesis and Degradation of Vinyl Polymers with Evenly Distributed Thioacetal Bonds in Main Chains: Cationic DT Copolymerization of Vinyl Ethers and Cyclic Thioacetals," *Angewandte Chemie International Edition* 62 (2023): e202215021.
- [11] Y. Xia, T. Shao, Y. Sin, J. Wang, C. Gu, C. Zhang, X. Zhang, "Precise Placement of Thioester Bonds Into Sequence-Controlled Polymers Containing ABAC-type Units," *Nature Communications* 16 (2025): 1974.
- [12] Y. Akae and P. Theato, "Aggregation Behavior of Cyclodextrin-Based [3]Rotaxanes," *Chemistry—a European Journal* 29 (2023): e202301582.
- [13] M. Uchiyama, M. Imai, and M. Kamigaito, "Synthesis of Degradable Polymers via 1,5-Shift Radical Isomerization Polymerization of Vinyl Ether Derivatives With a Cleavable Bond," *Polymer Journal* 56 (2024): 359–368.
- [14] Y. Akae, "Cyclodextrin-Based Rotaxanes for Polymer Materials: Challenge on Simultaneous Realization of Inexpensive Production and Defined Structures," *Beilstein Journal of Organic Chemistry* 20 (2024): 3026–3049.
- [15] H. G. Hester, Z. B. A. Abel, and G. W. Coates, "Ultra-High-Molecular-Weight Poly(Dioxolane): Enhancing the Mechanical Performance of a Chemically Recyclable Polymer," *Journal of the American Chemical Society* 145 (2023): 8800–8804.
- [16] Y. Akae and T. Takata, "O-Acylation Vinylation of Cyclodextrin-Based [3]Rotaxane Towards Rotaxane Crosslinkers," *European Journal of Organic Chemistry* 26 (2023): e202300009.
- [17] A. Tardy, J. Nicolas, D. Gimes, C. Lefay, and Y. Guillaeneuf, "Radical Ring-Opening Polymerization: Scope, Limitations, and Application to (Bio)degradable Materials," *Chemical Reviews* 117 (2017): 1319–1406.
- [18] H. Sogawa, C.-G. Wang, S. Monjiyama, Y. Akae, and T. Takata, "Aliphatic Ditopic Nitrile N-Oxide Crosslinker: Synthesis, Chemical Stability, and Catalyst-Free Crosslinking Reactions," *Polymer* 213 (2021): 123291.
- [19] C. Weng, X. Li, X. Tang, "Solvent-Dependent Sequence-Controlled Copolymerization of Lactones: Tailoring Material Properties from Robust Plastics to Tough Elastomers," *Angewandte Chemie International Edition* 64 (2025): e202415388.
- [20] R. D. Rittinghaus, J. Zenner, A. Pich, M. Kol, and S. Herres-Pawlis, "Master of Chaos and Order: Opposite Microstructures of PCL-co-PGA-co-PLA Accessible by a Single Catalyst," *Angewandte Chemie International Edition* 61 (2022): e202112853.
- [21] M. Uchiyama, Y. Murakami, K. Satoh, M. Kamigaito, "Synthesis and Degradation of Vinyl Polymers with Evenly Distributed Thioacetal Bonds in Main Chains: Cationic DT Copolymerization of Vinyl Ethers and Cyclic Thioacetals," *Angewandte Chemie International Edition* 62 (2023): e202215021.
- [22] T. Kimura, K. Kuroda, H. Kubota, and M. Ouchi, "Metal-Catalyzed Switching Degradation of Vinyl Polymers via Introduction of an "In-Chain" Carbon–Halogen Bond as the Trigger," *ACS Macro Letters* 10 (2021): 1535–1539.
- [23] Y. Akae, H. Sogawa, and T. Takata, "Cyclodextrin Based [3]Rotaxane Crosslinked Fluorescent Polymer: Synthesis and De Crosslinking Using Size Complementarity," *Angewandte Chemie International Edition* 57 (2018): 14832–14836.
- [24] K. Watanabe, N. Kaizawa, B. J. Ree, T. Yamamoto, K. Tajima, T. Isono, and T. Satoh, "One-Shot Intrablock Cross-Linking of Linear Diblock Copolymer to Realize Janus-Shaped Single-Chain Nanoparticles," *Angewandte Chemie International Edition* 60 (2021): 18122–18128.
- [25] J. J. Lessard, G. M. Scheutz, S. H. Sung, K. A. Lantz, T. H. Epps, III, and B. S. Sumerlin, "Block Copolymer Vitrimers," *Journal of the American Chemical Society* 142 (2020): 283–289.
- [26] M. Appold, C. Mari, C. Lederle, J. Elbert, C. Schmidt, I. Ott, B. Stühn, G. Gasser and M. Gallei, "Multi-stimuli responsive block copolymers as a smart release platform for a polypyridyl ruthenium complex," *Polymer Chemistry* 8 (2017): 890–900.
- [27] Y. Akae, Y. Koyama, H. Sogawa, Y. Hayashi, S. Kawauchi, S. Kuwata, T. Takata, "Structural Analysis and Inclusion Mechanism of Native and Permethylated α -Cyclodextrin-Based Rotaxanes Containing Alkylene Axles," *Chemistry – A European Journal* 22 (2016): 5335–5341.
- [28] K. Satoh, D.-H. Lee, K. Nagai, M. Kamigaito, "Precision Synthesis of Bio-Based Acrylic Thermoplastic Elastomer by RAFT Polymerization of Itaconic Acid Derivatives," *Macromolecular Rapid Communication* 35 (2014): 161–167.
- [29] Y. Akae, T. Arai, Y. Koyama, H. Okamura, K. Johmoto, H. Uekusa, S. Kuwata, and T. Takata, "One-Pot Synthesis of Permethylated α -CD-Based Rotaxanes Having Alkylene Chain Axles and Their Structural Characteristics," *Chemistry Letters* 41 (2012): 806–808.
- [30] J. Li, R. M. Stayshich, and T. Y. Meyer, "Exploiting Sequence to Control the Hydrolysis Behavior of Biodegradable PLGA Copolymers," *Journal of the American Chemical Society* 133 (2011): 6910–6913.
- [31] A. Rave "Step-Growth Polymerization and Step-Growth Polymers." in *Principles of Polymer Chemistry*, Springer, New York (2012), pp. 403–535.
- [32] M. Ueda, K. Kimura, and T. Yokozawa "Polycondensation" in *Polymer Synthesis*, (Eds.: T. Endo), Kodansha, Tokyo (2010), pp. 569–744.
- [33] T. Yokozawa, Y. Ohta, "Transformation of Step-Growth Polymerization into Living Chain-Growth Polymerization," *Chemical Review* 116 (2016): 1950–1968.
- [34] A. Yokoyama, T. Yokozawa, "Converting Step-Growth to Chain-Growth Condensation Polymerization," *Macromolecules* 40 (2007): 4093–4101.
- [35] S. Sakai, T. Nakamura, S. Uchida, Y. Nakauchi, M. Uchiyama, T. Kubo, M. Kamigaito, and K. Satoh, "Controlled/Living" Click Polymerization with Possible Bidirectional Chain-Growth Propagation during Polyaddition," *Journal of the American Chemical Society* 147 (2025): 21459–21467.
- [36] J. Yang, L. Chen, M. Zhu, M. W. Ishaq, S. Chen, and L. Li, "Investigation of the Multimer Cyclization Effect during Click Step-Growth Polymerization of AB-Type Macromonomers," *Macromolecules* 55 (2022): 6830–6840.
- [37] R. Ejima, M. Nakahata, Y. Kamon, A. Hashidzume, "Synthesis and Metal Ion Adsorption Properties of a Dense Triazole Polymer Carrying Cysteine Residues," *Journal of Polymer Science* 63 (2025): 1570–1579.
- [38] E. Delebecq, J. P. Pascault, B. Boutevin, and F. Ganachaud, "On the Versatility of Urethane/Urea Bonds: Reversibility, Blocked Isocyanate, and Non-Isocyanate Polyurethane," *Chemical Reviews* 113 (2013): 80–118.
- [39] D. Liu, C. Huyan, H. Li, J. Ge, F. Chen, L. Zhang, "Recycling and Upcycling of Polyurethane Thermosets: The Second Life of Polymers," *Advanced Materials in Press* (<https://doi.org/10.1002/adma.202515809>).
- [40] E. Balla, D. N. Bikaris, N. Pardalis and N. D. Bikaris, "Toward Sustainable Polyurethane Alternatives: A Review of the Synthesis,



- Applications, and Lifecycle of Non-Isocyanate Polyurethanes (NIPUs)," *Polymers* 17 (2025): 1364.
- [41] A. Gomez-Lopez, F. Elizalde, I. Calvob and H. Sardon, "Trends in non-isocyanate polyurethane (NIPU) development," *Chemical Communication* 57 (2021): 12254.
- [42] F. Orabona, F. Recupido, G. C. Lama, K. Polaczek, F. Taddeo, T. Salmi, M. Di Serio, L. Verdolotti and V. Russo, "Cutting-edge development of non-isocyanate polyurethane (NIPU) foams: from sustainable precursors to environmental impact evaluation," *Green Chemistry* 27 (2025): 7403.
- [43] C. Liang, U. R. Gracida-Alvarez, E. T. Gallant, P. A. Gillis, Y. A. Marques, G. P. Abramo, T. R. Hawkins, and J. B. Dunn, "Material Flows of Polyurethane in the United States," *Environmental Science & Technology* 55 (2021): 14215-14224.
- [44] N. G. Jaques, A. Llevot, É. Grau, T. Vidil, M. A. R. Meier, and H. Cramail, "High Molar Mass Non-Isocyanate Polyurethanes by Transurethanization of Diols with Isophorone-Based Bismethylcarbamate," *Macromolecular Chemistry and Physics* 226 (2025): 2500068.
- [45] F. C. Destaso, C. Libretti, C. L. Coz, E. Grau, H. Cramail and M. A. R. Meier, "Optimized synthesis of a high oleic sunflower oil derived polyamine and its lignin-based NIPUs," *Green Chemistry* 27 (2025): 1440.
- [46] J. Sawada, H. Sogawa, H. Marubayashi, S. Nojima, H. Otsuka, K. Nakajima, Y. Akae, T. Takata, "Segmented Polyurethanes Containing Movable Rotaxane Units on the Main Chain: Synthesis, Structure, and Mechanical Properties," *Polymer* 193 (2020): 122358.
- [47] Y. Akae and P. Theato, "Polyurethane Type Poly[3]rotaxanes Synthesized from Cyclodextrin Based [3]Rotaxane Diol and Diisocyanate," *Macromolecular Rapid Communications* 45 (2024): 2400441.
- [48] H. Sogawa, M. Abe, R. Shintani, T. Sotani, K. Tabaru, T. Watanabe, Y. Obora, F. Sanda, "Polyurethanes containing platinum in the main chain: synthesis, structure and mechanofluorochromism," *Polymer Journal* 55 (2023): 1119–1128.
- [49] P. Schara, A. M. Cristadoro, R. P. Sijbesma, and Z. Tomovic, "Solvent-Free Synthesis of Acetal-Containing Polyols for Use in Recyclable Polyurethanes," *Macromolecules* 56 (2023): 8866–8877.
- [50] Y. Akae, K. Iijima, M. Tanaka, T. Tarao, and T. Takata, "Main Chain-Type Polyrotaxanes Derived From Cyclodextrin-Based Pseudo[3]Rotaxane Diamine and Macromolecular Diisocyanate: Synthesis, Modification, and Characterization," *Macromolecules* 53 (2020): 2169–2176.
- [51] J. Futter, M. Holzer, B. Rieger, "Formic Acid as Feedstock in the Phosgene-Free Dehydrogenative Coupling of Formamides and Alcohols to Polyurethanes," *Macromolecules* 58 (2025): 1817–1826.
- [52] Q. Jaussaud, I. M. Ogbu, G. G. Pawar, E. Grau, F. Robert, T. Vidil, Y. Landais, and H. Cramail, "Synthesis of polyurethanes through the oxidative decarboxylation of oxamic acids: a new gateway toward self-blown foams," *Chemical Science* 15 (2024): 13475.
- [53] T. Noda, A. Tanaka, Y. Akae, and Y. Kohsaka, "Unsaturated Polyurethanes Degradable by Conjugate Substitution Reactions With Amines and Carboxylate Anions," *RSC Advances* 13 (2023): 20336–20341.
- [54] J. Lee, S. Baek, H. H. Moon, S. U. Son, and C. Song, "Furandiacylazide: A Biomass-Derived Versatile Polymer Platform toward Photodegradable and Nonflammable Polyurethanes," *ACS Applied Polymer Materials* 3 (2021): 5767–5777.
- [55] H. Tomita, F. Sanda, T. Endo, "Model Reaction for the Synthesis of Polyhydroxyurethanes from Cyclic Carbonates with Amines: Substituent Effect on the Reactivity and Selectivity of Ring-Opening Direction in the Reaction of Five-Membered Cyclic Carbonates with Amine," *Journal of Polymer Science: Part A: Polymer Chemistry* 39 (2001): 3678–3685.
- [56] S.-D. Lee, F. Sanda, T. Endo, "A Novel Synthetic Method of a Polyurethane from an Aminimide as a "Latent Monomer", " *Journal of Polymer Science: Part A: Polymer Chemistry* 35 (1997): 1333–1335.
- [57] S. Neffgen, H. Keul, and H. Höcker, "Cationic Ring-Opening Polymerization of Trimethylene Urethane: A Mechanistic Study," *Macromolecules* 30 (1997): 1289–1297.
- [58] L. Rubino, V. Patamia, A. Rescifina, M. Galimberti and V. Barbera, "Cyclic carbamates based on (R)-(+)-limonene oxide for ring-opening polymerization," *Scientific Reports* 14 (2024): 23521–1297.
- [59] D. Zhang, Y. Zhang, Y. Fan, M.-N. Rager, V. Guefineau, L. Bouteiller, M.-H. Li, and C. M. Thomas, "Polymerization of Cyclic Carbamates: A Practical Route to Aliphatic Polyurethanes," *Macromolecules* 52 (2019): 2719–2724.
- [60] E. A. Hoff, G. X. de Hoe, C. M. Mulvaney, M. A. Hillmyer, and C. A. Alabi, "Thiol-Ene Networks From Sequence-Defined Polyurethane Macromers," *Journal of the American Chemical Society* 142 (2020): 6729–6736.
- [61] T. Mondal, L. Charles, and J.-F. Lutz, "Damage and Repair in Informational Poly(N-Substituted Urethane)s," *Angewandte Chemie, International Edition* 59 (2020): 20390–20393.
- [62] J. V. Hoorde, N. Badi, and F. E. Duprez, "Scalable Design of Uniform Oligourethanes for Impact Study of Chain Length, Sequence and End Groups on Thermal Properties," *Polymer Chemistry* 15 (2024): 4319.
- [63] H. Yamauchi, S. Inayama, M. Nakabayashi, and S. Hayashi, "Systematic Order-Made Synthesis of Sequence-Defined Polyurethanes With Length, Types, and Topologies," *ACS Macro Letters* 12 (2023): 1264–1271.
- [64] W. Forsyia, A. Lizak, and R. Szweda, "Sequence of Monomers and Position of Stereocenters Matter for Thermal Properties of Stereocontrolled Oligourethanes," *ChemPhysChem* 25 (2024): e202400366.
- [65] J. R. Sculuk, H. A. Fargher, E. V. Anslyn, "The Utility of Chain-End Degradation for De Novo Sequencing of Sequence-Defined Oligourethanes" *Acc. Chem. Res.* 59 (2026): 958-968.
- [66] S. D. Dahlhauser, P. R. Escamilla, A. N. VandeWalle, J. T. York, R. M. Rapagnani, J. S. Shei, S. A. Glass, J. N. Coronado, S. R. Moor, D. P. Saunders, E. V. Anslyn, "Sequencing of Sequence-Defined Oligourethanes via Controlled Self-Immolation" *J. Am. Chem. Soc.* 142 (2020): 2744-2749.
- [67] W. Forsyia, S. Kozub, Ł. John, and R. Szweda, "Discrete oligourethanes of sequence-regulated properties – impact of stereocontrol" *Polym. Chem.* 13 (2022): 2980-2987.
- [68] A. Sharma, P. Cwynar, A. Jose, V. Gupta, and R. Szweda, "Step-economy approach for scalable synthesis of stereocontrolled and sequence-defined polyurethanes" *Eur. Polym. J.* 236 (2025): 114120.
- [69] Y. Akae, M. Sakurai, and T. Takata, "Alcohol Moiety-Tethering Acylazides as Versatile Isocyanate Precursors for Polymerization Initiators and Monomers," *Macromolecules* 54 (2021): 8488–8494.
- [70] Y. Akae and P. Theato, "Polyurethanes by Ring-Opening Polymerization Initiated From Alcohol Moiety-Tethering Acylazide," *Journal of Polymer Science* 62 (2024): 4127–4135.
- [71] Y. Shen, P. Theato, and Y. Akae "Tailored Polyurethane Synthesis from AB-Type Monomers," *Macromolecules* 57 (2024): 8162-8175.
- [72] J. Reeb, Y. Shen, P. Theato, and Y. Akae, "Controllable Photo-Degradability on Polyurethane From AB-Type Monomers," *Macromolecules* 58 (2025): 2701–2708.
- [73] X. Kneidl, L. Forkel, T. Cui, P. Theato, and Y. Akae, "The Effect of Aliphatic or Aromatic Substituents on the Synthesis and Properties of Polyurethanes From AB-Type Monomers," *J. Polym. Sci.* 64 (2026): 366–375.
- [74] D. V. Palaskar, A. Boyer, E. Cloutet, C. Alfios, and H. Cramail, "Synthesis of Biobased Polyurethane From Oleic and Ricinoleic Acids as the Renewable Resources via the AB-Type Self-Condensation Approach," *Biomacromolecules* 11 (2010): 1202–1211.



- [75] A. S. More, B. Gadenne, C. Alfos, and H. Cramail, "AB Type Polyaddition Route to Thermoplastic Polyurethanes From Fatty Acid Derivatives," *Polymer Chemistry* 3 (2012): 1594.
- [76] A. S. More, L. Maisonneuve, T. Lebarbe, B. Gadenne, C. Alfos, and H. Cramail, "Vegetable-Based Building-Blocks for the Synthesis of Thermoplastic Renewable Polyurethanes and Polyesters," *European Journal of Lipid Science and Technology* 115 (2013): 61–75.
- [77] C. Sivakumar and A. S. Nasar, "Hydroxyl- and Amine-Terminated Hyperbranched Polyurethanes Using AB₂-Type Azide Monomers: Synthesis, Characterization, Fluorescence, and Charge-Transfer Complexation Studies," *Journal of Polymer Science Part A: Polymer Chemistry* 47 (2009): 3337–3351.
- [78] T. Shioiri, K. Ishihara, and M. Matsui, "Cutting Edge of Diphenyl Phosphorazidate (DPPA) as a Synthetic Reagent – A Fifty-Year Odyssey," *Organic Chemistry Frontiers* 9 (2022): 3360.
- [79] Y. Akae, J. Sawada, K. Nakajima, and T. Takata, "The Effect of the Axle End Structure and Number of Through-Space Bonds on the Properties of Rotaxane Crosslinked Polymers," *Angewandte Chemie International Edition* 62 (2023): e202303341.
- [80] Y. Akae, H. Sogawa, and T. Takata, "Effective Synthesis and Modification of α -Cyclodextrin Based [3]Rotaxanes Enabling Versatile Molecular Design," *European Journal of Organic Chemistry* 22 (2019): 3605–3613.
- [81] Y. Akae, H. Sogawa, and T. Takata, "Evaluation of Induced Circular Dichroism via Through Space Chirality Transfer in α -Cyclodextrin-Based Rotaxanes Directed toward Fine Tuning," *Bulletin of the Chemical Society of Japan* 92 (2019): 1413–1418.
- [82] T. Shioiri, K. Ninomiya, and S. Yamada, "Diphenylphosphoryl Azide. New Convenient Reagent for a Modified Curtius Reaction and for Peptide Synthesis," *Journal of the American Chemical Society* 94 (1972): 6203–6205.
- [83] See ESI.
- [84] Y. Akae, H. Okamura, Y. Koyama, T. Arai, and T. Takata, "Selective Synthesis of a [3]Rotaxane Consisting of Size-Complementary Components and Its Stepwise Deslippage," *Organic Letters* 14 (2012): 2226–2229.
- [85] Y. Akae, Y. Koyama, S. Kuwata, and T. Takata, "Cyclodextrin-Based Size-Complementary [3]Rotaxanes: Selective Synthesis and Specific Dissociation," *Chemistry - A European Journal* 20 (2014): 17132–17136.
- [86] Y. Akae, H. Sogawa, and T. Takata, "Synthesis of a Structure Definite α -Cyclodextrin Based Macromolecular [3]Rotaxane Using a Size-Complementary Method," *Angewandte Chemie International Edition* 57 (2018): 11742–11746 (*Angew. Chem.* 130 (2018): 11916–11920).
- [87] O. Shelef, S. Gnaim, and D. Shabat, "Self-Immolative Polymers: An Emerging Class of Degradable Materials With Distinct Disassembly Profiles," *Journal of the American Chemical Society* 143 (2021): 21177–21188.
- [88] R. E. Yardley, A. R. Kenaree, and E. R. Gilles, "Triggering Depolymerization: Progress and Opportunities for Self-Immolative Polymers," *Macromolecules* 52 (2019): 6342–6360.
- [89] G. I. Peterson, M. B. Larsen, A. J. Boydston "Controlled Depolymerization: Stimuli-Responsive Self-Immolative Polymers," *Macromolecules* 45 (2012): 7317–7328.



The data supporting this article have been included as part of the Supplementary Information.

View Article Online
DOI: 10.1039/D6PY00409A

