Integration of Metal-Free Ring-Opening Metathesis Polymerization and Organocatalyzed Ring-Opening Polymerization through a Bifunctional Initiator

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Integration of Metal-Free Ring-Opening Metathesis Polymerization and Organocatalyzed Ring-Opening Polymerization through a Bifunctional Initiator

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We have investigated the use of metal-free ring-opening metathesis polymerization (MF-ROMP) in combination with organocatalyzed ring-opening polymerization (o-ROP) to produce diblock copolymers with highly disparate block compositions via exclusively metal-free methods. Use of a bifunctional initiator bearing a vinyl ether as organic initiator for MF-ROMP and an alcohol for initiation of o-ROP allowed for investigation of three synthetic approaches: 1) sequential polymerization with isolation of the intermediate macroinitiators, 2) simultaneous bidirectional polymerizations, and 3) "one-pot" sequential monomer addition. Macroinitiators formed by first conducting o-ROP were successfully used in subsequent MF-ROMP to prepare diblock copolymers. Simultaneous MF-ROMP and o-ROP was thwarted by incompatible cross-combinations of catalysts and monomers. Finally, a straightforward "one-pot" synthesis of block copolymers, using o-ROP followed by MF-ROMP, was realized by sequential addition of each monomer-catalyst combination.

Introduction:

The unique physicochemical properties of block copolymers make them attractive materials for a wide range of applications,[1] such as thermoplastic elastomers,[2] substrates for lithographic patterning,[3] and micelles for drug delivery systems.[4] Since block copolymers have applications in a broad array of areas, there has been tremendous effort focusing on their preparation. Traditionally, there are three different ways to prepare well-defined block copolymers: 1) polymer-polymer chain coupling of different segments;[5a-5e] 2) sequential addition of different monomers that can be polymerized by the same mechanism;[6a-6c] and 3) sequential or simultaneous polymerization of monomers that convert via different mechanisms, often realized by either post-modification techniques or bifunctional initiator approaches.[7a-7c] Although each method has unique strengths, we were attracted by the ability of dual polymerizations to create disparate block compositions arising from unique polymerization mechanisms of each block. For example, using a hetero-bifunctional initiator is an attractive method for growing a unique polymer segment from each initiator moiety. Moreover, since bifunctional initiators bear two initiation sites for two distinct polymerizations, block copolymers can be envisioned from 1) polymerization of an A-block, isolation of the resulting macroinitiator, and subsequent polymerization of a B-block; 2) one-pot sequential polymerizations of each block; and 3) simultaneous (orthogonal) polymerizations of two monomer classes, provided the reactive species of the different polymerizations are co-compatible. Thus far, numerous bifunctional initiators combining different polymerization methods (e.g., ATRP, RAFT, ROP, ROMP) have been synthesized and used to prepare well-defined block copolymers.[8a-8g] In general, for metal-mediated ROMP processes, numerous protocols have been developed for removing metallic byproducts from final materials, since residual complex may cause limitations in biomedical applications and interfere with electronic or optical properties.[9a] Moreover, in many industrial applications the metal initiators are not recoverable from thermoset materials and therefore present a recurring cost of manufacture.[9b] With the recent introduction of metal-free ROMP (MF-ROMP),[10a-10f] we became curious whether this method could be integrated with other polymerizations to provide an entirely organocatalyzed approach to block copolymers via dual polymerization from bifunctional initiators. Although appropriate bifunctional initiators could be obtained from standard synthetic outlay, a potential challenge was the fact that MF-ROMP exhibits much lower functional compatibility in comparison with traditional metal-mediated ROMP.[10d] Therefore, the exploration of

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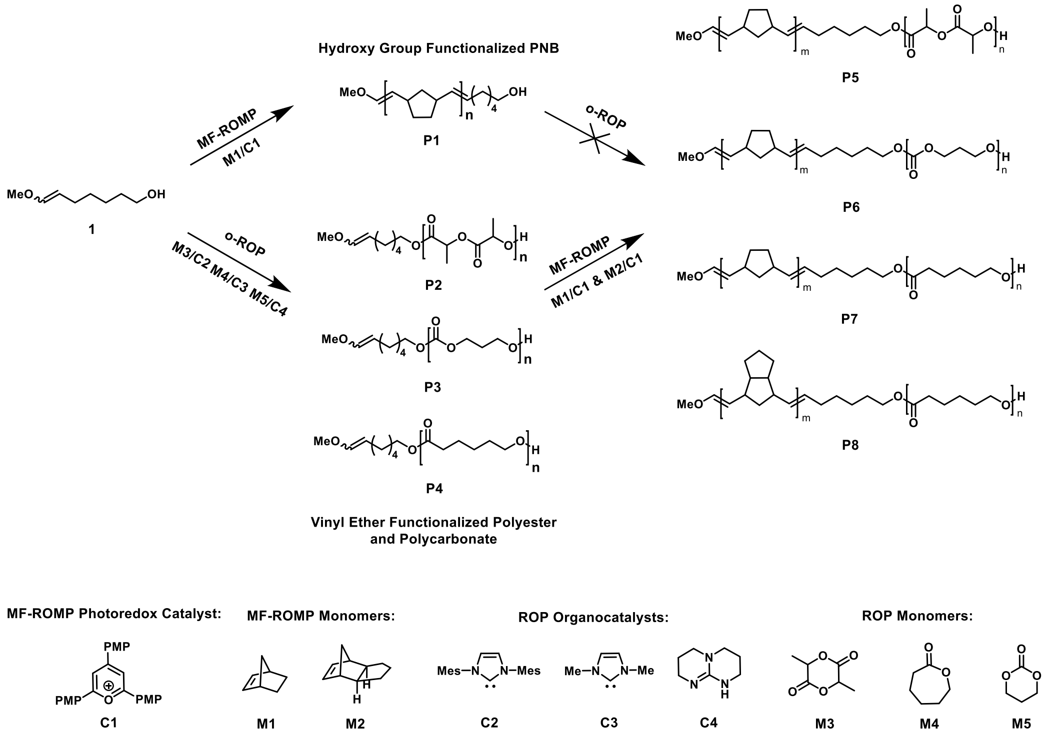


Scheme 1. Synthetic route toward functional block copolymers from bifunctional initiator **1**

compatibility is necessary, and the current study illustrates efficient, successful advances.

Results and Discussions

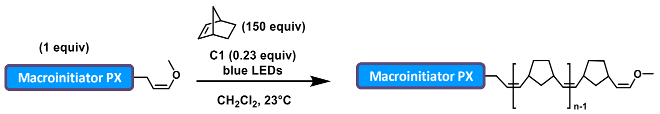
MF-ROMP is a type of controlled polymerization mediated by organic photoredox catalysts.[11a-11d] Instead of using metal-alkylidene initiators, MF-ROMP utilizes vinyl ethers as organic initiators that are reversibly activated through one-electron oxidation. To complement this polymerization, we selected organocatalyzed ROP (o-ROP), which can be mediated by nucleophilic organocatalysts.[12a-12c] Besides their metal-free merits, the combination of MF-ROMP and o-ROP also offer backbone compositions that display highly disparate physicochemical properties.[13]

To investigate the feasibility of integrated MF-ROMP and o-ROP from a single unit, we first prepared a bifunctional initiator bearing a vinyl ether at one terminus and a hydroxyl group at the other (**1**). We chose norbornene (**M1**) and exo-dihydrodicyclopentadiene (**M2**) as MF-ROMP monomers and three different o-ROP monomers, specifically *rac*-lactide (**M3**), *Ɛ*-caprolactone (**M4**), and cyclic trimethylene carbonate (**M5**).

The MF-ROMP of norbornene from bifunctional initiator **1** achieved decent conversion (55%). The resulting hydroxy end-capped polymer (**P1**) was isolated and then used as a macroinitiator for o-ROP. The following o-ROP from **P1** was met with limited success and we observed unreacted macroinitiator as determined by SEC analysis. The combination of low MF-ROMP conversion and incomplete chain extension from some fractions of **P1** indicated to us that the hydroxyl groups might undergo side reactions with activated vinyl ethers during MF-ROMP.[10d] It was demonstrated by Moeller and coworkers that single-electron oxidation of nucleophilic vinyl ethers will reverse their polarity to form electrophilic radical cations, which can be trapped by nucleophiles, such as alcohols.[14a-14c] In a previous report by Moeller and coworkers, it was discovered that compound **1** indeed resulted in products of methanol trapping of the radical cation.[15a, 15b]

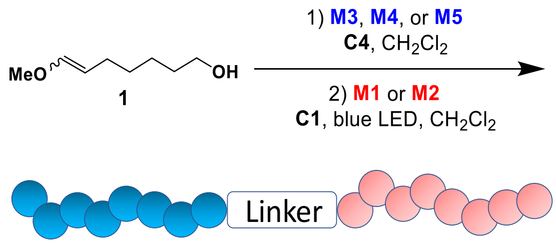
Upon switching the order of the polymerizations, bifunctional initiator **1** was found to facilitate o-ROP of each corresponding monomer and polymerizations reached high conversions (97% for **M3**, 88% for **M4**, and 99% for **M5**). In each case, we used an organocatalyst that had been previously reported to facilitate o-ROP of the specific monomer.[16a, 16b] The isolated macroinitiators (**P2**, **P3**, and **P4**) were then each used in attempted MF-ROMP to form diblock copolymers. Each macroinitiator was found to participate in MF-ROMP of norbornene (**M1**) with moderate to high conversion (Table 1), and SEC analysis of each crude product revealed monomodal molecular weight distributions consistent with high fidelity of chain extension. Since the T_g of the PNB blocks were close to the T_m of the polycaprolactone (PCL) blocks, we switched to **M2** for the MF-ROMP. Homopolymers of **M2** (PDCPD-H_2) are reported to have a T_g near 130 °C.[10b] DSC analysis clearly indicated thermal transitions characteristic of each block, which provided further support for successful preparation of block copolymers (See ESI for corresponding DSC thermogram).

Table 1. Characterization of block copolymers by MF-ROMP grafting from isolated macroinitiators



Entry	P*X*	$M_{n,GPC}$ of P*X* (kDa)	MF-ROMP conversion[f] (%)	$M_{n,GPC}$ of BCP[e] (kDa)	$Đ_{GPC}$[e]	PNB wt %[f]	thermal transition[g] (°C)
1	**P2**[b]	9.8	70	25.4	1.49	67	T_g: 35 and 55
2	**P3**[c]	19.7	64	32.3	1.45	33	T_g: 35 T_m: 56
3[a]	**P3**	19.7	60	38.5	1.39	44	T_g: 130 T_m: 56
4	**P4**[d]	16.1	85	33.6	1.69	50	T_g: -27 and 35

[a]M2 was used as monomer for MF-ROMP, [b][M3]/[1]/[C2]: 50/1/1.5, [c][M4]/[1]/[C3]: 200/1/1, [d][M5]/[1]/[C4]: 200/1/0.01, [e]Determined by gel permeation chromatography using in-line multiangle laser scattering and RI detection. Molecular weight dispersity (Đ) = M_w/M_n, [f]Calculated by ^{1}H-NMR analysis, [g]Determined by DSC.



Scheme 2. One-pot, two-step process for preparation of functional block copolymers integrating MF-ROMP and o-ROP (See ESI for detailed procedure)

The successful preparation of block copolymers from macroinitiators encouraged us to explore a one-pot method for tandem o-ROP and MF-ROMP (Scheme 2). Notably, MF-ROMP in the presence of monomeric lactide, caprolactone, or propylene carbonate failed to reach good conversion (Table S1). Presumably, the o-ROP monomeric species display greater nucleophilicity than their corresponding polymeric repeat units, which could be ascribed to steric encumbrance in the latter. Considering these observations, we did not pursue further a simultaneous dual polymerization. Additionally, these results indicated to us that high conversion of the o-ROP monomer would be required for success in the subsequent MF-ROMP. Since TBD could be used as an organocatalyst for each of the o-ROP monomers (**M3**, **M4**, and **M5**), it was chosen for the o-ROP process in this one-pot method.[17] In each polymerization, the o-ROP reactants and organocatalyst were combined in CH_2Cl_2 and stirred at room temperature. Aliquots were withdrawn for ^{1}H NMR and SEC analyses. Once maximum conversion of the o-ROP monomer was observed by ^{1}H NMR spectroscopy, the MF-ROMP monomer and photoredox catalyst were added to the solution in a single portion. Key results are summarized in Table 2.

As alluded to previously, the success of the MF-ROMP in the second polymerization was found to be dependent upon the monomer conversion achieved in the first (o-ROP) polymerization. When *rac*-lactide (**M3**) and cyclic trimethylene carbonate (**M5**) were chosen as monomers for the o-ROP process, high conversions were achieved and thus the following MF-ROMP process showed excellent conversion of norbornene (**M1**) as well (Table 2, entries 1 – 6). However, when *Ɛ*-caprolactone (**M4**) was selected as the o-ROP monomer, its conversion could not be raised greater than 78%, which stifled monomer conversion in the following MF-ROMP process. We also found that slightly increasing the loading of the MF-ROMP photoredox catalyst (**C1**) to compensate for consumption by the TBD significantly increased conversion in the MF-ROMP. It is noteworthy that TBD has been reported to dramatically decrease the rate of traditional Ru-mediated ROMP.[8f]

With successful methods for block copolymer synthesis at hand, we next focused on compositional and thermal characterization. SEC analyses (Figure 1A) were consistent with successful chain extension and high initiator efficiency in the formation of the second block. In each case, a monomodal distribution with increased molecular weight was observed for the block copolymer sample in comparison with the corresponding macroinitiator intermediate. Analysis by ^{1}H NMR spectroscopy clearly revealed signals consistent with each polymer block (Figure 1B). Based upon signal integrations, the composition of each block copolymer was found to correlate well with the monomer feed ratios and conversions, indicating that initiation effiency was high for each polymerization type. Copolymer compositions determined from TGA were also found to be consistent with ^{1}H NMR data. This was especially evident for **P5** and **P6**, which contain polylactide (PLA) and poly(trimethylene carbonate) (PTMC) blocks, because there was a plateau region in each TGA plot (Figure 1C). In general, thermal properties of block copolymers of the same composition were agnostic to either a two-post or one-pot method of synthesis (Figure 1D). One exception was PCL-b-PDCPD-H_2 (**P8**), which could be explained by different block lengths based upon the method of synthesis. Specifically, **P8** prepared from macroinitiator **P4** displayed distinguishable thermal transitions by DSC, whereas **P8** prepared via the one-pot method only showed thermal transitions for the PCL block (Figure 1D, orange line). Again, this is likely ascribed to relatively shorter PDCPD-H_2 blocks from the one-pot method,[18] which originated from lower **M2** conversion and therefore inhibition of MF-ROMP.

Conclusions

In conclusion, we successfully demonstrate an expanded utility of MF-ROMP by preparation of block copolymers via an integration of MF-ROMP and o-ROP from a bifunctional initiator. With the separation of intermediate macroinitiators after o-ROP, grafting-from MF-ROMP efficiently afforded diblock copolymers in high efficiency. Furthermore, a one-pot process was developed and that allowed for easy access block copolymers without isolation of intermediate macroinitiators. We anticipate useful variations of integrated MF-ROMP to provide entirely metal-free copolymers for a range of applications.

Table 2. One-pot preparation of block copolymers by MF-ROMP and o-ROP

entry	monomers	o-ROP		MF-ROMP		M_n after o-ROP(kDa)	M_n after MF-ROMP (kDa)	*Đ*
		[**M*X***]:[**1**]:[**C4**]	conversion (%)	[**M*X***]:[**1**]:[**C1**]	conversion (%)			
1	**M3/M1**	50 : 1.0 : 0.1	99	100 : 1.0 : 0.3	83	6.2	15.2	1.30
2	**M3/M1**	75 : 1.0 : 0.1	99	100 : 1.0 : 0.3	85	8.6	17.8	1.60
3	**M3/M1**	100 : 1.0 : 0.1	98	100 : 1.0 : 0.3	79	20	30.3	1.24
4	**M3/M1**	150 : 1.0 : 0.1	98	150 : 1.0 : 0.3	60	30	40.1	1.28
5	**M5/M1**	100 : 1.0 : 0.1	99	100 : 1.0 : 0.3	86	13	24.8	1.79
6	**M5/M1**	200 : 1.0 : 0.1	99	100 : 1.0 : 0.3	75	18	25.6	1.72
7	**M4/M1**	50 : 1.0 : 0.4	78	100 : 1.0 : 0.5	41	7.5	13.6	1.35
8	**M4/M2**	50 : 1.0 : 0.4	78	100 : 1.0 : 0.5	35	7.5	10.3	1.46

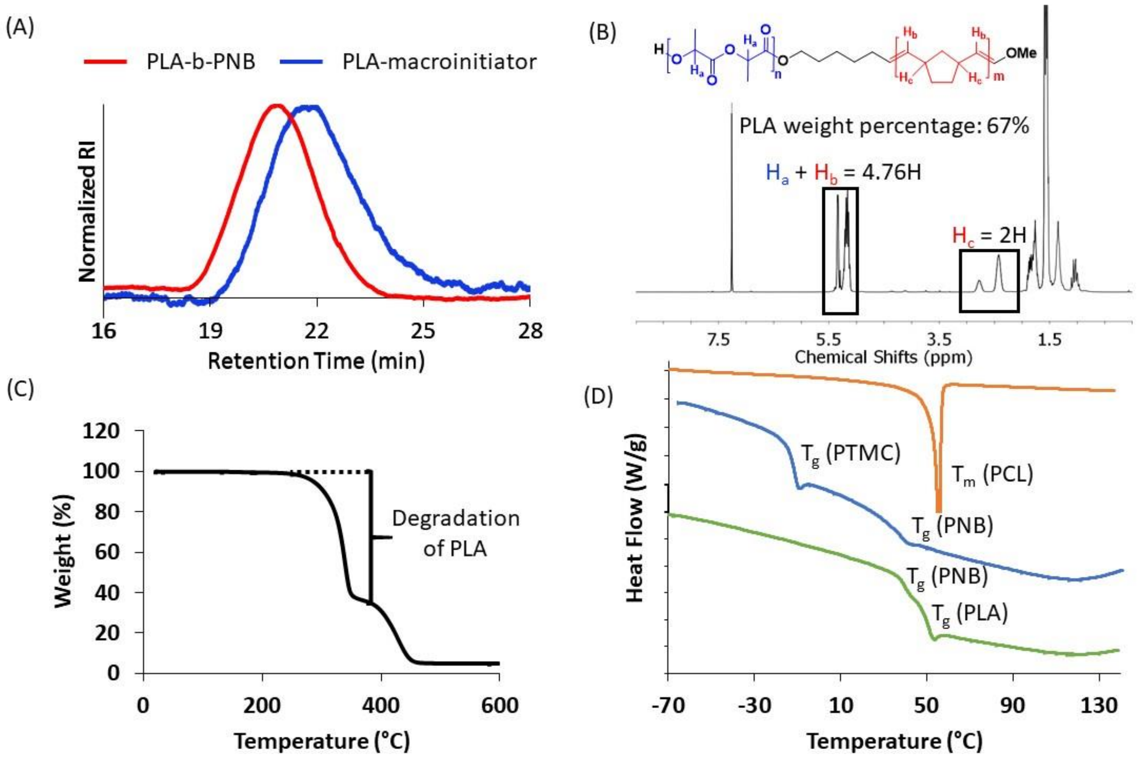


Figure 1. (A) SEC overlay of PLA-macroinitiator and PLA-b-PNB (entry 3 from Table 2), (B) ^{1}H-NMR spectrum of PLA-b-PNB (entry 3 from Table 2) and (C) TGA plot of PLA-b-PNB (entry 3 from Table 2) with 64 wt% of PLA block, (D) DSC thermograms (exotherm up) of block copolymers made from one-pot process (under nitrogen with a scanning rate of 5 °C/min). Orange line: entry 8 from Table 2; Blue line: entry 5 from Table 2; Green line: entry 4 from Table 2.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

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Notes and references

1 C. M. Bates and F. S. Bates, *Macromolecules*, 2017, **50**, 3-22.

2 J. Zhang, D. K. Schneiderman, T. Li, M. A. Hillmyer and F. S. Bates, *Macromolecules*, 2016, **49**, 9108-9118.

3 C. M. Bates, M. J. Maher, D. W. Janes, C. J. Ellison and C. G. Willson, *Macromolecules*, 2014, **47**, 2-12.

4 M. Elsabahy and K. L. Wooley, *Chem. Soc. Rev.*, 2012, **41**, 2545-2561.

5 (a) J. A. Opsteen and J. C. M. v. Hest, *Chem. Commun.*, 2005, **0**, 57-59; (b) W. Agut, D. Taton and S. Lecommandoux, *Macromolecules*, 2007, **40**, 5653-5661; (c) H. Durmaz, A. Dag, O. Altintas, T. Ergodan, G. Hizal and U. Tunca, *Macromolecules*, 2007, **40**, 191-198; (d) W. Lin, Q. Fu, Y. Zhang and J. Huang, *Macromolecules*, 2008, **41**, 4127-4135; (e) J. M. Notestein, L.-B. W. Lee and R. A. Register, *Macromolecules*, 2002, **35**, 1985-1987.

6 (a) M. Ouchi and M. Sawamoto, *Macromolecules*, 2017, **50**, 2603-2614; (b) S. Perrier, *Macromolecules*, 2017, **50**, 7433-7447; (c) C. W. Bielawski and R. H. Grubbs, *Prog. Polym. Sci.*, 2007, **32**, 1-29.

7 (a) M. Szwarc, *J. Polym. Sci., Part A: Polym. Chem.*, 1998, **36**, 9-15; (b) Y. Yagci and M. A. Tasdelen, *Prog. Polym. Sci.*, 2006, **31**, 1133-1170. (c) X. Guo, B. Choi, A. Feng and S. H. Thang, *Macromol. Rapid Commun.*, 2018, **39**, 1800479.

8 (a) O. Altintas, I. Yilmaz, G. Hizal and U. Tunca, *J. Polym. Sci., Part A: Polym. Chem.*, 2006, **44**, 3242-3249; (b) C. St Thomas, R. Guerrero-Santos and F. D'Agosto, *Polym. Chem.*, 2015, **6**, 5405-5413; (c) N. Chagneux, T. Trimaille, M. Rollet, E. Beaudoin, P. Gerard, D. Bertin and D. Gigmes, *Macromolecules*, 2009, **42**, 9435-9442; (d) C. Aydogan, C. Kutahya, A. Allushi, G. Yilmaz and Y. Yagci, *Polym. Chem.*, 2017, **8**, 2899-2903; (e) C. Fu, J. Xu, M. Kokotovic and C. Boyer, *ACS Macro. Lett.*, 2016, **5**, 444-449; (f) H. Jung, N. t. Brummelhuis, S. K. Yang and M. Weck, *Polym. Chem.*, 2013, **4**, 2837-2840; (g) I. Freudensprung, M. Klapper and K. Mullen, *Macromol. Rapid Commun.*, 2016, **37**, 209-214.

9 (a) G. C. Vougioukalakis, *Chem.-Eur. J.*, 2012, **18**, 8868-8880. (b) J. C. Mol, *J. Mol. Catal. A: Chem.* 2004, **213**, 39-45.

10 (a) K. A. Ogawa, A. E. Goetz and A. J. Boydston, *J. Am. Chem. Soc.*, 2015, **137**, 1400-1403; (b) A. E. Goetz and A. J. Boydston, *J. Am. Chem. Soc.*, 2015, **137**, 7572-7575; (c) L. M. M. Pascual, D. G. Dunford, A. E. Goetz, K. A. Ogawa and A. J. Boydston, *Synlett*, 2016, **27**, 759-762; (d) A. E. Goetz, L. M. M. Pascual, D. G. Dunford, K. A. Ogawa, Jr., D. B. Knorr and A. J. Boydston, *ACS Macro Lett.*, 2016, **5**, 579-582; (e) L. M. M. Pascual, A. E. Goetz, A. M. Roehrich and A. J. Boydston, *Macromol. Rapid Commun.*, 2017, **38**, 1600766; (f) P. Lu, N. M. Alrashdi and A. J. Boydston, *J. Polym. Sci., Part A: Polym. Chem.*, 1998, **55**, 2977-2982.

11 (a) N. A. Romero and D. A. Nicewicz, *Chem. Rev.*, 2016, **116**, 10075-10166; (b) N. Corrigan, S. Shanmugam, J. Xu and C. Boyer, *Chem. Soc. Rev.*, 2016, **45**, 6165-6212; (c) S. Dadashi-Silab, S. Doran and Y. Yagci, *Chem. Rev.*, 2016, **116**, 10212-10275; (d) J. T. Trotta and B. P. Fors, *Synlett*, 2016, **27**, 702-713.

12 (a) N. E. Kamber, W. Jeong, R. M. Waymouth, R. C. Pratt, B. G. G. Lohmeijer and J. L. Hedrick, *Chem. Rev.*, 2007, **107**, 5813-5840; (b) M. K. Kiesewetter, E. J. Shin, J. L. Hedrick and R. M. Waymouth, *Macromolecules*, 2010, **43**, 2093-2107; (c) H. Sardon, A. Pascual, D. Mecerreyes, D. Taton, H. Cramail and J. L. Hedrick, *Macromolecules*, 2015, **48**, 3153-3165.

13 S. Hu, J. Zhao, G, Zhang and H. Schlaad, *Prog. Polym. Sci.*, 2017, **74**, 34-77.

14 (a) A. Sutterer and K. D. Moeller, *J. Am. Chem. Soc.*, 2000, **122**, 5636-5637; (b) K. D. Moeller, *Synlett*, 2009, **8**, 1208-1218; (c) K. D. Moeller, *Chem. Rev.*, 2018, **118**, 4817-4833.

15 (a) B. Liu, S. Duan, A. C. Sutterer and K. D. Moeller, *J. Am. Chem. Soc.*, 2002, **124**, 10101-10111; (b) J. M. Campbell, H.-C. Xu and K. D. Moeller, *J. Am. Chem. Soc.*, 2012, **134**, 18338-18344.

16 (a) G. W. Nyce, T. Glauser, E. F. Connor, A. Mock, R. M. Waymouth and J. L. Hedrick, *J. Am. Chem. Soc.*, 2003, **125**, 3046-3056; (b) F. Nederberg, B. G. G. Lohmeijer, F. Leibfarth, R. C. Pratt, J. Choi, A. P. Dove, R. M. Waymouth and J. L. Hedrick, *Biomacromolecules*, 2007, **8**, 153-160.

17 B. G. G. Lohmeijer, R. C. Pratt, F. Leibfarth, J. W. Logan, D. A. Long, A. P. Dove, F. Nederberg, J. Choi, C. Wade, R. M. Waymouth and J. L. Hedrick, *Macromolecules*, 2006, **39**, 8574-8583.

18 L. Zhu, Y. Chen, A. Zhang, B. H. Calhoun, M. Chun, R. P. Quirk, S. Z. D. Cheng, B. S. Hsiao, F. Yeh and T. Hashimoto, *Phys. Rev. B.*, 1999, **60**, 10022-10031.

Integration of Metal-Free Ring-Opening Metathesis Polymerization and Organocatalyzed Ring-Opening Polymerization through a Bifunctional Initiator

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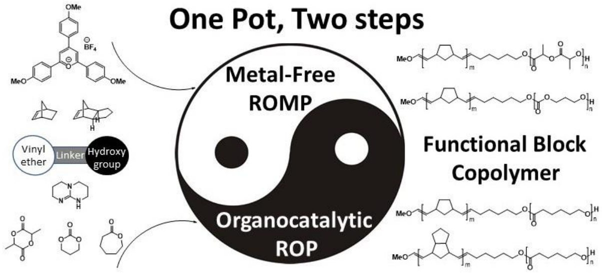
TOC Graphic



We demonstrate the first integration of metal-free ROMP and organocatalyzed ROP to provide entirely metal-free syntheses of block copolymers.