

Bio-derived Glycidyl Ethers: a Versatile Platform for Functional Polymers via Epoxide Polymerization

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Sandra Schüttner

Für meine Familie

*„The most enjoyable part of science is doing it.
It is sometimes very hard, sometimes very frustrating,
but extremely rewarding when you suddenly understand something.“*

Kip Thorne

Danksagung / Acknowledgments

Author Contributions

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Motivation and Objectives

Staudinger's groundbreaking work "On polymerisation" in 1920 marks the starting point of the field of polymer science.^{1,2} Less than a decade later, he reported on the synthesis of the aliphatic polyether poly(ethylene glycol) (PEG), emphasizing its unique water solubility (Figure 1).³ Today, more than 90 years later, PEG represents the gold standard of biomedical polymers, owing to its biocompatibility and unprecedented water solubility among aliphatic polyethers.^{4,5} In addition, its backbone inertness, high chain flexibility as well as a melting temperature, that can be adjusted in the physiological temperature range, renders PEG suitable for a plethora of applications.^{4,6,7} Since its commercialization beginning in the 1930s and 1940s, the use of PEG and its derivatives has been extended not exclusively to lubricants, non-ionic surfactants, food additives, cosmetics, polymer electrolytes and biomedical applications, for instance via the so called "PEGylation".^{4-6,8} In 2021, the global market of PEG alone was valued at approximately 4.5 billion dollars with an expected compound annual growth rate of 4.8%.⁹

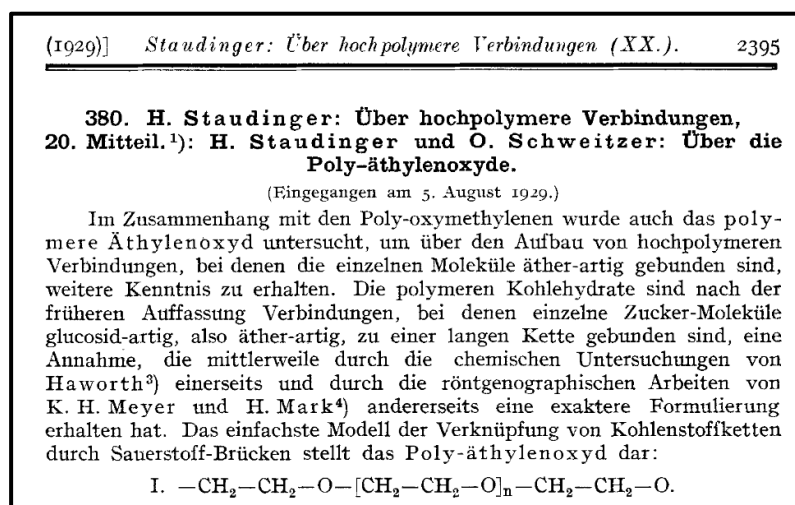


Figure 1: Extract from Staudinger's publication "Über die Poly-äthylenoxyde". Adapted with permission from Staudinger, H.; Schweitzer, O. Über hochpolymere Verbindungen, 20. Mitteil.: Über die Poly-äthylenoxyde. *Ber. dtsh. Chem. Ges. A/B* 1929, 62, 2395–2405.³ Copyright © 1929 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim.

Among several polymerization techniques, the anionic ring opening polymerization (AROP), characterized by its living nature, classically serves as the method of choice to synthesize well-defined PEGs with low dispersities.^{4,10} Given that PEG possesses inherently low backbone functionality, many researchers have dedicated efforts towards its functionalization. This illustrates the need as well as the versatile application potential for multifunctional PEGs (*mf*-PEG). Accordingly, the copoly-

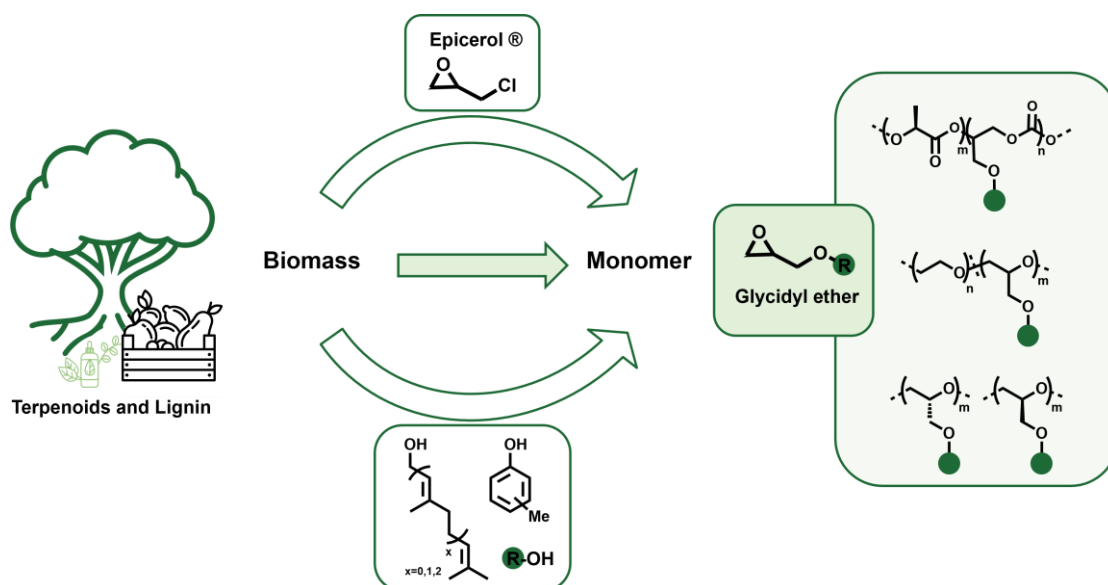
merization of ethylene oxide (EO) with functional epoxides is a facile strategy to overcome the limited functionality and produce tailor-made *mf*-PEGs.¹⁰

Lately, the predominant dependence on depleting fossil fuel resources and increasing environmental awareness have become important drivers for the synthesis of renewable and more sustainable polymer materials.¹¹ Although only 6 – 7% of world-wide oil and gas consumption accounts for polymer manufacturing, the vast majority of commercial polymers are derived from fossil-fuel raw materials.^{12,13} In 2022, 2.23 megatons of polymers were produced from bio-derived feedstock, yet, this capacity currently represents less than one per cent of the globally produced polymers (390 megatons).¹⁴ En route to more sustainable (polymer) chemistry, the concept of “green chemistry”, a term coined by Anastas and Warner in 1991, is comprised of 12 principles and plays a key role in terms of sustainability assessment. Postulating that “a raw material or feedstock should be renewable rather than depleting, wherever technically and economically practicable”, the 7th principle further highlights the prospective transformation from petrochemicals to biomass.^{15,16}

Despite the hitherto non-renewable nature of *mf*-PEGs, according to Williams and Hillmyer it is safe to presume that “polymers from renewable resources are here to stay”.¹³ Consequently, the functionalization of PEG is to be achieved in a bio-renewable manner. Nature provides a plethora of valuable hydrocarbon building blocks as renewable feedstock, such as terpenes, terpenoids and lignin. Although terpenes and terpenoids are naturally abundant in limited amounts, the technological progress of microbial terpene production via biosynthesis will most likely increase the availability and feasibility of these building blocks, without adversely affecting nature and competing against food production.^{17,18} Further, this family of compounds has received considerable attention as an attractive class of monomer precursors owing to their large functional and structural variety.^{12,19} The variety of polymerizable moieties as well as the access to easy-to-synthesize monomer synthons provides a versatile library of renewable monomers for polymerizations.^{12,19,20} Moreover, lignin biomass is globally distinguished as the largest natural source of aromatic carbon, as it constitutes a major component of lignocellulose. The deconstruction of this phenolic biopolymer creates a diverse range of lignin-derived compounds, such as monomeric phenols, for monomer synthesis and subsequent polymerization.^{21,22}

To address the emerging trend in polymer science towards the replacement of petrochemical monomers by biomass-derived building blocks for *mf*-PEGs, this doctoral thesis comprises the synthesis of bio-renewable epoxides and their subsequent

utilization in ring opening (co)polymerizations (ROP) (Scheme 1). The versatile applicability of terpenoid- and lignin-derived glycidyl ethers (GEs) is demonstrated via several ROP techniques to afford novel, partially bio-derived polymers.



Scheme 1: Schematic overview of the holistic pathway of (partially) bio-derived glycidyl ethers from biomass and their respective utilization for functional polymers via epoxide polymerization.

Specifically, the lack of bio-derived epoxide alternatives for the synthesis of *mf*-PEG sets a major objective of this thesis, which relies on the following questions:

- 1) “Can we expand the scope of functional epoxide monomers with bio-sourced alternatives, which in turn are polymerizable via ring opening polymerization (ROP)?”

Inspired by increasing efforts towards bio-renewable monomers, we investigated GEs based on terpenoid and lignin-based phenols, to expand the available epoxide toolbox with bio-derived alternatives (Chapter 2 – 4). This approach relies on the general structural motif of GEs, which are an easy-to-synthesize, but still underrated class of monosubstituted epoxides.²³ Following a facile one-pot synthesis protocol, epichlorohydrin (ECH)s is reacted with selected alcohols - either terpenoids or lignin-derived phenols, which have transpired as highly versatile monomeric building blocks.²⁴ Factors that influenced the monomer design were the required monosubstitution of the epoxide (i), followed by its stability under basic AROP conditions (ii).¹⁰ GEs (iii) are hardly prone to the well-known monomeric proton abstraction when targeting moderate molecular weights, while high purity (iv) is known to aid in avoiding transfer and termination reactions during polymerization.²⁵ To achieve the targeted bio-renewable character, the availability of green ECH poses a key prerequisite. Since starting production in 2012, Epicerol®, a bio-based ECH generated from renewable glycerol, is produced in amounts of 100 kilotons per annum.^{26–28} After

the design and synthesis of novel epoxide monomers, the general applicability of the GEs, namely terpenyl glycidyl ethers (TGEs) and phenyl glycidyl ethers (PhGEs), are explored in the anionic and catalytic ROP to produce amphiphilic polyethers, low- T_g polycarbonates for soft blocks in thermoplastic elastomers (TPEs) as well as isotactic poly(phenyl glycidyl ethers) (iPPhGEs).

Particularly, sustainable polycarbonates are of high interest due to their biocompatibility and biodegradability while using the greenhouse gas carbon dioxide (CO_2) as a C1 building block.^{12,29} Hence, we targeted the synthesis of a fully bio-renewable TPE based on CO_2 , citronellol glycidyl ether (CitroGE) and L-lactide acid (LLA) in Chapter 3. In addition, poly(L-lactide acid) (PLLA) is the only commercial polymer that is bio-based, biocompatible and biodegradable.³⁰ The resultant PLLA-b-PCitroGEC-b-PLLA triblock copolymers were studied in regard to their thermal and mechanical properties as well as phase-separation behavior and offer the possibility to be employed in biomedical applications.^{31,32}

2) *“Are terpenyl glycidyl ethers as bio-renewable alternatives suitable for the synthesis of well-defined amphiphilic polyether structures?”*

The copolymerization of EO with a hydrophobic monomer such as propylene oxide or alkyl glycidyl ethers leads to the formation of amphiphilic polyethers of statistical and blocklike structures that can self-assemble in aqueous solution.^{23,33} Banking on their high hydrophobicity, both the novel farnesyl glycidyl ether (FarGE), a TGE based on the sesquiterpenoid farnesol (C_{15}), and its hydrogenated derivative hexahydrofarnesyl glycidyl ether (HHFarGE) were investigated for the design of amphiphilic polyethers by systematically tailoring the comonomer ratio. With the aim of exploring their potential as partially bio-renewable (co)surfactants, the amphiphilic behavior in aqueous solution as well as their ability to enhance solubilization of microemulsions, the so-called “efficiency boosting effect”, were investigated (Chapter 2.1 and 2.2).^{34,35}

3) *“Terpenyl glycidyl ether: What kind of copolymerization behavior do the TGE/EO comonomer pairs feature in a statistical copolymerization?”*

Expanding the general scope of TGE monomers by varying the side chain length and conformation, unsaturated alkene moieties are introduced along the polyether backbone. Not only do chemical and physical properties of statistical *mf*-PEG strongly depend on the choice of comonomer and the comonomer ratio, but a detailed understanding of respective microstructure is essential to fine-tune the properties in

bulk and aqueous solution.^{4,36} In consequence, the systematic determination of the reactivity ratios and microstructure of each TGE/EO comonomer pair poses key objectives of Chapters 2.1 and 2.3. Further, the *in situ* ¹H NMR kinetic studies revealed the collective impact of structural differences of the TGEs on the copolymerization behavior regarding chain length (i), hydrophobicity (ii) and flexibility (iii).

4) “Is it possible to produce a polyether stereocomplex starting from bio-derived glycidyl ethers by manipulating the stereoregularity of poly(glycidyl ethers)?”

The AROP of a GE racemate generally leads to the formation of an amorphous, non-stereoregular (atactic) polyether. Yet, manipulating the stereoregularity of a polyether presents a compelling strategy to fundamentally alter the physical properties and thereby the possible fields of application.^{37,38} Particularly, stereocomplexation, which is defined as the stereoselective interaction of two enantiomerically complementary polymers that interlock, leads to improved crystallinity and has been shown to enhance the thermal and mechanical properties of polymers beyond what is possible via homocrystallization.³⁸ Capitalizing on a highly enantioselective catalyst, the stereoregular ROP of lignin-derived PhGE isomers is successfully explored to produce high-molecular weight *i*PPhGEs featuring an almost exclusive isotactic stereosequence.^{39,40} In an effort to generate a polyether stereocomplex *in situ* from a monomer racemate, a comparison of enantiopure and racemic *i*PPhGEs with regard to their thermal properties and PXRD patterns provide insight into the stereoselective interactions of opposite enantiomeric *i*PPhGE chains (Chapter 4). This stereoselective interaction is assumed to require strong dipole–dipole interactions or H-bonding, as observed for poly(lactide acid) stereocomplexes, the most widely studied stereocomplex representative.^{38,41} Consequently, stereocomplexation is hardly known for the class of polyethers. Hitherto, only one investigation on the formation of a polyether stereocomplex, synthesized from a sugar-based oxetane, has been reported.³⁷

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Bio-derived glycidyl ethers: a versatile platform for functional polymers via epoxide polymerization

Amphiphilic copolyethers as (co)surfactants

Terpenyl copolyethers: microstructure and functionalization

Bio-based TPEs for regenerative medicine

Bio-derived glycidyl ethers

Stereocomplex from a racemic monomer mixture

Capitalizing on the facile synthesis and wide application scope of GEs, this underrated monomer class represents the reoccurring theme throughout all thesis chapters (Figure 1). After a brief introduction in **Chapter 1**, this work focuses on the anionic ring opening (co)polymerization (ARO(c)P) of novel terpenyl glycidyl ethers (TGEs) in **Chapter 2**, including fundamental studies of the synthetic conditions and resulting properties. Farnesyl glycidyl ether (FarGE), a terpenoid-derived epoxide, represents a central building block, which set the foundation for this chapter. **Chapter 3** embodies

the potential of combining TGEs with carbon dioxide (CO₂) to generate novel thermoplastic elastomer (TPE) soft blocks. A joint venture utilizing lignin-derived glycidyl ethers with stereoselective catalysts for epoxide ROP presents the first stereocomplex formation starting from a racemic monomer mixture, as illustrated in **Chapter 4**.

Chapter 1 provides a brief introduction into the synthesis and properties of multifunctional polyethylene glycol (*mf*-PEG) structures, available synthons and targeted applications. A detailed illustration on the statistical copolymerization kinetics of epoxides and on the relevance of the reactivity ratios regarding the microstructure is provided, as *in situ* NMR kinetics represent a key technique of this thesis. The ROP of epoxides is presented with an emphasis on stereoregularity, thus, illuminating the fundamentals of the AROP and catalytic, stereoselective ROP (CSROP). In the context of stereoregularity, the phenomenon of stereocomplexation as a strategy to enhance polymer properties beyond enantiopure or atactic analogues is exemplified with key polymer representatives. As the identification and utilization of biomass-derived monomers for sustainable polymer synthesis poses a key challenge to scientists in both industry and academia, the promising class of terpenes and terpenoids is reviewed as a feedstock for sustainable polymer synthesis.

In **Chapter 2** the overlooked class of TGEs as terpene-derived monomer building blocks is explored and fundamentally investigated in the AROP. Despite their easy-to-synthesize nature, TGEs have been scarcely investigated in previous reports. This section consists of three important subchapters.

Chapter 2.1 presents the AROcP of the hydrophobic epoxide FarGE with ethylene oxide (EO). Due to the highly controlled nature of the AROP, series of well-defined, amphiphilic polyethers of block-like and random structure have been synthesized, allowing for facile tunability of the polymer properties by the FarGE monomer feed content. In-depth investigation of the properties in aqueous solution reveals self-assembly of the polymeric amphiphiles into micelles, characterized by very low critical micelle concentrations (CMCs). In summary, these partially biobased, farnesol-derived block copolymers represent an interesting alternative to fossil fuel-based, nonionic surfactants.

In the field of surfactants and surface-active materials, an enhanced solubilization performance offers the potential to reduce both environmental and ecological consequences. In **Chapter 2.2** an elaborated synthetic strategy towards partially bio-derived, amphiphilic polyethers as non-conventional surfactants is presented, utilizing

FarGE and its hydrogenated analogue hexahydrofarnesyl glycidyl ether (HHFarGE). Banking on previous work by Verkoyen et. al. and the excellent control over the polymerization during crown ether-assisted AROP, two series (using FarGE and HHFarGE) of well-defined, non-ionic block copolymer surfactants with tailor-made amphiphilicity and low CMCs are obtained. In a collaboration with the Sottmann group (University of Stuttgart), the synthesized amphiphiles were applied as co-surfactants to investigate the phase behavior in microemulsions, demonstrating an improved efficiency for all block copolymers. The concept of efficiency boosting relies on the adsorption of amphiphilic copolymers into the surfactant membrane, from where they extend in a mushroom-like conformation into the oil and water interlayer, respectively.

Chapter 2.3 expands the general scope of TGE monomers by varying the side chain length and conformation, allowing for fine-tuning of *mf*-PEG properties via copolymerization with EO. To elucidate the microstructure of the copolymers, the copolymerization behavior of each TGE/EO comonomer pair was examined via ^1H NMR *in situ* kinetic measurements. This reveals a change from ideally random to gradient copolyether microstructure ($r_{\text{EO}} > r_{\text{TGE}}$), influenced by the chain length and hydrophobicity of the respective TGE. The resulting statistical copolymers are enriched with unsaturated alkene moieties towards the polymer chain end, paving the way to post-functionalization such as thiol-ene click and hydrogenation. To the best of our knowledge, the diimide reduction using potassium azodicarboxylate is presented for the first time in polymer hydrogenation, which is attractive due to facile purification.

Chapter 3 addresses the sequential synthesis of a novel, fully bio-derived TPE, namely PLLA-*b*-PCitroGEC-*b*-PLLA. The key aspect of this work is the application of a peculiar, low glass transition temperature polycarbonate, poly(citronellyl glycidyl ether carbonate) (PCitroGEC), and, in turn, phase-separation by combining chemically and structurally dissimilar blocks. Thermal and small-angle X-ray scattering investigations indicate the anticipated phase-separation, allowing for the compilation of an experimental phase-diagram for this series of triblock copolymers. Mechanical measurements demonstrate elasticity of these polycarbonate-polyester TPEs with low E-moduli (1.43 to 2.5 MPa), rendering the PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers suitable as materials in soft tissue engineering.

Chapter 4 highlights the *in situ* polyether stereocomplex formation from a racemic phenyl glycidyl ether mixture. Synthetically, the enantioselective and isoselective ROP was explored using both the enantiopure and racemic version of a cobalt salen bimetallic complex, resulting in highly isotactic polyethers. While enantioselective

polymerization produces an enantiopure polyether strand, isoselective ROP leads to concurrent formation of both stereoconfigurations (*R* and *S*). Isoselective ROP and mixing equimolar amounts of the enantiopure isotactic polyethers (*R* and *S* produced separately via enantioselective ROP) both result in stereocomplexation and a considerably higher melting temperature compared to the homochiral parent polymer. Intriguingly, the high polyether tacticity in combination with potential phenyl stacking is sufficient for the formation of a polyether stereocomplex, despite the absence of significant dipole-dipole interactions.

Appendix Chapters (contributions as a coauthor)

Chapter A1 covers a fundamental investigation of the carbanionic polymerization of 4-trimethylsilylstyrene (4TMSS), featuring ambiguous electronic characteristics. Besides well-defined di- and triblock copolymers, statistical copolymers with isoprene and styrene were prepared. Real-time ^1H NMR kinetic measurements unraveled a moderate, gradient-like composition profile due to copolymerization, however, reactivity ratios are inverted for the 4TMSS/*S* and 4TMSS/*I* comonomer pairs. Overall, the utilization of 4TMSS allows for the synthesis of tailor-made copolymer structures with respect to thermal properties and overall hydrophobicity.

Chapter A2 investigates the copolymerization behavior of EO and two GEs, respectively, via *in situ* NMR kinetic measurements with respect to monomer structure and solvent. The experiments reveal preferred incorporation of the respective GE compared to EO, irrespective of the solvent utilized during polymerization. Density functional theory (DFT) calculations emphasize that the microstructure is strongly affected by the chelation capability of GEs with the polymer chain end counterion and, in turn, by the ether-containing monomer side groups. Differences in solvent polarity influence (i) counterion solvation and (ii) chelation capability, leading to a disparity of the reactive ratios with decreasing solvent polarity.

In **Chapter A3**, a new approach to crosslinkable copolyethers without post-polymerization modifications is presented. To this end, a tailorable amount of cinnamoyl side chains is incorporated into poly(glycerol) by capitalizing on the monomer-activated ROP of a glycidyl ester, namely glycidyl cinnamate (GC), with ethoxyethyl glycidyl ether (EEGE). Subsequent to copolymerization, the primary hydroxyl functionalities are released to increase polymer hydrophilicity, and UV light exposure enables photo-crosslinking via dimerization of the cinnamoyl moiety.

Zusammenfassung

Die vorliegende Doktorarbeit befasst sich mit der Synthese und Anwendung bio-basierter Glycidylether (GEs) als neuartige Bausteine für multifunktionelle Polyether und Polycarbonate. Die Synthesestrategie beruht auf dem Einsatz bio-basierter Rohstoffe wie Terpenoide und lignin-basierten Verbindungen in Epoxid-Synthone, welche sich für den Einsatz in der Ringöffnungspolymerisation (ROP) eignen. Als vorherrschender Trend in der Polymerwissenschaft zielt die Substitution endlicher fossiler Rohmaterialien durch biologisch erneuerbare Alternativen darauf ab, Wege zu nachhaltigeren, aber maßgeschneiderte Polymermaterialien zu eröffnen.

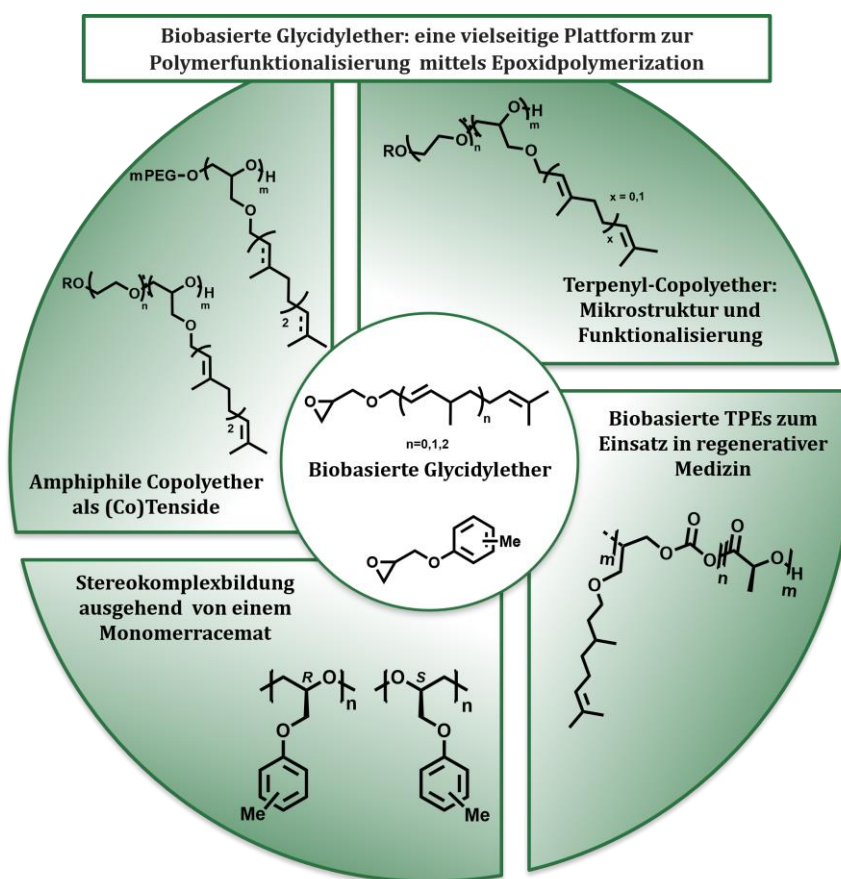


Abbildung 1: Übersicht der eingesetzten bio-basierten Glycidylether und ihren jeweiligen Umfang in der Polymersynthese sowie Anwendungsbereiche.

Basierend auf der einfachen Synthese und breiten Anwendung von Terpenylglycidylethern (TGEs) repräsentiert diese unterschätzte Monomerklasse das Leitmotiv in allen Kapiteln dieser Arbeit (Abbildung 1). Nach einer kurzen Einleitung in **Kapitel 1** konzentriert sich der nächste Abschnitt auf die anionische ringöffnende (Co-)Polymerisation (ARO(c)P) neuartiger TGEs in **Kapitel 2**, das grundlegende Untersuchungen der Synthesebedingungen und der resultierenden Polymereigen-

schaften einschließt. Farnesylglycidylether (FarGE), ein terpenbasiertes Epoxid, stellt einen zentralen Baustein dar, der die Grundlage für dieses Kapitel bildet.

Kapitel 3 verdeutlicht das Potenzial der Kombination von TGEs mit Kohlenstoffdioxid (CO₂) als neuartige TPE-Weichblöcke. Eine Zusammenarbeit mit dem Arbeitskreis von Geoffrey Coates (Cornell University, USA) zur Verwendung von lignin-basierten GEs mit stereoselektiven Katalysatoren für die ringöffnende Epoxidpolymerisation zeigte erstmals eine Stereokomplexbildung eines Polyethers ausgehend von einer racemischen Monomermischung, wie in **Kapitel 4** dargestellt.

Kapitel 1 bietet eine kurze Einführung in die Synthese und Eigenschaften von multifunktionalem Poly(ethylenglykol) (*mf*-PEG) unter Einbeziehung verfügbarer Synthone und möglichen Anwendungsbereichen.

Im Zusammenhang mit der Epoxid-Copolymerisation wird ein Einblick in die Theorie der zugrundeliegenden statistischen Copolymerisationskinetik sowie der Bedeutung der Copolymerisationsparameter für die Mikrostruktur gegeben, da ¹H-NMR-Kinetikuntersuchungen von Epoxiden ein zentrales Thema dieser Arbeit darstellen. Die ROP von Epoxiden wird in Bezug auf die Grundlagen der AROP sowie der katalytischen, stereoselektiven ROP (CSROP) beleuchtet, wobei ein zusätzlicher Schwerpunkt auf der Stereoregularität von Polyethern liegt. In diesem Kontext wird das Phänomen der Stereokomplexierung als Strategie zur Verbesserung von Polymereigenschaften im Vergleich zu ihren enantiomerenreinen oder ataktischen Analoga anhand von polymeren Schlüsselverbindungen veranschaulicht. Da die Identifizierung und Nutzung von aus Biomasse gewonnenen Monomeren eine zentrale, aktuelle Herausforderung für Polymerwissenschaftler darstellen, wird die vielversprechende Klasse der Terpene und Terpenoide als Ausgangsmaterial für eine nachhaltigere Polymersynthese präsentiert.

In **Kapitel 2** wird die terpenoid-basierte Monomerkategorie der TGEs sowie deren Polymerisationsverhalten in der AROP untersucht. Trotz ihrer einfachen Synthesemöglichkeiten sind bisher nur wenige wissenschaftliche Arbeiten bekannt.

Kapitel 2.1 stellt die AROcP des terpenoid-basierten, hydrophoben FarGE mit Ethylenoxid (EO) vor. Aufgrund der hervorragenden Kontrolle der AROP wurde eine Reihe definierter, amphiphiler Polyether synthetisiert, die von statistischen zur blockartigen Mikrostrukturen reichen. Sowohl die Amphiphilie als auch die thermischen Polymereigenschaften werden dabei über das Comonomerverhältnis gesteuert. Eine eingehende Untersuchung der Eigenschaften in wässriger Lösung zeigt

eine Selbstorganisation der polymeren Amphiphile zu Mizellen, die durch sehr niedrige kritische Mizellkonzentrationen (CMCs) charakterisiert sind.

Im Gebiet der Tenside und oberflächenaktiven Materialien bietet eine verbesserte Solubilisierungsleistung das Potenzial, sowohl ökologische Auswirkungen als auch Kosten zu reduzieren und kann damit maßgeblich zu nachhaltigeren Anwendungslösungen beitragen. In **Kapitel 2.2** wird die Synthesestrategie für partiell bio-basierte, amphiphile Polyethertenside unter Verwendung von FarGE und seinem hydrierten Analogon Hexahydrofarnesylglycidylether (HHFarGE) vorgestellt. Aufbauend auf den Vorgängerarbeiten von Verkoyen et. al. werden zwei Serien (unter Einsatz von FarGE und HHFarGE) wohldefinierter Block-Copolymer-Tenside mit maßgeschneiderter Amphiphilie und niedrigen CMCs erhalten. In Zusammenarbeit mit dem Arbeitskreis Sottmann (Universität Stuttgart) wurden die synthetisierten Amphiphile als Co-Tenside eingesetzt, um das Phasenverhalten in Mikroemulsionen zu untersuchen. Es zeichnete sich durch die Zugabe kleiner Diblockcopolymermengen eine Effizienzsteigerung für alle synthetisierten Strukturen ab. Hierbei beruht das Konzept der Effizienzsteigerung (efficiency boosting) auf der Adsorption der amphiphilen Copolymere in die Tensidmembran, von wo aus sie sich in einer pilzartigen Konformation in die Öl-Wassergrenzschicht ausbreiten.

In **Kapitel 2.3** wird der Anwendungsbereich der TGE-Monomere aufgrund ihrer strukturellen Vielfalt bezüglich der Seitenkettenlänge und -konformation erweitert, sodass die Polymereigenschaften gezielt durch den Einbau von Seitenketten entlang des PEG-Polymerückgrats variiert werden können. Um die Mikrostruktur der Copolymere zu bestimmen, wurde das Copolymerisationsverhalten jedes TGE/EO-Comonomer-Paars mittels *in situ* ^1H -NMR-Kinetikmessungen untersucht. Dabei zeichnet sich der Trend ab, dass mit zunehmender Seitenkettenlänge und -hydrophobizität der jeweiligen TGEs die Differenz der Copolymerisationsparameter steigt. Der Übergang von einer ideal statistischen zu einer gradientartigen Copolyether-Mikrostruktur ($r_{\text{EO}} > r_{\text{TGE}}$) resultiert demnach in einem bevorzugten Einbau der TGEs am Polymerkettenende. Die Doppelbindungen der Alkenylseitenketten können in einer polymeranalogen Reaktion, wie eine Thiol-En-Click-Reaktion und durch Hydrierung, teilweise quantitativ modifiziert werden. Nach unserem Kenntnisstand wird die Diimid-Reduktion unter Verwendung von Kaliumazodicarboxylat zum ersten Mal in der Polymerhydrierung eingesetzt und bringt insbesondere Vorteile in Bezug auf den Aufreinigungsprozess mit sich.

Kapitel 3 befasst sich mit der sequenziellen Synthese eines neuartigen, biobasierten PLLA-*b*-PCitroGEC-*b*-PLLA Triblockcopolymer-TPEs. Der Schlüsselaspekt dieser Arbeit ist sowohl die Verwendung des Poly(citronellylglycidylethercarbonat)s (PCitroGECs), welches durch seine niedrige Glasübergangstemperatur eine besondere Stellung unter Polycarbonaten einnimmt, als auch die gezielte Phasenseparation durch den Einsatz chemisch unterschiedlicher und somit nicht-mischbarer Blockstrukturen. Thermische Untersuchungen und Röntgenkleinwinkelstreuung bestätigen die erwartete Phasentrennung und ermöglichen die Erstellung eines experimentell bestimmten Phasendiagramms der hergestellten Triblockcopolymeren. Mechanische Messungen belegen die Elastizität dieser Polycarbonat-Polyester-TPEs mit niedrigen E-Modulen (1,43 bis 2,5 MPa), wodurch sich diese als weiche Materialien in der regenerativen Medizin eignen.

Kapitel 4 beleuchtet die *in situ*-Bildung von Polyether-Stereokomplexen ausgehend von einem Phenylglycidylether-Racemat. Synthetisch wurde die enantioselektive und isoselektive ROP unter Einsatz eines Cobalt-Salen-Bimetallkomplexes durchgeführt, welche beide zu hoch isotaktischen Polyethern führten. Während die enantioselektive Polymerisation einen enantiomerenreinen Polyetherstrang erzeugt, führt die isoselektive ROP zur gleichzeitigen Bildung enantiomerenreiner Polyether gegensätzlicher Stereokonfigurationen (*R* und *S*). Sowohl die isoselektive ROP als auch das Mischen äquimolarer Mengen der enantiomerenreinen, isotaktischen Polyether (*R* und *S*, getrennt durch enantioselektive ROP hergestellt) führt zur Stereokomplexierung und damit verbundenen höheren Schmelzpunkten im Vergleich zum enantiomerenreinen Polyether. Interessanterweise ist aufgrund der hohen Polyethertaktizität und potenzieller „Phenylstapelung“ die Bildung eines Polyether-Stereokomplexes ohne signifikante Dipol-Dipol-Wechselwirkungen möglich.

Anhang-Kapitel

Kapitel A1 behandelt die grundlegende Untersuchung der carbanionischen Polymerisation von 4-Trimethylsilylstyrol (4TMSS), welches sich durch komplexe elektronische Eigenschaften auszeichnet. Neben gut definierten Di- und Triblockcopolymeren wurden statistische Copolymeren mit Isopren und Styrol hergestellt. Zeitaufgelöste ¹H-NMR-Kinetikmessungen ergaben einen Gradientenmikrostruktur für die Copolymerisationen, jedoch wird im direkten Vergleich eine Inversion der Copolymerisationsparameter für die 4TMSS/*S*- und 4TMSS/*I*-Comonomerpaare festgestellt. Insgesamt ermöglicht die Verwendung von 4TMSS die Synthese maßgeschneiderter

Copolymerstrukturen, insbesondere in Bezug auf deren thermische Eigenschaften und Hydrophobie.

In **Kapitel A2** wird das Copolymerisationsverhalten zweier GE mit EO mittels *in situ* ^1H -NMR-Kinetikmessungen im Hinblick auf den Einfluss der Monomerstruktur und des Lösungsmittels untersucht. Die Experimente offenbarten einen bevorzugten Einbau des jeweiligen GEs im Vergleich zu EO, unabhängig von dem zur Polymerisation verwendeten Lösungsmittel. Dichtefunktionaltheoretische (DFT-) Berechnungen zeigen, dass die Polyethermikrostruktur stark von der Komplexierungsfähigkeit des GEs mit dem Gegenion des Polymerkettenendes und somit auch von den etherhaltigen Monomerseitengruppen beeinflusst wird. Polaritätsunterschiede des Lösungsmittels beeinflussen (i) die Solvatisierung des Gegenions und (ii) die Komplexierungsfähigkeit, sodass es mit abnehmender Lösungsmittelpolarität zu einer stärkeren Ungleichheit der Copolymerisationsparameter des jeweiligen Comonomerpaars kommt.

In **Kapitel A3** wird ein neuer Ansatz zu vernetzbaren Copolyethern vorgestellt, für die keine polymeranaloge Modifizierung zur Vernetzung erforderlich ist. Zu diesem Zweck wird ein gezielter Anteil von Cinnamoyl-Seitenketten in Polyglycerol eingebaut, indem Glycidylesterglycidylcinnamat (GC) mit Ethoxyethylglycidylether (EEGE) mittels monomeraktivierter ROP copolymerisiert wird. Anschließend werden die primären Hydroxylfunktionalitäten freigesetzt, um die Hydrophilie des Polymers zu erhöhen. Die Photovernetzung erfolgt über die Dimerisierung der Cinnamoyl-Einheiten mit UV-Licht.

Graphical Abstract

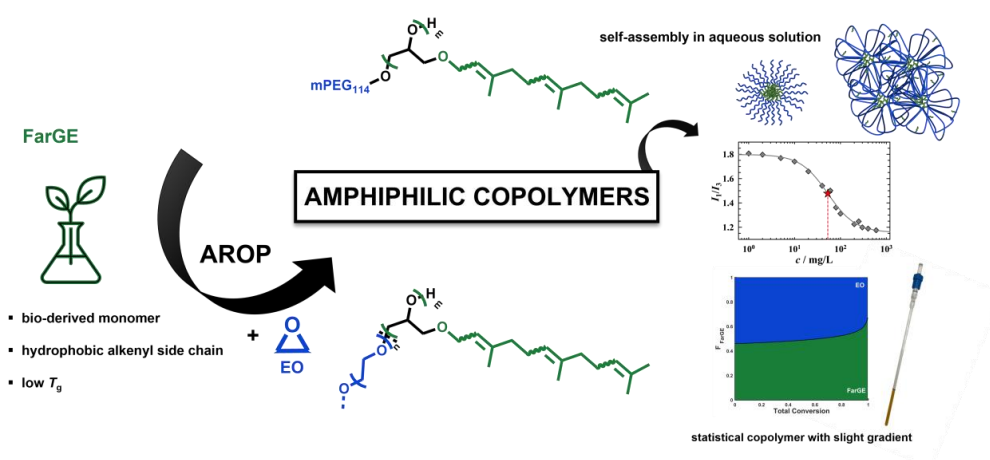
Graphical Abstract

Chapter 2:

Terpenyl Glycidyl Ethers in Anionic Ring Opening Polymerization

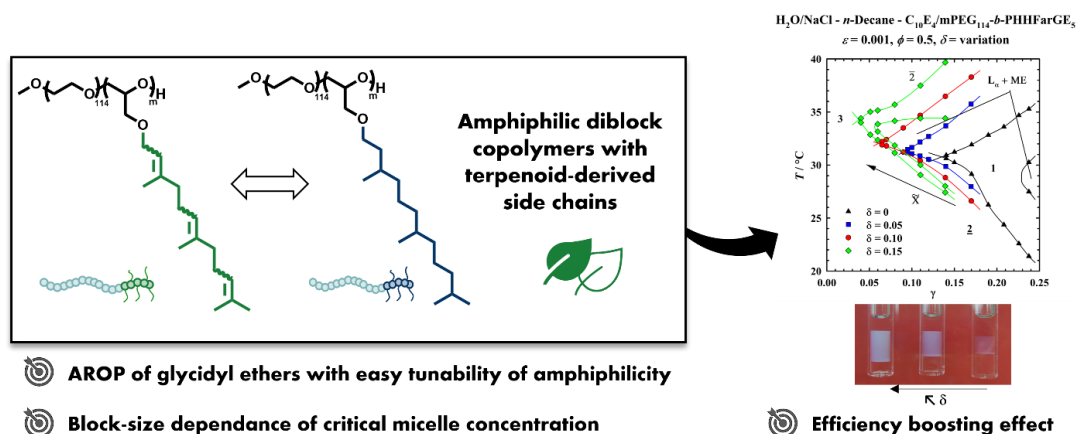
Chapter 2.1:

Anionic Ring Opening Copolymerisation of Farnesyl Glycidyl Ether: Fast Access to Terpenoid-derived, Amphiphilic Polyether Architectures



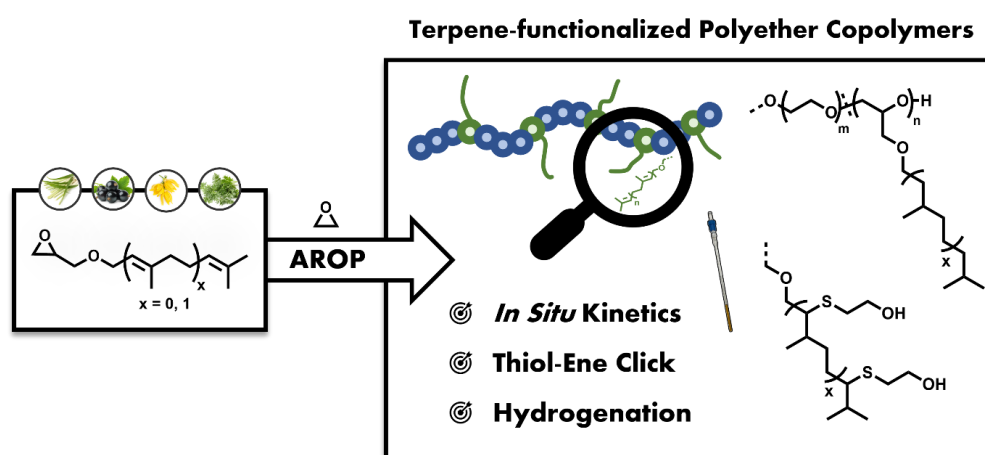
Chapter 2.2

Amphiphilic Bio-Based Farnesyl Glycidyl Ether Block Copolymers: Aqueous Self-Assembly and Solubilization Enhancement



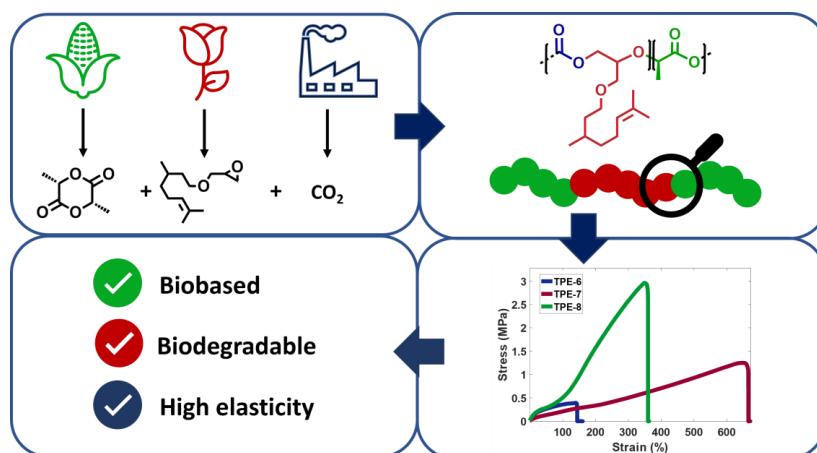
Chapter 2.3

Poly(Terpenyl Glycidyl Ether)s: Copolymerization with Ethylene Oxide, Properties, and Functionalization



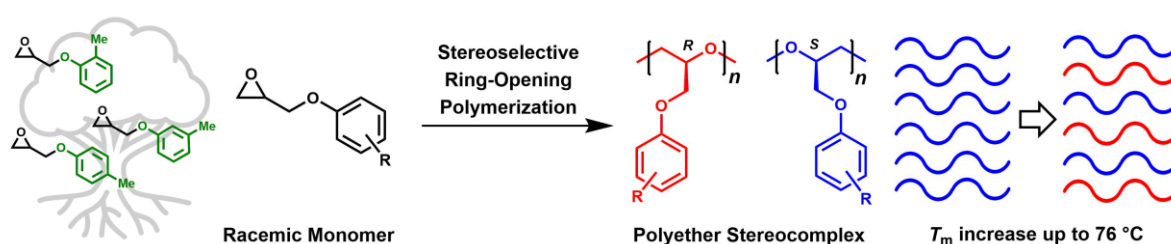
Chapter 3

Biobased Thermoplastic Elastomers derived from Citronellyl Glycidyl Ether, CO₂ and Polylactide



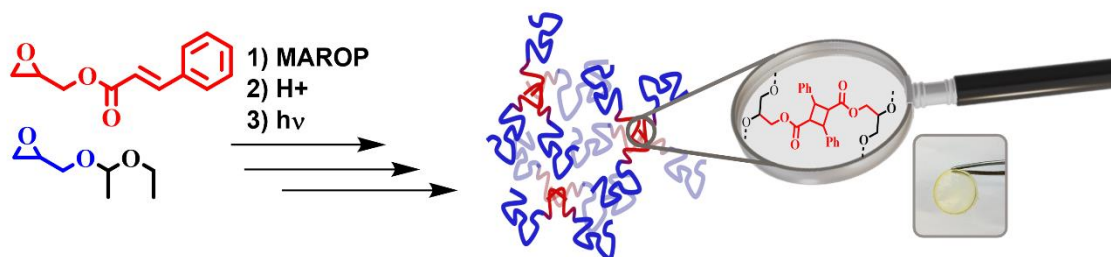
Chapter 4:

Stereoregular Poly(Phenyl Glycidyl Ether)s: *In Situ* Formation of a Polyether Stereocomplex from a Racemic Monomer Mixture



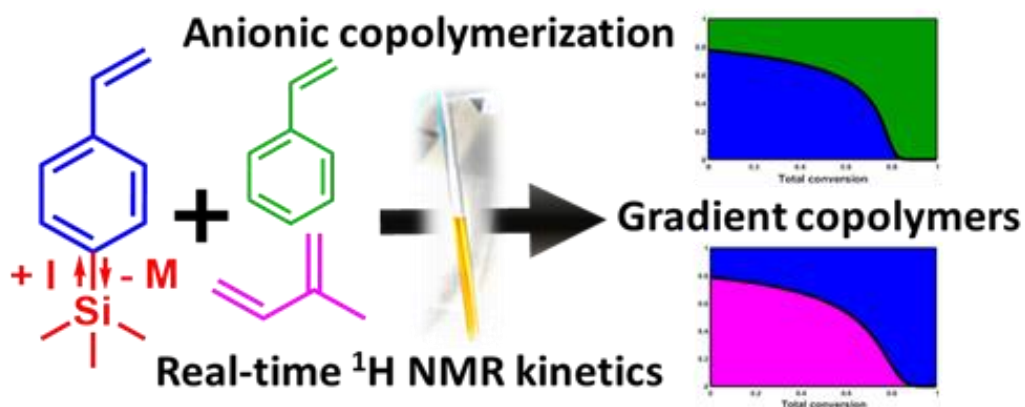
Appendix Chapter A1:

Glycidyl Cinnamate: Copolymerization with Glycidyl Ethers, In-Situ NMR Kinetics, and Photocrosslinking



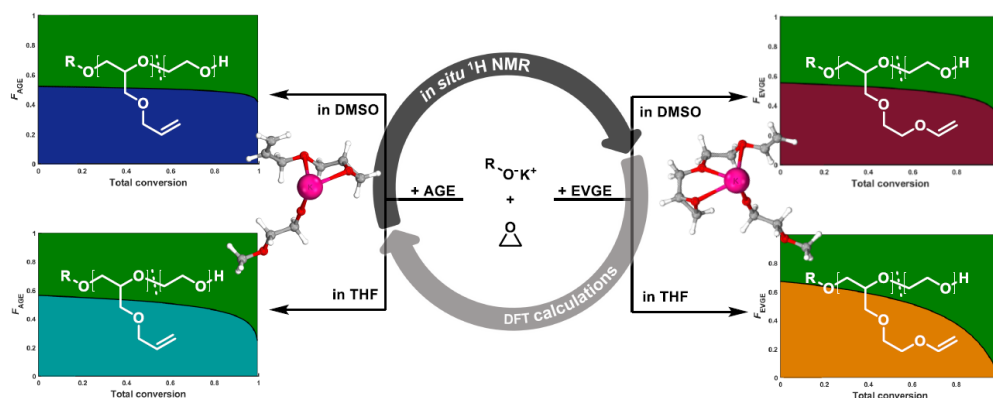
Appendix Chapter A2:

Anionic Copolymerization of 4-Trimethylsilylstyrene: From Kinetics to Gradient and Block Copolymers



Appendix Chapter A3:

In Situ Kinetics Reveal the Influence of Solvents and Monomer Structure on the Anionic Ring-Opening



Chapter 1

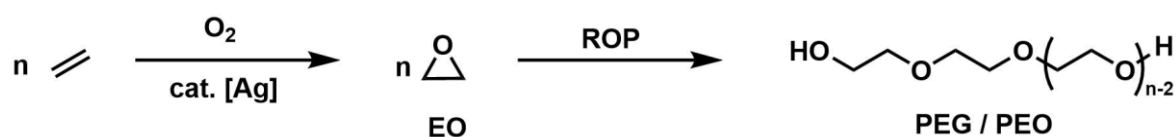
Introduction

1 Introduction

This chapter provides an overview of the synthesis and properties of multifunctional poly(ethylene glycols) (*mf*-PEGs) via anionic ring opening polymerization (AROP), including polymerization kinetics, and catalytic stereoselective ring opening polymerization (CSROP). Particular focus has been placed on the underrated class of glycidyl ethers (GEs) as epoxide building blocks to afford novel types of multifunctional polyethers. Highlighting the effects of stereoregularity in polymers, the concept of stereocomplexation is discussed. Furthermore, terpenes and terpenoids are presented as highly versatile class of monomer building blocks to achieve more sustainable polymer synthesis.

Polyethylene glycol

Poly(ethylene glycol) (PEG) is generated by the ring opening polymerization (ROP) of ethylene oxide (EO), described by Wurtz as early as 1863.¹ Staudinger and Schweitzer pioneered the AROP of EO in 1929, which remains the most relevant technique in both industry and academia.^{2,3} Scheme 1 shows the general synthesis sequence for the manufacture of PEG. Traditionally, EO is produced via silver-catalyzed epoxidation of ethylene at high pressure and a temperature of 300 °C.^{4,5} Moreover, recent efforts toward bio-renewability of commodity chemicals include the redox-mediated electrosynthesis of EO from CO₂ and water.⁶



Scheme 1: General synthesis sequence of PEG, starting from silver-catalyzed ethylene oxidation and subsequent ROP of EO.

As the most prominent representative of the class of aliphatic polyethers, PEG is characterized by its CH₂-CH₂-O-ether linkage in the polymer backbone.⁵ When exceeding molecular weights of 30.000 g mol⁻¹, it is also known as poly(ethylene oxide) (PEO), referring to its pristine monomer building block.⁷ In the biomedical context, the abbreviation PEG is exclusively used, whereas the IUPAC nomenclature gives the term poly(oxyethylene)-α-hydro-ω-hydroxy.^{5,7} PEG is distinguished by its remarkable property profile and excels due to its biocompatibility and excellent solubility in both water and organic solvents.^{2,7-9} PEG's hydrophilic character is based on a superior structural compatibility between water and the polyether backbone, which is attributed

to the intermolecular spacing of the oxygen atoms in the backbone.⁹ This allows the formation of an effective hydration sphere, consisting of up to four aggregated water molecules per EO unit.^{10,11} Intriguingly, the methylene group of polypropylene oxide (PPO) is already sufficient to prevent the organization of water along the backbone, consequently reducing the aqueous solubility.⁸ Yet, PEG does not feature unlimited aqueous solubility when heated as the beneficial hydration sphere is dissipated due to entropic effects.¹⁰ Hence, PEG is not soluble above the so-called lower critical solution temperature (LCST) of 100 °C. When copolymerizing EO with a functional epoxide, the incorporation of functional groups along the polyether backbone permits the aqueous solubility and thermoresponsive behavior to be tailored.³ Exemplarily, short-chain glycidyl ethers (SCAGEs), introducing inert ether side chains along the polymer backbone, have proven to be useful building blocks to alter the LCST to be in line with the physiologically relevant range.^{12,13}

Regarding the bulk properties, PEG itself is characterized by its high crystallinity, featuring a melting temperature (T_m , >2000 g/mol) approximating 65 °C, as well as a highly flexible backbone translating to a glass transition temperature (T_g) in the range of -50 to -60 °C.^{7,14} On the contrary, PPO is a fully amorphous polymer with a T_g of -73 °C, highlighting the effect of a simple methyl group to fully suppress crystallinity.¹⁵ Further, the physical properties are strongly dependent on the molecular weight (MW). PEGs with a MW of 600 g/mol possess a melting range of 17 – 22 °C, appear as viscous liquids and can be employed as solvents and wetting agents in body lotions. With increasing degree of polymerization (P_n) and hence MW, the aggregate state changes from wax-like (1000 g/mol) to solid when exceeding a MW of 2000 g/mol.⁵ Consequently, mixing PEGs of differing MW allows for specifically tailoring the T_m in the physiologically relevant range owing to the plasticizing effect of the low MW components.^{5,16}

PEG's unique property profile makes it attractive for a plethora of applications, ranging from cream formulations in cosmetics and pharmaceuticals to polymer electrolytes to non-ionic surfactants as a hydrophilic block (e.g. in poloxamers).^{5,7,17} Another example is polyether polyols for polyurethane foams based on propylene oxide (PO) and EO.¹⁸ Furthermore, PEO is still the predominant solid polymer electrolyte in lithium-ion batteries due to its overall performance profile.¹⁹ As the gold standard of biomedical applications, PEG is of central importance in the context of "PEGylation".^{5,7,20} This covalent attachment of active substances or proteins to the polymer chains induces a so-called "stealth effect" and therefore enhances blood circulation times drastically.^{20–22} Despite the general advantages of PEGylation and previous indications of PEGs low

immunogenicity, increasing evidence for the existence of anti-PEG antibodies has been revealed in the last decade.^{23–26} Capitalizing on glycidyl methyl ether (GME), Frey and coworkers have most recently introduced a P(EG-*co*-GME) copolymer, known as “RandoPEG”, as a promising alternative for protein bioconjugation.^{27,28} Eliminating the adverse immune reaction while maintaining the beneficial PEG properties, P(EG-*co*-GME) copolymers may represent a new generation of polymers for bioconjugation.^{27,28}

Ring Opening Polymerization of Epoxides

Polyethers are a ubiquitous class of polymers with immense commercial value. Their predominant manufacture strategy is the ROP of epoxides, which comprises three major polymerization techniques: (i) anionic, (ii) cationic and (iii) metal-coordinated.^{7,29} The high ring strain of the epoxide (EO: 110–115 kJ/mol) is the main driving force of the ROP.^{30,31} Based on the above mentioned polymerization mechanisms, various synthetic approaches have been developed and modified, ranging from alkali metal-mediated anionic to monomer-activated to organocatalytic ROP.^{7,32,33} In the quest for metal-free alternatives, borane-catalyzed ROP of epoxides as well as the AROP utilizing phosphazene-bases have emerged as alternatives to metal catalysts.^{34–36} Industrially, the “double metal cyanide catalyst” (DMC catalyst) is employed for specialty polyols, but also features a broad substrate scope.^{7,37} The aforementioned methods produce atactic polyethers from a racemic epoxide. However, the catalytic ROP with its diversity of metal catalysts, allows for the synthesis of stereoregular and optically active polyethers with semicrystalline properties.^{7,29}

With the manifold choices of polymerization methods and the immense range of functional epoxides at hand, this toolbox enables the precise design of various polyether property profiles subject to their application. Many reviews have reported the advances in the synthesis of polyethers while highlighting the advantages and limitations of the respective methods.^{7,29,32–36}

In this thesis, the classical AROP initiated with metal alkoxides as well as the CSROP using a bimetallic cobalt catalyst have been applied and will be further elucidated in the following sections.

Anionic Ring Opening Polymerization of Epoxides

In his 1956 *Nature* publication, Michael Szwarc introduced the concept of living, anionic polymerization by studying the mechanism of the anionic polymerization of styrene.³⁸ Essential prerequisites for a living mechanism include that neither chain transfer nor termination takes place, resulting in an active polymer chain end even after complete monomer consumption. It further relies on a fast initiation step ($k_{\text{initiation}} > k_{\text{propagation}}$), enabling a uniform chain growth, molecular weight control and a narrow dispersity ($\bar{D}$).^{38,39} His significant discovery paved way for a versatile synthetic platform, enabling the precise preparation of various polymeric materials and architectures.⁴⁰

Not only was the first AROP of EO already reported by Schweitzer and Staudinger in 1929, but Flory had established the base-initiated mechanism of EO polymerization as early as 1940.^{2,41} Thereby, Flory was able to show the living character of AROP and that the resulting molecular weight distributions correspond to a Poisson distribution.⁴¹ In this context, the relationship between the $\bar{D}$ and the P_n follows:⁴¹

$$\bar{D} = \frac{M_w}{M_n} = 1 + \frac{1}{P_n} \quad \begin{array}{l} M_w = \text{weight average MW} \\ M_n = \text{number average MW} \end{array} \quad (1)$$

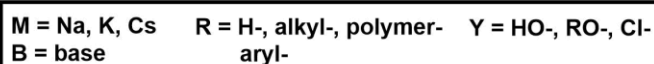
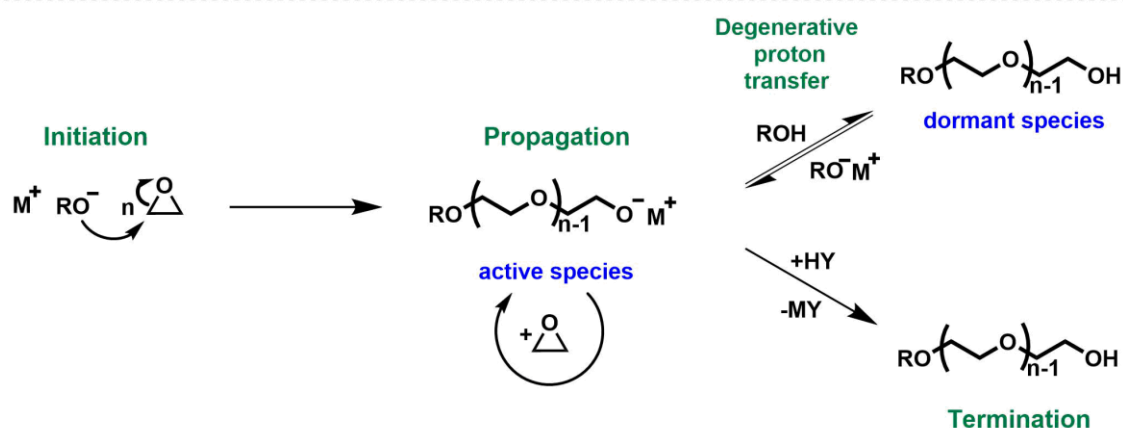
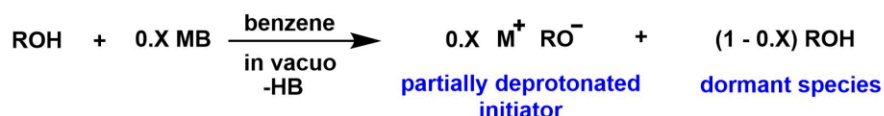
Furthermore, the MW and thus the P_n is determined solely by the monomer-to-initiator ratio.

The oxyanionic polymerization is generally driven by the high epoxide ring strain, but additional electronic and steric factors influence the monomer reactivity.^{7,30} The AROP is usually carried out utilizing strongly nucleophilic initiators, such as sodium, potassium or cesium alkoxides, in aprotic, polar solvents like tetrahydrofuran, 1,2-dimethoxyethane, dimethyl sulfoxide, hexamethylphosphoramide or a mixture thereof.^{42–45} The absence of impurities, particularly water or protic residues in the monomer, are crucial to maintain polymerization control and end group fidelity. As a consequence, the AROP has to be performed with solely dry initiators, solvents and monomers under vacuum or in an inert atmosphere.⁷

Merely partial deprotonation of the alkoxide initiator is required due to a rapid proton exchange between alkoxide and alcohol, also known as degenerative proton transfer. The resulting equilibrium of the active and a dormant species is substantially faster than propagation ($k_{\text{proton exchange}} \gg k_{\text{propagation}}$) (Scheme 2).⁷ Partial deprotonation also favors the solubility of multifunctional initiators and avoids aggregation. In the following, Scheme 2 depicts the general polymerization mechanism. After the formation and

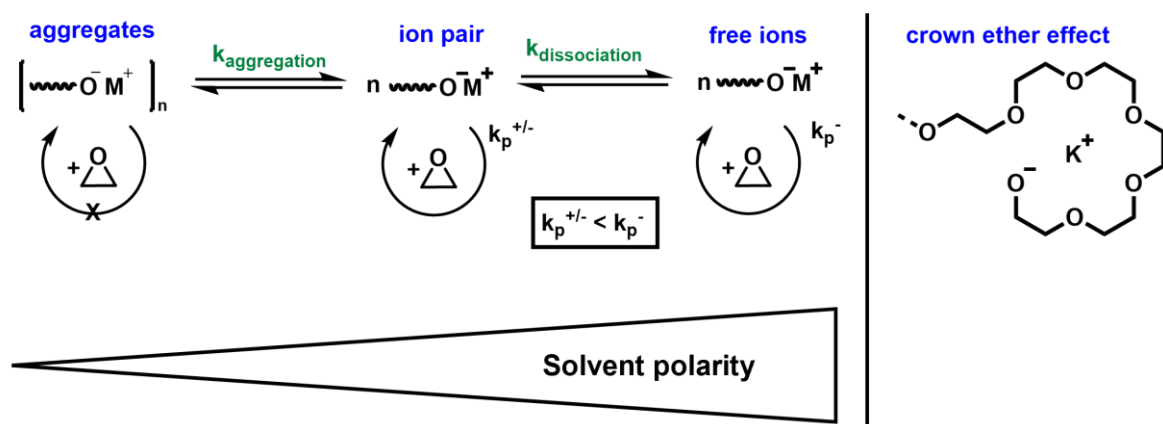
thorough drying of a partially deprotonated initiator, a fast initiation step occurs upon monomer addition. The following propagation step is based on a nucleophilic ring opening of the epoxide via S_N2 mechanism. The propagating species promotes chain growth while being in a constant equilibrium with a dormant species. Termination is induced by the addition of protonating agents.

Initiator formation



Scheme 2: Mechanism of the AROP of EO including the initiator deprotonation step and degenerative proton transfer.⁷

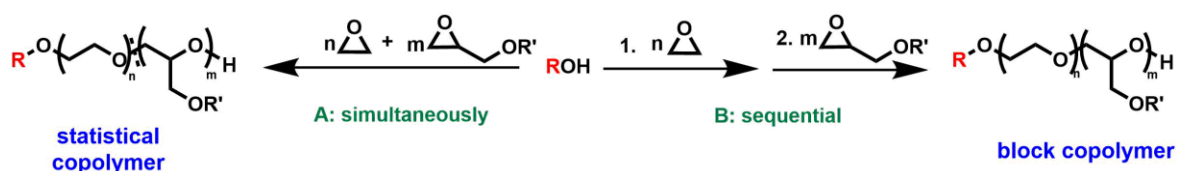
Both the choice of the solvent and the initiator counterion are essential factors in the reactivity of the active chain and hence the polymerization rate constant.⁴⁶ In solution, the alkoxide chain ends are present as aggregates, ion pairs or free ions (Scheme 3).⁷ Based on the HSAB (“Hard and Soft Acids and Bases”) concept,⁴⁷ the “hard” oxyanion forms strong aggregates with smaller “hard” counterions such as lithium cations, consequently impeding polymerization.⁷ Increasing the size of the counterion, softer cations like potassium or cesium ions enable dissociation of the aggregates, resulting in faster chain propagation.⁴⁸ Dissociation is further enhanced by either increasing the solvent polarity or adding a cryptand, both promoting chain end reactivity.^{49–53} Strikingly, a crown-ether effect of the PEG backbone itself (Scheme 3, right) is observed at a $P_n > 10$, translating into an auto-acceleration of the polymerization.⁴⁸



Scheme 3: Ionic equilibrium of metal alkoxide in AROP (left). The crown ether effect between the polyether chain and counter ion of the alkoxide chain end (right).⁷

Owing to inherently low backbone functionality with solely two terminal functionalities per polymer chain, the application range of PEG for special purposes is limited. In pursuit of synthesizing smart, (multi)-responsive materials, that can be addressed via external stimuli, it is required to enhance the functionality of PEG.⁵⁴ Hence, the copolymerization of EO with functional epoxides represents a powerful tool to tune the properties of PEG (Scheme 4).^{3,7} Since a plethora of monosubstituted epoxides has been investigated, such as glycidyl amines, (methylthio)ethyl glycidyl ether and ethyl glycidyl ether, the resulting *mf*-PEG renders itself suitable as pH-,⁵⁵ oxidation-,⁵⁶ and thermo-responsive materials.¹³ Several reviews have been published, highlighting the impact of the copolymerization on *mf*-PEG's properties.^{3,7,54,57,58}

As seen in Scheme 4, this toolbox of comonomers can be utilized in a statistical copolymerization with EO, in which the pendant groups are distributed along the polyether backbone. An understanding of the resulting monomer compositional profile can be accessed by determining the reactivity ratios of the comonomer pair.⁵⁹ Another copolymerization strategy is a sequential addition of both monomers, resulting in a block copolymer structure.

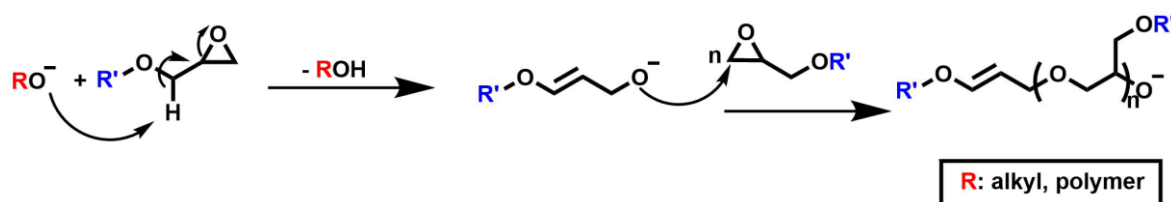


Scheme 4: Copolymerization strategies for *mf*-PEGs via AROP.⁵⁷

During the copolymerization of EO with a monosubstituted epoxide, the nucleophilic attack occurs in a regioselective manner at the sterically less hindered carbon atom of the epoxide ring, resulting in a head-to-tail linkage in the polymer.^{7,60} Nevertheless, beside the chain propagation, the chain transfer reaction to the monomer, a well-known

limitation in AROP of substituted epoxides, is possible (Scheme 5).⁶¹ Under the basic conditions, the alkoxide is capable of abstracting a proton in α -position of the epoxide, resulting in an allylic species. The allylic alkoxide species can act as an initiator, but it also increases the overall amount of initiator. This ultimately changes the monomer-to-initiator ratio and limits MWs.^{61,62}

Established strategies to suppress the side reaction are exemplarily (i) the addition of crown ether or strongly polar solvents or (ii) applying mild polymerization conditions by lowering the polymerization temperature and reducing the degree of initiator deprotonation.^{61–65}

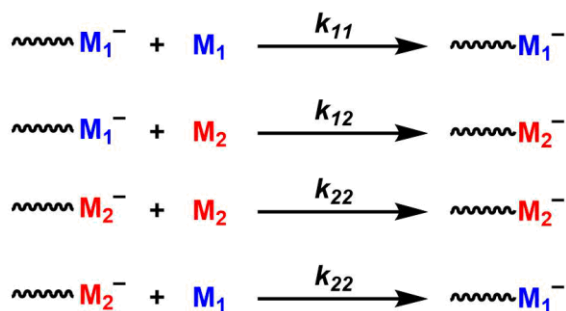


Scheme 5: General mechanism of the proton abstraction and concurrent chain transfer reaction of AROP.⁶¹

Kinetics of the Anionic Ring Opening Copolymerization

The copolymerization of two monomers is a compelling strategy to alter a polymer's properties, which are strongly dependent on the compositional profile of the polymer chain.^{59,66} A detailed understanding of the copolymerization behavior, such as the determination of the reactivity ratios, as well as the resulting microstructure is critical to establish structure–property relationships as a function of copolymer composition.⁶⁶ In general, the reactivity ratios can be described as the tendency of an active chain end to self-propagate rather than enchaining the other monomer.⁶⁶ They are commonly used to describe a copolymer microstructure, which can range from gradient, random, alternating, and block-like.^{66,67} *In situ* ¹H NMR spectroscopy has rendered itself as an excellent method to precisely monitor the copolymerization of gaseous EO with a comonomer in a vacuum-sealed NMR tube.^{59,68} In consequence, the reliable determination of the reactivity ratios is possible.

Fundamentally, the copolymerization of two monomers is based on the homo- and cross-propagation and their respective reaction rates. Scheme 6 comprises these homo- and cross-propagation reactions of the statistical copolymerization of epoxide monomers M_1 and M_2 .^{66,67}



Scheme 6: Homo- and cross-propagation reactions of statistical copolymerization of monomer M_1 and M_2 .

A characteristic feature of ionic polymerization, such as the AROP, is their tendency to follow an ideal behavior.⁶⁷ In this case, the rate of monomer incorporation does not possess a strong dependency on the identity of the terminal unit, but is controlled solely by the nature of the reacting monomer.⁶⁶ Previous publications on the copolymerization behavior of epoxides have revealed that the product of the reactivity ratios tends toward unity, supporting the above assertion.^{59,66,69–71} Relying on the “living” nature of AROP, the copolymerization of epoxides is expected to follow a so-called non-terminal copolymerization model.^{59,72}

Wall introduced a non-terminal, ideal copolymerization model and was the first to use relative rates to describe the copolymerization (independence of chain end identity) while the resulting reactivity ratios r_1 and r_2 represent the compositional drift due to different comonomer reactivities:⁷³

$$\frac{d[\text{M}_1]}{d[\text{M}_2]} = r_1 \frac{k_1[\text{M}_1]}{k_2[\text{M}_2]} \quad (2)$$

$$\frac{d[\text{M}_1]}{[\text{M}_1]} = r_1 \frac{d[\text{M}_2]}{[\text{M}_2]} \quad (3)$$

$$\text{with } r_1 = \frac{k_1}{k_2}$$

The integration of the rearranged Wall’s equation (3) leads to the Jaacks equation (4):⁷⁴

$$\log \frac{[\text{M}_1, t=x]}{[\text{M}_1, t=0]} = r_1 \log \frac{[\text{M}_2, t=x]}{[\text{M}_2, t=0]} \quad (4)$$

The Jaacks equation allows for the determination of the reactivity ratios at any comonomer ratio when ideal copolymerization conditions are applicable ($r_1 \cdot r_2 = 1$).⁷⁴ According to the principle of Ockhams razor, the non-terminal model represents the most basic model for the determination of the reactivity ratios and poses the model of choice to avoid overfitting.^{70,75} Despite the previously made assertions, experimental data strongly suggest its suitability for the copolymerization of EO and monosubstituted epoxides, which tend to obey ideal copolymerization behavior.^{59,66,71}

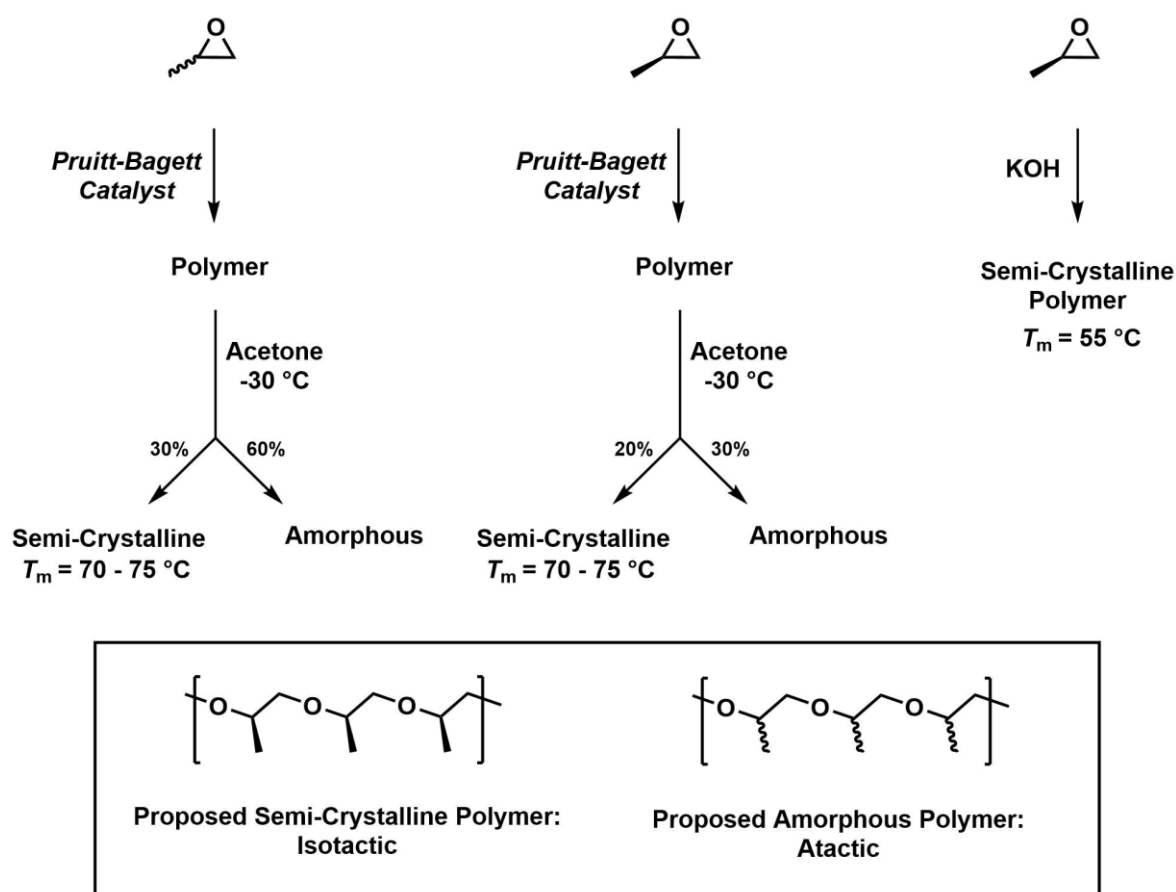
Literature-known factors, which influence the copolymerization behavior of epoxides during AROP are (i) the complexation ability of the pendant group, (ii) polarity of solvent, (iii) choice of counterion as well as (iv) the addition of crown ethers.^{59,69,72} Furthermore, the compositional profile of a copolyether can be strongly altered by the choice of copolymerization techniques.^{59,70,71}

Stereoselective Ring Opening Polymerization of Epoxides for Stereoregular Polyethers

Despite the large relevance of atactic polyethers both in academia and industry, their stereoregular analogues, featuring superior thermal and mechanical properties, have not garnered much attention.

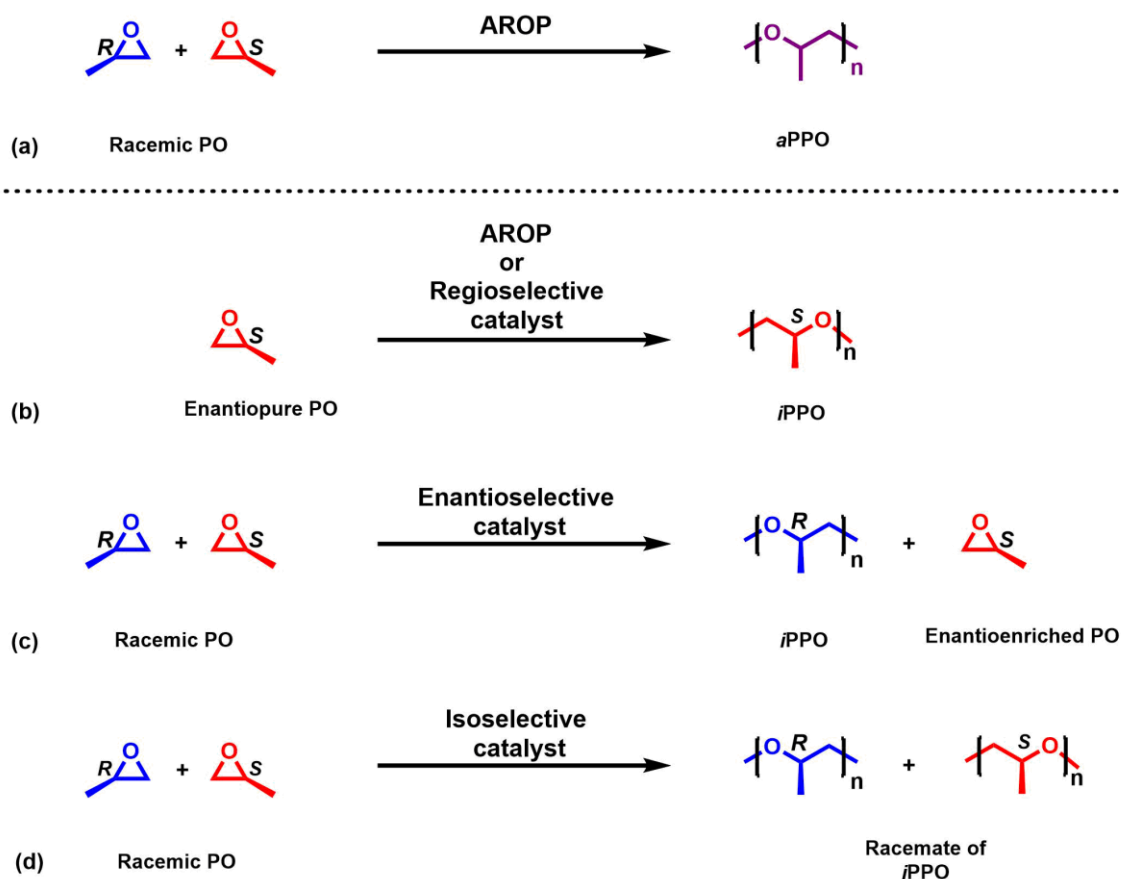
Isotactic poly(propylene oxide) (*i*PPO) was first discovered by Pruitt and Baggett in 1949 at Dow Chemical, revealing iron (III) chloride (FeCl_3) as the first stereoselective, heterogenous catalyst for epoxide polymerization.^{29,76–78} As seen in Scheme 7, the reaction of racemic propylene oxide (*rac*-PO) and FeCl_3 , the so-called Pruitt-Baggett catalyst, leads to a brown, rubbery and solid polymer. This mixture of atactic polypropylene oxide (*a*PPO) and *i*PPO was separated via recrystallization in acetone, yielding 25% of *i*PPO with a T_m of 70 °C.²⁹ Stimulated by these findings, in 1956 Price and coworkers polymerized enantiopure *L*-PO with FeCl_3 and KOH, respectively (Scheme 7). Herein, only the AROP using KOH produced *i*PPO while FeCl_3 still afforded a mixture of *i*PPO and *a*PPO (Scheme 7, middle and right). Banking on these important investigations, Price postulated at least two active sites in the Pruitt-Baggett catalyst, concurrently forming atactic and isotactic polyethers.^{79,80} This historical extract demonstrates the start of the field of stereoregular polymers right after Natta discovered isotactic poly(propylene) (*i*PPE) employing a heterogeneous catalyst system.⁸¹

Noteworthy, the synthesis of *i*PPO precedes the discovery of *i*PPE in 1955.^{29,81} Despite the historical parallels in the discovery of the semicrystalline polymers, only *i*PPE emerged in commercial large-scale production, becoming one of the most important industrial polymers of our time.^{29,82} Today, most commercial PPEs are highly isotactic whereas all commercial PPOs are produced via AROP or DMC-catalyzed ROP from cost-effective *rac*-PO, resulting in atactic PPO (*a*PPO).^{7,83} The lack of commercial *i*PPO is attributed to the high costs of enantiopure PO and slower progress in developing effective catalysts for producing highly isotactic PPO.^{29,83}



Scheme 7: Polymerization of propylene oxide using the Pruitt-Baggett catalyst.²⁹

Inspired by the findings of Jacobsen on the kinetic resolution of *rac*-PO using chiral cobalt-based salen complexes, a significant breakthrough in the CSROP was achieved by Coates and coworkers between 2005 and 2010.^{83–86} Their development of (bimetallic) Co(III) catalysts with excellent enantioselectivity provided semicrystalline, isotactic polyethers, featuring high MW. Relying on these enantioselective chiral catalysts, there are three potential routes to isotactic polyethers, which are further elucidated for *i*PPO (Scheme 8, (b) – (c)).^{7,29,86} While the AROP of a *rac*-PO mixture will exclusively form amorphous PPO (a), a regioselective polymerization of the costly, enantiopure PO affords *i*PPO. Owing to the ring opening mechanism of the AROP, it is possible to produce *i*PPO from enantiopure PO, but MWs are limited to 6 000 g/mol due to well-known chain transfer reaction (compare Scheme 5) under highly basic conditions.^{61,79,87,88} However, the high cost of enantiopure epoxides renders this route unfeasible for large scale applications. On the contrary, enantio- and isoselective ROP circumvents the kinetic resolution step of the epoxide monomer.⁸⁹



Scheme 8: Synthetic routes to iPPO in contrast to AROP.^{29,86}

In the case of enantioselective polymerization, also known as kinetic resolution polymerization, an enantiopure, chiral catalyst selectively polymerizes one enantiomer to provide iPPO, while leaving unreacted, enantioenriched PO of the opposite stereoconfiguration.⁸⁵ Intriguingly, this reaction provides two desirable products: enantiopure epoxides and stereoregular polyethers.⁸⁵ Finally, the isoselective ROP utilizes a racemate of an enantioselective catalyst, forming a racemate of iPPO starting from *rac*-PO. Herein, the yields from a *rac*-PO are maximized while high stereoregularity is maintained.^{85,86,90}

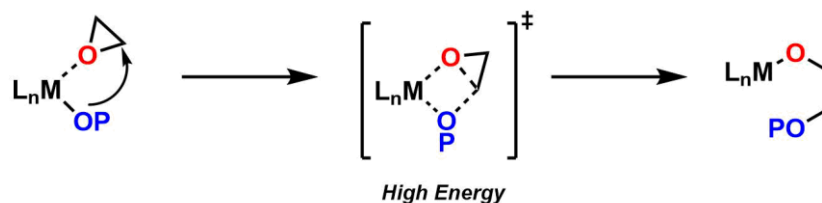
The comprehensive review by Childers et al. summarized the state-of-the-art of CSROP of epoxides until 2014, providing an outline of highly selective and well-defined catalysts to produce high MW polyethers as well as polycarbonates.²⁹ Although CSROP has been an exclusive domain of metal-based catalysts to date, Naumann and coworker have recently reported on the organocatalyzed synthesis of iPPO, applying chiral diboranes as co-catalysts. While this approach does not outperform the metal-based systems, it may offer a glimpse of the potential interplay of polymerization control, functional group tolerance and stereoselectivity.^{34,91} Nevertheless, the development of new metal-based catalysts that can achieve industrial relevance is yet to take off, and

the portfolio of catalysts to manufacture isotactic polyethers remains limited. The following section introduces three high-performing, bimetallic catalysts relevant for this work, outlining their scope of application, assets and drawbacks.

Bimetallic Catalysts for the Stereoselective Ring Opening Polymerization of Epoxides

In analogy to Jacobsen's catalysts for the kinetic resolution of epoxides, Peretti et al. reported on a highly active, isospecific cobalt complex ((salph)CoOAc) for the PO polymerization in 2005.^{83,84} The resulting triad analysis revealed high isotacticity of $[mm] > 99\%$ for the polymerization of *rac*-PO while only modest activity was observed for the polymerization of butylene oxide and hexylene oxide.⁸³ To further understand the direction of catalyst developments, Figure 1 contrasts the potential mechanism and transition states of epoxide ROPs.^{29,85} The bimetallic mechanism is proposed by a less strained transition state with lower energy. Moreover, elegant studies by Jacobsen have conclusively delineated the bimetallic mechanism of enantioselective epoxide hydrolysis using chiral cobalt salen catalysts.^{29,92,93}

Monometallic Ring Opening



Bimetallic Ring Opening

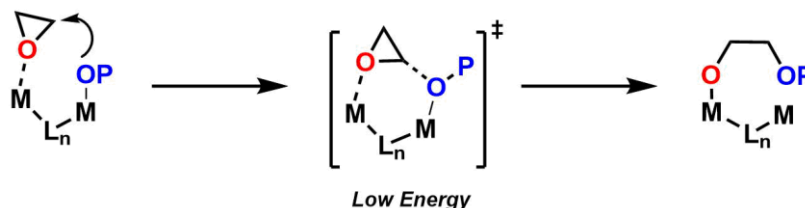


Figure 1: Potential mechanisms and transition states for mono- and bimetallic ring opening of epoxides.²⁹

Furthermore, mechanistic studies suggested that a $\text{Co}\cdots\text{Co}$ separation of $\sim 6 \text{ \AA}$ was ideal for epoxide polymerization (Figure 2, top right).⁸⁵ In 2008, Hirahata et al. reported on the preparation of the first generation of bimetallic cobalt salen catalyst with ideal $\text{Co}\cdots\text{Co}$ separation (Figure 2, 1st generation). The bimetallic (salen)Co^{III} catalyst rapidly polymerizes epoxides with excellent stereocontrol. Selectivity factors (*s*-factors) exceeded 40 in an enantioselective ROP, while isoselective ROP from racemic epoxides resulted in high yields of high molecular weight, isotactic polyethers.⁸⁵ A follow-up

work expanded the substrate scope to a variety of monosubstituted epoxides and glycidyl ethers, enabling a novel variety of isotactic polyether architectures.⁸⁶ However, for this first generation of catalyst, molecular weight (M_n) control was poor, yielding rather broad molecular weight distributions.

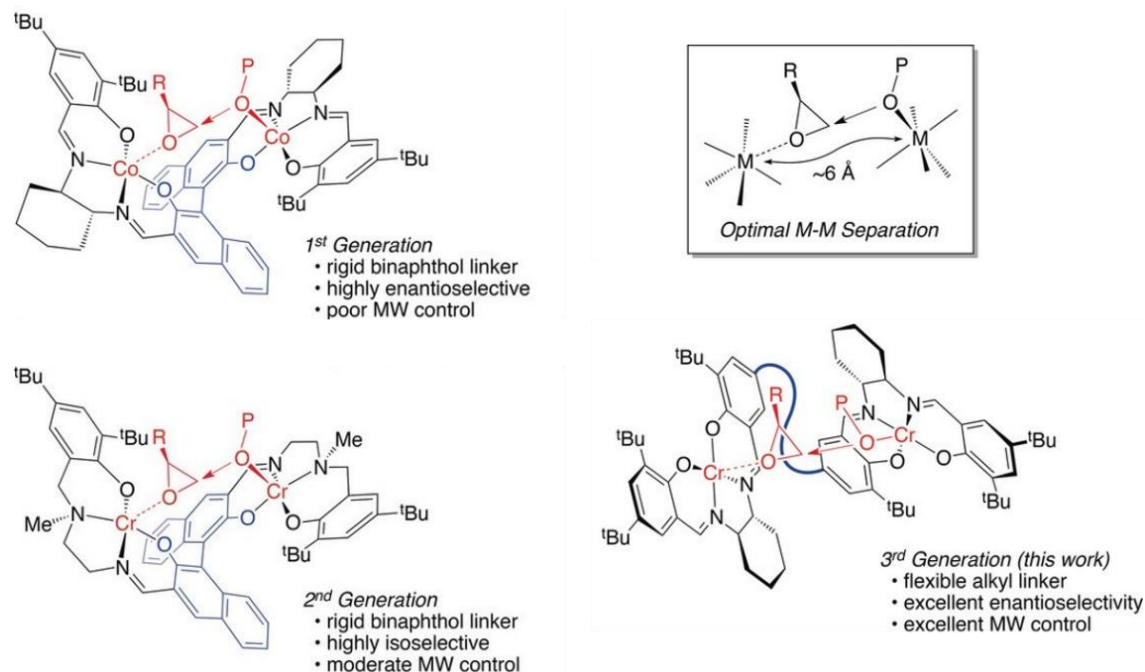
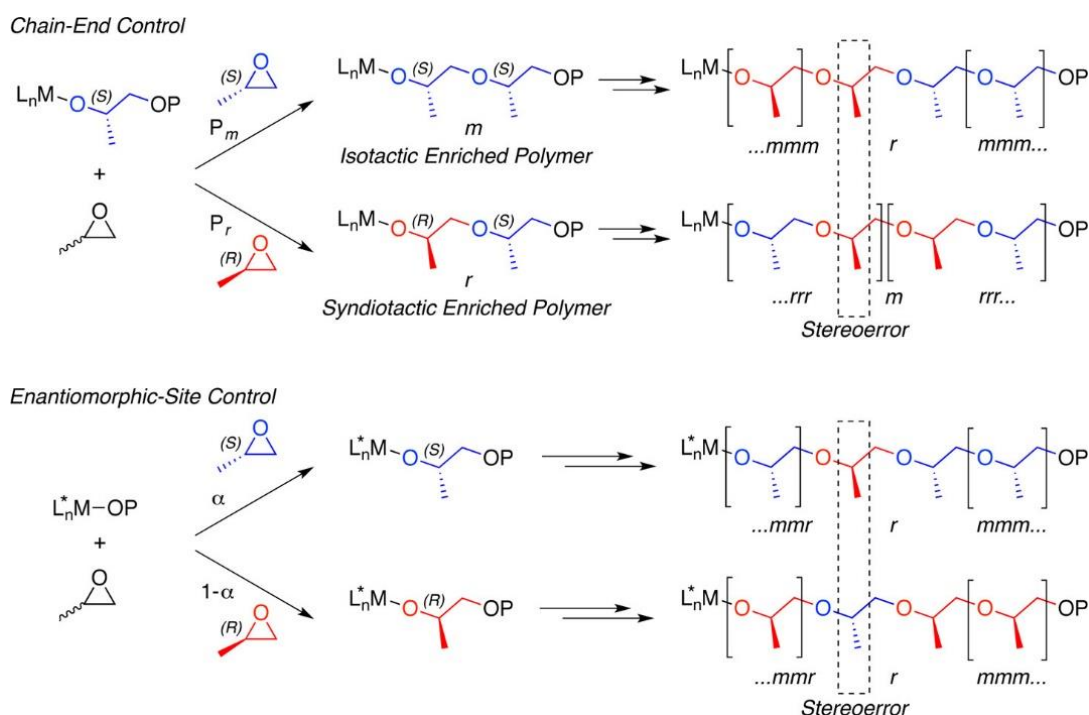


Figure 2: Three generations of bimetallic catalysts for the stereoselective ring opening polymerization of epoxides.⁸⁹ Adapted and altered with permission from Morris, L. S.; Childers, M. I.; Coates, G. W. Bimetallic Chromium Catalysts with Chain Transfer Agents: A Route to Isotactic Poly(propylene oxide)s with Narrow Dispersities. *Angew. Chem.* 2018, 57, 5731–5734. © 2018 Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim.

Targeting better control of the M_n , a synthetically more accessible bimetallic (salalen)Cr^{III} catalyst (2nd Generation, Figure 2), linked through a binaphthol moiety, was designed. The catalyst was explored in the enantio- and isoselective ROP of PO in conjunction with chain shuttling agents.⁹⁰ While targeted M_n with moderate control of dispersity were accomplished, a high loading of chain shuttling agent limited theoretically possible M_n . The 3rd generation of catalysts poses a bimetallic complex comprised of two (salen)CrOAcF₃ centers linked by six methylene units, also known as tethered catalyst (Figure 2). In combination with chain shuttling agents, this catalyst produces low dispersity, isotactic and semicrystalline PPO with moderate M_n .⁸⁹ In conclusion, the choice of catalyst has to be made in accordance with targeted applications and substrate scope. As a part of this thesis, the 1st generation catalyst has been applied based on its high activity towards GEs (Chapter 4).

The aforementioned catalysts generally follow an enantiomorphic-site control mechanism (Scheme 9), evidenced by the ratio of stereoerrors of the ¹³C triad analysis ($[mr] = [rm] \approx [rr]$).^{29,85,86,90} In this context, monomer enchainment is dependent on the

ligand set ($\text{Ln}^\star$) in the catalyst. Enantiomorphic site control occurs if the active site is chiral due to a ligand set and overrides the influence of the polymer chain end to regulate stereoregularity.^{29,67}



Scheme 9: Scheme 4. Chain-End and Enantiomorphic-Site Mechanisms of Stereocontrol. $\text{Ln}^\star$ is a chiral ligand set.²⁹ Adapted with the permission of Childers, M. I.; Longo, J. M.; van Zee, N. J.; LaPointe, A. M.; Coates, G. W. Stereoselective epoxide polymerization and copolymerization. *Chem. Rev.* 2014, 114, 8129–8152. Copyright © 2014 American Chemical Society.

Stereocomplexation

Highly stereoregular polymers often exhibit enhanced properties compared to their irregular analogues.⁹⁴ While high tacticity or enantiopurity results in a highly ordered packing of polymer chains, stereocomplexation can further elevate a polymer's properties beyond those of the enantiomeric analogue.⁹⁵ Generally, stereocomplexation is defined as the stereoselective interaction of two polymers chains of complementary stereoregularity, which subsequently interlock via co-crystallization.^{96,97} The enhanced molecular order during stereocomplexation as well as the resultant properties, such as an increase in T_m , are mainly controlled by inter- and intrachain interactions (dipole–dipole interactions and H-bonding).^{95,96} Among stereocomplexed polymers, poly(lactic acid) (PLA) is the most prominent and extensively studied representative.^{98–101} Further examples of available stereocomplexes include polymethylmethacrylates,^{102–106} polycarbodiimides,¹⁰⁷ polycarbonates,^{108–114} polyhydroxyalkanoates^{115,116} and a wider range of polyesters.^{97,117–122} To date, Buchard has reported on the only stereocomplexed

polyether, which was synthesized via regioselective ROP of an enantiopure, sugar-based oxetane.¹²³

Stereocomplexes are usually formed by mixing two enantiomerically complementary polymers in equivalent amounts, resulting in enhanced properties compared to the enantiopure polymers, such as higher degrees of crystallization and T_m .^{96,124} A 1:1 mixture of PLLA and PDLA melts at 230 °C, mirroring a 50 °C increase of the T_m compared to the enantiopure analogues ($T_m = 180$ °C).^{98–101} An intriguing example of the change in polymer properties has been reported for isotactic poly(limonene carbonate) (*i*PLimC), which exists as an amorphous polymer in its enantiopure form. Upon mixing at a 1:1 ratio, a so-called “zippering” interaction takes place to form a semi-crystalline stereocomplex.¹¹⁴ Despite mixing, the isoselective polymerizations represent a feasible approach for the *in situ* stereocomplex formation from racemic monomers, yet has been scarcely explored due to its high synthetic demands towards catalyst design.^{125–129}

Although stereocomplexation represent a compelling strategy to improve and alter polymer properties, most reports have focused on the synthesis of stereocomplexes as well as its effect solely regarding polymer properties.⁹⁵ Yet, the next step is to take advantage of these peculiar polymer property profiles and expand their use in application (Figure 3) as envisioned by Tutoni et al..⁹⁵ Polycarbonates and polyester stereocomplexes, in particular, are rendered highly relevant for biomedical use due to their potential for complete bio-renewability, bio-compatibility and bio-degradability.^{95,130–133}

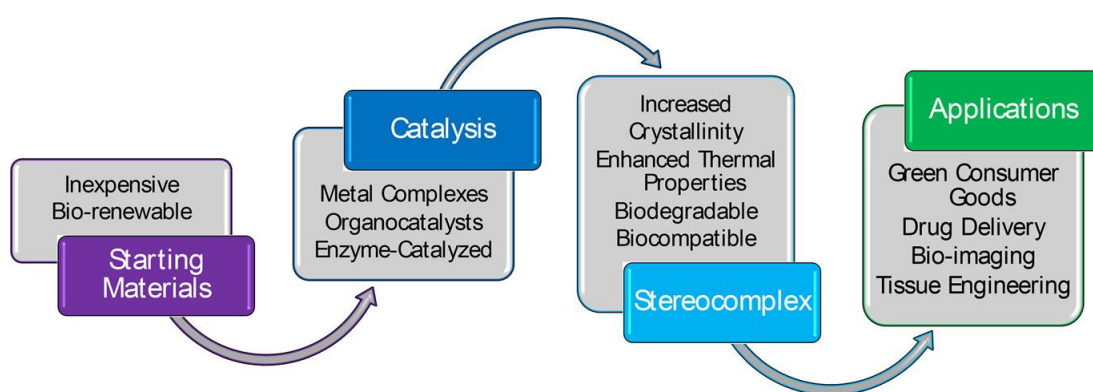


Figure 3: Stereocomplexed polyester and polycarbonate synthesis, properties, and applications.⁹⁵ Adapted with permission of Tutoni, G.; Becker, M. L. Underexplored Stereocomplex Polymeric Scaffolds with Improved Thermal and Mechanical Properties. *Macromolecules* 2020, 53, 10303–10314. Copyright © 2020 American Chemical Society.

Polymerization of Terpene-derived Monomers

Our current predominant dependence on dwindling fossil raw materials and the rising awareness of the effect polymers have on the environment have led to immense efforts for a more sustainable design of polymers, including improved recycling and bio-derived synthetic strategies.^{134–136} In the pursuit of sustainable polymers, Haque et. al have identified the efficient and sustainable biomass-to-polymer conversion as a major challenge, requiring a careful identification and assessment of feedstock-based monomer precursors.^{136,137} Aiming at replacing fossil fuel-based chemicals by those from bio-renewable feedstock, terpenes and terpenoids are garnering increased attention as a bio-renewable feedstock resource.^{138,139} Within the last two decades, several reviews have highlighted the immense potential of the terpenes as polymer building blocks for manifold polymerization techniques, ranging from catalytic to radical to anionic polymerization.^{139–145}

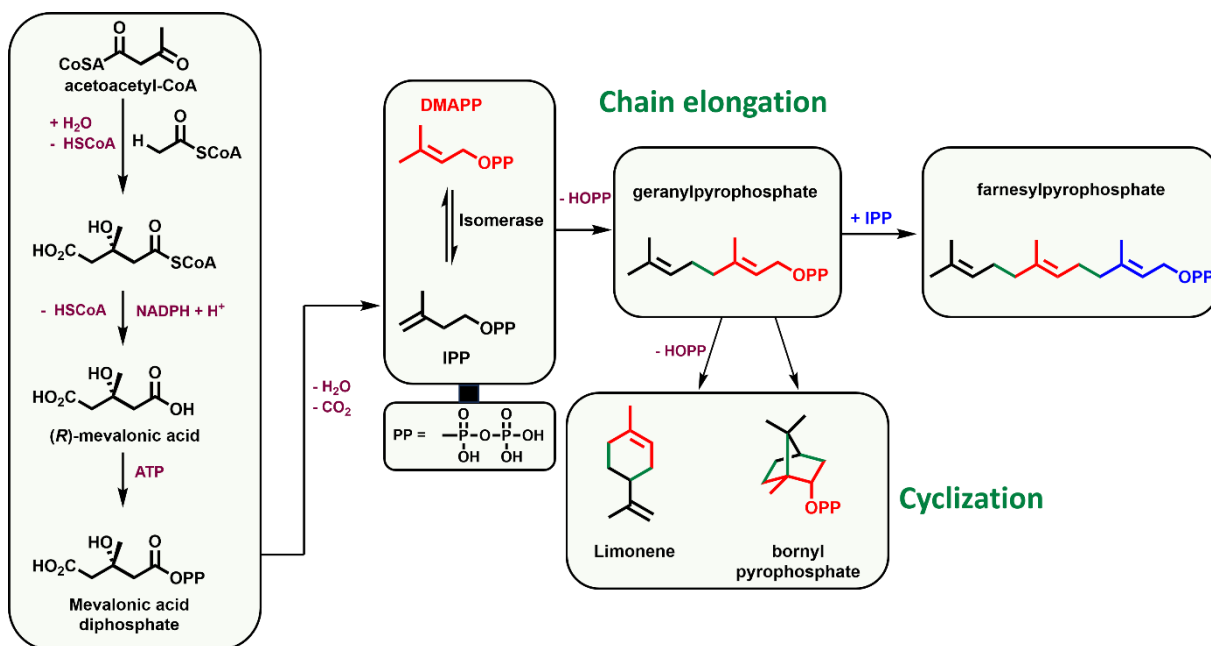
Terpenes and Terpenoids as Bio-renewable Feedstock

Terpenes represent a valuable family of naturally abundant compounds and offer an extensive structural variety, with more than 30 000 structures known in literature.^{138,145} Terpenes originate from trees, plants and fruits and are commonly utilized in flavors, fragrances, spices and pheromones.¹⁴⁶ In a medicinal and pharmaceutical context, terpenes are used owing to their antiviral, antibacterial and anti-inflammatory effects.¹⁴⁶

The huge variety of terpenes and their functional derivatives, so-called terpenoids, include linear, cyclic as well as bicyclic skeletons. The available functionalities range from alcohols, ethers, aldehydes, ketones to higher oxygenated derivatives.^{146–148} Further, any terpene framework is subject to the “isoprene rule”, referring to $(C_5H_8)_n$ units as the common structural feature it is composed of. The number of isoprene (*2-Methylbutane*) units enables a systematic categorization of terpenes and terpenoids, such as hemi- (C_5), mono- (C_{10}) and sesquiterpenoids (C_{15}).^{146,149} Consequently, the isoprene rule is fundamental to elucidate the chemical structure of terpenes and hormones, for which Ruzicka was awarded the Noble Prize in 1939.^{149,150}

In nature the synthesis of terpenes and terpenoids relies on the mevalonate pathway (MVP) or isoprenoid pathway.¹⁴⁶ Scheme 10 illustrates extracts of the MVP, starting from acetoacetyl-CoA which is transformed into mevalonic acid (MA) in a two-step sequence. Next, MA is phosphorylated by adenosine triphosphate (ATP), providing the diphosphate of mevalonic acid. Subsequently, its decarboxylation and dehydration

results in the important building blocks isopentenylpyrophosphate (IPP) and γ,γ -dimethylallylpyrophosphate (DMAPP), which is produced via isomerase of IPP.¹⁴⁶ The assembly of IPP and DMAPP catalyzed by enzymes results in chain elongation, e.g. the phosphorylated monoterpene geranylpyrophosphate. If this chain elongation is repeated with an equivalent of IPP, farnesylpyrophosphate is generated. Alternatively, cyclization results in the production of limonene. Intriguingly, the structural and stereochemical diversity of the chemical library of terpenes solely derives from two simple precursors, IPP and DMAPP.¹⁵¹

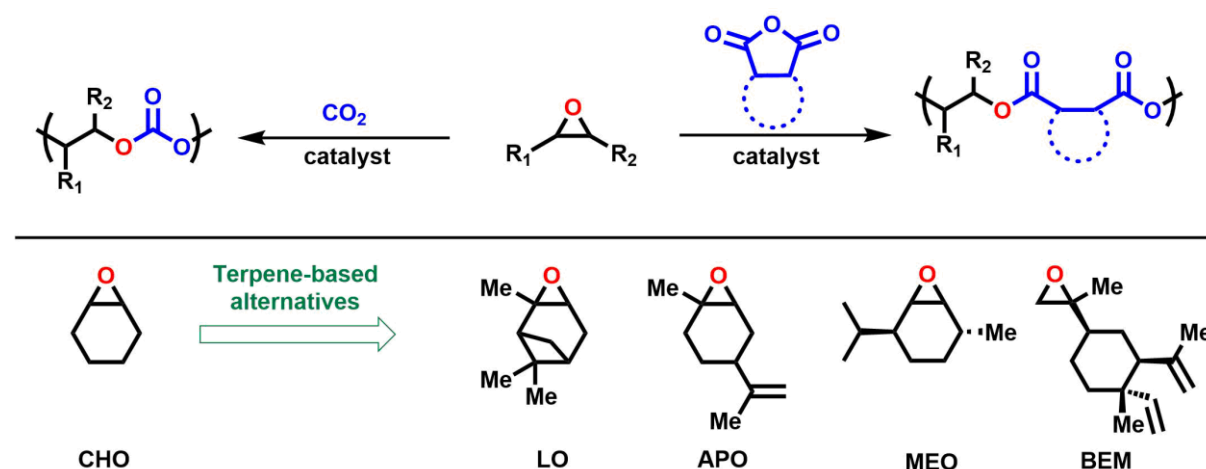


Scheme 10: Scheme of the biogenesis of mono- and sesquiterpenes via MVP.^{146,151}

Disubstituted Terpene-derived Epoxides for Ring Opening Copolymerization

Aliphatic polyesters and polycarbonates represent an attractive polymer class in terms of sustainability due to their potential for hydrolytic degradability and biocompatibility.^{130,131,152,153} Focusing on the metal-catalyzed ring opening copolymerization (ROCOP) of epoxides with carbon dioxide (CO₂) and cyclic anhydrides (Scheme 11), the polymerization of several terpene-derived, disubstituted epoxides has been reported in literature. The most predominant representatives are limonene oxide (LO), α -pinene oxide (APO), menthene oxide (MEO) and β -elemene mono oxide (BEM).^{144,154–159} These cyclic terpenoids feature a *p*-menthane scaffold and present a bio-derived alternative for petrochemical cyclohexene oxide due to their structural resemblance.¹⁴⁶ Exemplarily, facile epoxidation of both α -pinene and limonene affords the respective mono oxide, but the transformation of either limonene

enantiomer gives LO as a cis/trans mixture.¹⁴⁴ The two enantiomers of limonene occur in multiple natural sources, such as orange peel (*R*) and fir coin oil (*S*), while α -pinene is a major component of turpentine oil.^{144,160}



Scheme 11: Catalytic ROCOP of terpene-based, disubstituted epoxides with either (i) CO_2 toward aliphatic polycarbonates (left) or (ii) cyclic anhydrides to produce polyesters (right).^{144,161}

The general catalyst availability for the ROCOP of cyclic epoxide with CO_2 and cyclic anhydrides, respectively, has advanced to a high versatility in recent decades. Notably, the range of suitable catalysts for the targeted substrate scope is still limited.¹⁴⁴ Della Monica et al. provided an excellent overview of the ROCOP of terpene-derived monomers, whereas a review by Darensbourg and coworkers on the ROCOP of polycarbonates emphasizes the quest for truly sustainable and bio-renewable feedstock.^{144,159} Recently, Coates and coworkers have outlined the plethora of multifunctional catalysts that have been developed for the general copolymerization of epoxides with CO_2 , cyclic anhydrides, carbonyl sulfide and cyclic thioanhydrides.¹⁶²

In 2004, the ROCOP using β -diiminate zinc acetate ((BDI)ZnOAc) catalysts of limonene oxide with CO_2 was reported for the first time by Coates and coworkers.¹⁵⁴ Today, the resulting high T_g poly(limonene oxide) (PLimC) is the most widely studied terpene-based polycarbonate with LO being already commercially available.¹⁴⁴ Intriguingly, Auriemma et al. also synthesized both stereoregular PLimCs, which upon mixing formed the first crystalline stereocomplex from amorphous, enantiomeric polymers.¹¹⁴ Deploying the (BDI)ZnOAc catalyst as well as a series of metal salophen catalysts, polyesters based on LO and cyclic anhydrides have been materialized.^{163,164} Additionally, Robert et al. investigated a one-pot tandem approach, in which cyclic anhydride is formed *in situ* from dicarboxylic acids, followed by the ROCOP using a series of commercial salen complexes.¹⁵⁵

Directing the focus on the terpene-derived structural features, the resulting polycarbonates and -esters usually exhibit molecular weight dependent T_g s that can be tailored in the range of 59 – 243 °C due to their rigid backbone structures.¹⁴⁴ In this context, the variation of aromatic anhydrides in the ROCOP with LO resulted in differing T_g s of 131 °C and 243 °C.¹⁵⁸ In several works, Coates and Kleij have applied metal salen catalysts in the ROCOP of (partially) terpene-based anhydrides with PO and CHO, envisioning fully bio-based aliphatic polyesters with high T_g s.^{165–167} This synthetically demanding ROCOP of epoxides and cyclic anhydrides, both sourced from terpene biomass, was overcome by Williams and coworkers, utilizing an iron(III)/potassium(I) catalyst in the ROCOP of LO and MEO with terpene-based anhydrides.¹⁶⁸

Utilizing these promising terpene-derived alternatives to petroleum-derived monomer building blocks, the resulting polymers can be further modified in a variety of chemical transformations. For this purpose, PLimC, featuring free vinyl groups, has been valorized as a platform polymer to exploit several potential modifications and their effects on the material properties.¹⁶⁹ Figure 4 portrays two conceptual approaches of functionalization, thiolene-click (a) and “epoxy chemistry” (b+c). Thiolene functionalization enabled the introduction of various functional groups, transforming the thermoplastic into a rubber-like material via the installation of alkyl esters. Furthermore, it was possible to introduce antibacterial activity (via ammonium groups) or to increase the polymers hydrophilicity (Figure 4, route (a)). The epoxy chemistry involves a facile epoxidation step (Figure 4, route (b)) and subsequent introduction of thioether and alkyl ester functionalities onto the PLC backbone, decreasing both the T_g and Young modulus.¹⁶⁹ Ultimately, the work by Hauensteiner et al. revealed the vast potential of the terpene-derived epoxides and the corresponding polymers to fine-tune the material properties of terpene-derived polymers in manifold directions of application. However, this approach lacks access to low T_g polymers.

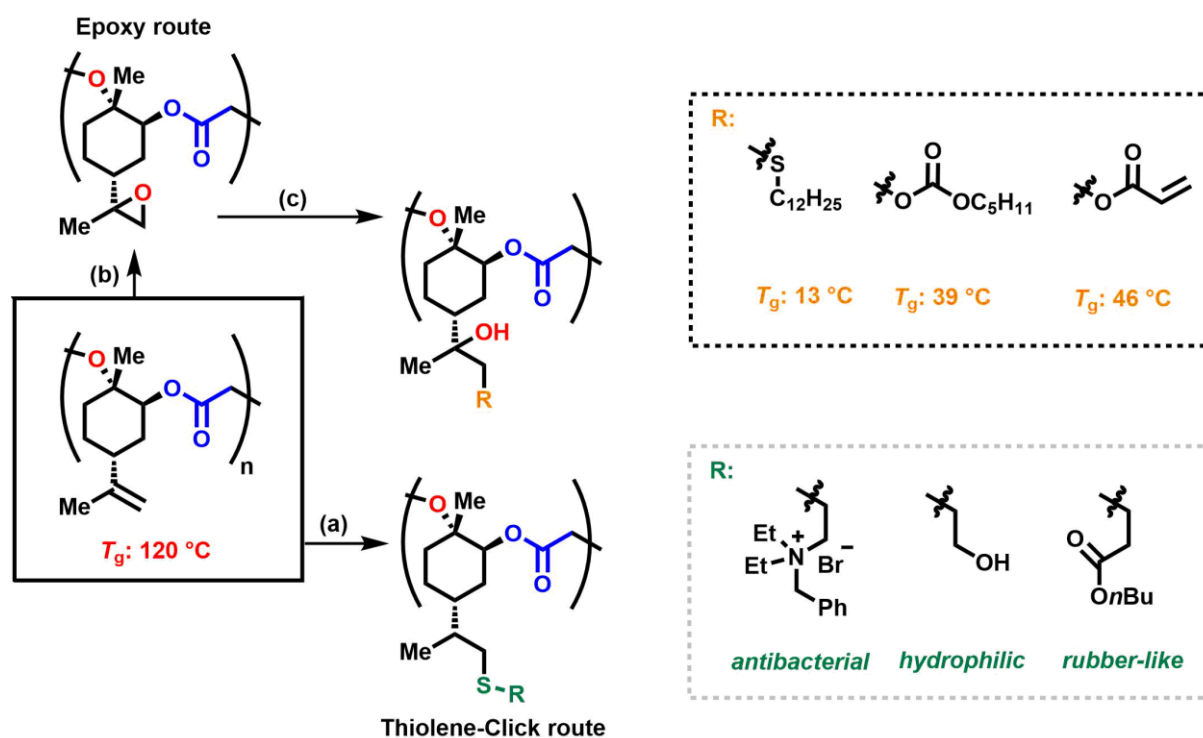


Figure 4: Post-polymerization modification of PLC via (a) thiolene-click, (b) epoxidation and (c) ring opening reactions.^{144,169}

Terpenyl Glycidyl Ethers – Second Generation of Terpene-Derived Epoxides

Synthesis of Terpenyl Glycidyl Ethers

Overall, the natural scaffold structure of terpenes only allows for the synthesis of disubstituted epoxides via epoxidation, followed by their subsequent utilization to produce polyester and polycarbonates.^{144,146} However, the lack of bio-derived epoxides for the synthesis of *mf*-PEGs motivated our group to synthesize an extensive library of novel terpenyl-derived glycidyl ethers (Figure 5, top).

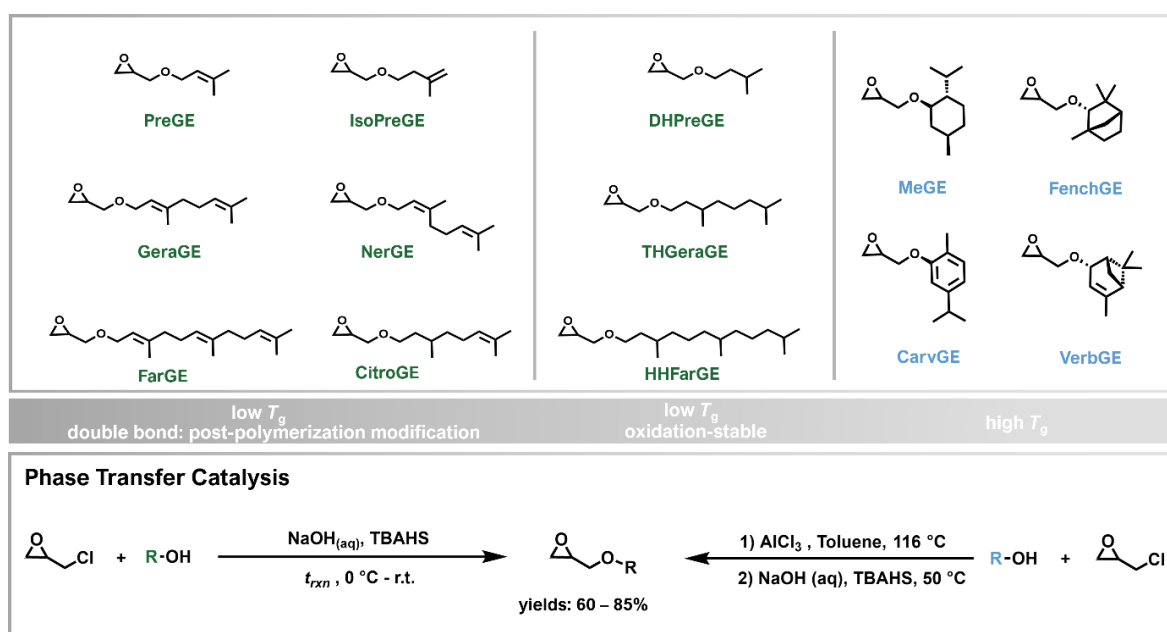
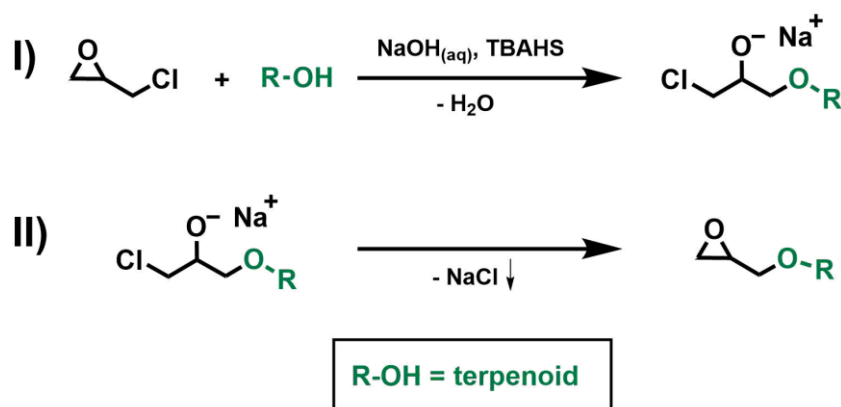


Figure 5: Top: Library of novel terpenyl glycidyl ethers (TGEs) as monomers for partially bio-based polyethers, polycarbonates and polyesters.^{170–178} Bottom: General scheme of the phase transfer catalysis of the TGEs covered in this thesis. TGEs from acyclic terpenoids are labelled in green, whereas more rigid, (bi)cyclic structures are coded in blue.

In contrast to the aforementioned disubstituted analogues, a prerequisite of a functional epoxide to be polymerizable in the AROP is its monosubstitution.⁷ To this end, GEs represent underrated, easy-to-synthesize epoxide building blocks, which in turn allow for a broad functional variety to be introduced (see Section 2.2).^{3,7,54,58} In general, there are various synthetic routes to produce racemic GEs, including the Prilezhaev epoxidation of an allyl ether with *meta*-chloroperbenzoic acid or the base-catalyzed ring-closure from a 1-chloro-3-alkoxypropan-1-ol.^{12,27,58,179} Owing to the various double bonds in the acyclic terpenoids, the epoxidation can result in multiple epoxide moieties per GE. The resulting multi-epoxy compounds are not attainable in the use of AROP as crosslinking would occur during polymerization.^{58,180} In addition, the targeted bio-renewability through terpenoids utilization renders the phase transfer catalysis

with epichlorohydrin (ECH) as the most feasible synthetic route (Figure 5, bottom). This facile one-pot synthesis strategy was first introduced by Mouzin et al. in 1983 and relies on the utilization of the respective alcohol, excess ECH, a basic solution, e.g. aqueous sodium hydroxide solution and a phase transfer catalyst.^{58,170,181} Contingent upon the alcohol employed (primary vs. secondary), diverging reaction conditions have been developed. The acyclic, linear terpenoids (green label in Figure 5) already react with ECH at a temperature range from 0 to 25 °C, whereas the secondary, cyclic and bicyclic alcohols (blue label) require elevated temperatures and aluminium trichloride (AlCl₃) for the additional activation of ECH.^{170,171} Exemplified for the acyclic TGEs, the reaction sequence comprises two steps as elucidated in Scheme 12.^{54,182} Firstly, the deprotonation of the terpenoid takes place in the presence of sodium hydroxide (NaOH_(aq)) and the respective alkoxide induces a nucleophilic ring opening of the epoxide. Subsequently, the formed intermediate undergoes an intramolecular ring closing via nucleophilic substitution of the chloride atom, producing the TGE driven by the concurrent precipitation of sodium chloride. Due to the immiscibility of the reactants, the presence of a phase transfer catalyst is required, exemplarily tetrabutylammonium hydrogen sulfate (TBAHS) or tetrabutylammonium bromide (TBAB).^{170,181}

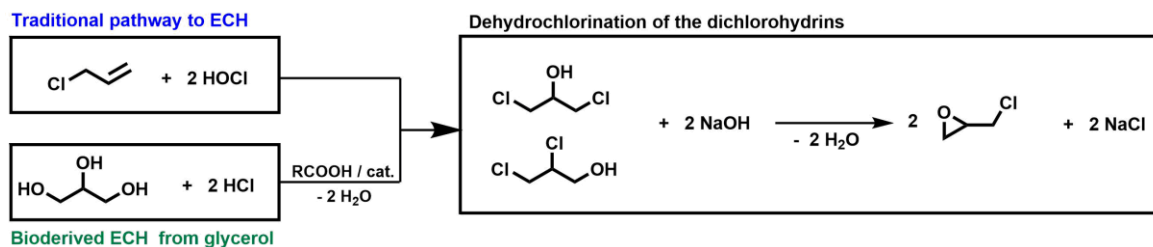


Scheme 12: General reaction sequence of the one-pot phase transfer catalysis according to Mouzin et al. for the synthesis of TGEs.^{58,170}

Despite its high efficiency and typical yields of 70 – 90%,^{170,181} the phase transfer catalysis is accompanied by elimination reaction of ECH under strongly basic conditions and, in turn, the formation of (3-chloroallyl) glycidyl ether (3-Chloro-AGE) is often observed.^{183,184} Purification via distillation is effective if the difference in boiling temperature is sufficient. On one hand, refraining the use of the phase transfer catalyst will eliminate the formation of 3-Chloro-AGE, but will also translate to lower yields.^{185,186} On the other hand, the careful design of the reaction conditions suppresses the formation of side products. For this purpose, the alterations of this synthesis

protocol in literature are manifold, including the utilization of solvents (e.g. benzene), addition of Lewis-acids to activate ECH, variations in temperature and reactions times as well as applying heterogenous conditions (potassium hydroxide pellets).^{170,171,183,187–190} Exemplarily for PreGE and IsoPreGE, our group circumvented column chromatography as an additional purification step while maintaining similar yields. This was possible by simply lowering the reaction temperature, the concentration of $\text{NaOH}_{(\text{aq})}$ and reaction times compared to the protocol by Mouzin et al.^{175,176} In addition, potential protic impurities in the TGEs were deactivated by treatment with methyl iodide and sodium hydride prior to polymerization.¹⁹¹ The resulting *O*-methylation of any residual terpenoid enables higher molecular weights and avoids undesired chain transfer reactions.^{172,173}

To explore the vast natural availability of differing terpenoid scaffolds, the availability of “green” ECH is a key requirement. Generally, ECH is a cost-effective volume commodity chemical with a production capacity of approximately two million metric tons per year.^{192,193} Traditionally, ECH is produced in a multi-step process from propylene and chlorine where the resulting allyl-chloride undergoes a hypochlorination to 1,3-dichlorohydrin (1,3-DCH) and 2,3-dichlorohydrin (2,3-DCH) at a ratio of 3:1 (Scheme 13, top).^{194,195} In the last step, the ring closure of DCH under basic conditions affords ECH.^{193,194} Yet, this process suffers from several disadvantages such as poor chlorine atom efficiency and undesired production of chlorinated organics, which are expensive to dispose of.^{193,195} Recent advances in environmentally friendly production processes have made “green” ECH available as a fully bio-sourced option via Solvay’s Epicerol® process.^{192,196,197} This two-step route employs bio-renewable glycerol (1,2,3-propane triol) as feedstock and is also known as the glycerin-to-epichlorohydrin (GTE) process (Scheme 13, bottom).¹⁹³ In the first step, a carboxylic acid catalyzed hydrochlorination of glycerol results in a mixture of DCHs (30-50 : 1 = 1,3-DCH : 2,3-DCH), followed by the base-catalyzed ring closure.¹⁹³

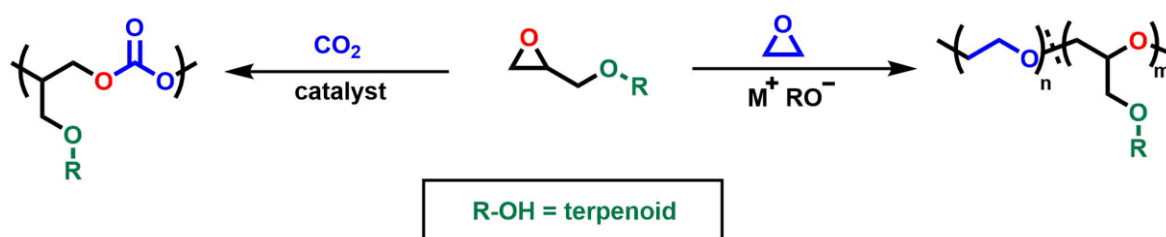


Scheme 13: Industrial production pathways for epichlorohydrin (ECH). The traditional pathway converts allyl chloride into DCH (top), whereas the acid-catalyzed GTE process starts from glycerol (bottom). In the second step, dehydrochlorination results in the targeted ECH.^{193,195}

It is important to note that glycerol is readily available at low cost as the major byproduct from bio-fuel production a ratio of biofuel : glycerol = 10:1.^{195,198} In addition, based on its availability from fermentation of sugars and lignocellulose, it is considered a platform chemical as its functionality offers opportunities for further functionalization.^{137,193,195} The GTE technology shows economic and environmental advantages compared to the traditional route due to several key factors: (i) utilization of bio-renewable feedstock, (ii) improved Cl atom efficiency, (iii) utilization of cost-effective hydrochloride, (vi) decrease of chlorinated side products and (v) reduced water consumption.^{193,195,198} Although Gibson et al. have already described the GTE process extensively in the 1930s, only the recent large availability of glycerol has prompted its commercialization.^{193,199} Conversely, glycerol was obtained from the hydrolysis of ECH as recent as 2006, but this manufacturing route has now completely ceased.¹⁹³ Since starting production in 2012, Solvay affiliate companies produce Epicerol® in amounts of 100 kilotons per annum.¹⁹² While the cost of petrochemical raw materials surge, the current ECH market price of \$1 per pound is irrespective of the production method, rendering it suitable as feedstock for higher value products and commodities.^{192,195}

Polymerization of Terpenyl Glycidyl Ether

The common structural motif of all TGEs is the monofunctional epoxide moiety, which generally offers a polymerization scope ranging from oxyanionic polymerization to catalytic ROP.^{172–176,178,186,200} To date, they have been scarcely employed in the synthesis of polymers, namely polyethers and polycarbonates (Scheme 14), despite their structural variety and easy-to-synthesize nature.^{178,186,200} The majority of investigation of TGE-based polymers have been conducted in recent years within our group. Hence, the following section will elucidate the structural features and arising opportunities of TGEs in polymer synthesis in a brief manner while detailed results can be found in the subsequent chapters.



Scheme 14: Polymerization pathways of TGEs: Catalytic ROCOP with CO₂ toward aliphatic polycarbonates (left) and AROCP with EO, resulting in aliphatic polyethers (right).

Overall, this “second generation” of terpene-derived epoxides offers a structural variety in the ether side chain while the backbone flexibility is maintained. Not only do linear, acyclic TGEs carry flexible side chain moieties to design low T_g materials^{145,172,173}, but chemically differing double bonds host the option for (selective) post-polymerization modifications (Figure 5, top left).^{139,145,169,178,186} In 2018, Morrison et. al demonstrated the cross-metathesis of polyethers based on prenyl glycidyl ether (PreGE) and isoprenyl glycidyl ether (IsoPreGE), which can be regarded as bio-derived allyl glycidyl ether (AGE) analogues.¹⁸⁶ Furthermore, citronellyl glycidyl ether (CitroGE) was polymerized under AROP conditions and the resulting polyether was subsequently transformed into organo- and hydrogels via click- triazolidione chemistry. Similar modification was demonstrated by Gardiner et. al on a CitroGE-based, low- T_g polycarbonate.²⁰⁰ In contrast to the polymers based on rigid disubstituted epoxides (Scheme 11), the low T_g of $-56\text{ }^{\circ}\text{C}$ of this poly(citronellyl glycidyl ether carbonate) (P(CitroGEC)) is a peculiar feature derived from the flexible ether side chain and allows for its use as a soft block in fully bio-derived thermoplastic elastomers (TPEs).^{173,200}

In an effort to hydrogenate the terpenyl side chain, we applied a novel strategy of diimide reduction in polymers using potassium azodicarboxylate (PADA) in this thesis.¹⁷⁵ Although partial hydrogenation is achieved, an alternative route to fully hydrogenated side chains is the hydrogenation of the TGE prior to polymerization. As seen in Figure 5 (top middle), three fully hydrogenated monomers with differing side chains from C_5 to C_{10} to C_{15} are available.^{174,175} Besides the increase in hydrophobicity, the absence of double bonds improve the stability against oxidation and crosslinking while maintaining access to a low T_g . Banking on the side chain hydrophobicity, these structures are particularly suitable to tailor the amphiphilicity of polyether (co)surfactants.^{172,174}

The third type of TGEs (Figure 5, top right) consists of more rigid structures in the side chain, such as menthyl glycidyl ether (MeGE) or fenchyl glycidyl ether (FenchGE). So far, these cyclic TPGEs have hardly been utilized in polymer synthesis, but their rigid structure is expected to possess a comparatively higher T_g than their acyclic analogues. Follow-up work by Holzmüller et al. is currently investigating these TGEs in both polyester and polycarbonate synthesis.¹⁷⁷

In conclusion, the substrate class of TGEs as well as disubstituted epoxides from terpene-based monomer precursors represent structurally diverse and bio-renewable monomer building blocks.^{139,143,144} The monomer scaffold with built-in olefinic bonds show versatile applicability to manufacture functional monomers via various

polymerization techniques.¹⁴⁴ Polyethers, polycarbonates and polyesters are accessible via AROP and ROCOP, allowing for fine tuning of the polymer properties towards various potential applications, which range from amphiphilic surfactants to packaging materials to soft segments in TPEs.^{169,173,174}

Despite the important quest for renewable feedstock for the synthesis of sustainable polymers, terpenes and terpenoids have generally been underexplored, with the exception of polyolefins.¹⁴⁴ Further, substantial progress has already been achieved for 1,3 dienes, namely β -myrcene- and β -farnesene, as they are already produced on an industrial scale from renewable feedstock, rendering them suitable as a realistic alternative for polyisoprene.^{145,201} Yet, regarding the feasibility of the utilization of terpene-derived epoxides, the large-scale availability from biomass resources has to be questioned.¹⁴³ Aiming at a sustainable route without adversely affecting the environment or competing with food chain products, advances in biocatalysis could provide the required technology to advance the development of a cost-effective, sustainable platform for the polymer industry.

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Chapter 2

Terpenyl Glycidyl Ethers in Anionic Ring Opening Polymerization

2 Terpenyl Glycidyl Ethers in Anionic Ring Opening Polymerization

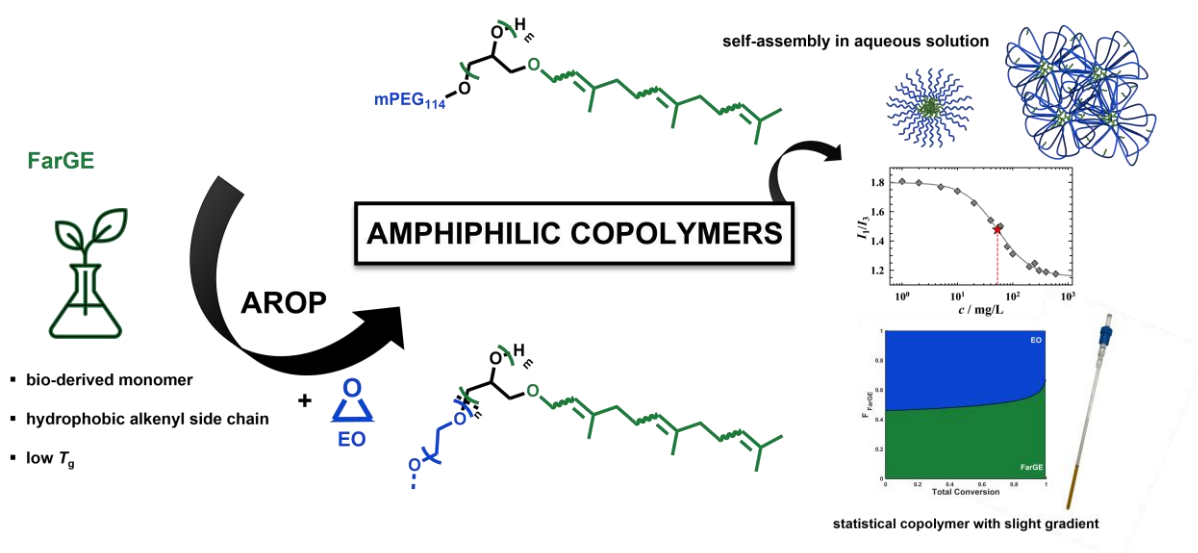
2.1 Anionic Ring Opening Copolymerisation of Farnesyl Glycidyl Ether: Fast Access to Terpenoid-derived, Amphiphilic Polyether Architectures

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Abstract

Motivated by increasing attention for bio-based and potentially sustainable polymers from renewable sources, this work describes the synthesis and anionic ring opening polymerization (AROP) of the terpenoid-derived farnesyl glycidyl ether (FarGE) as a hydrophobic epoxide building block for the synthesis of bio-based, amphiphilic polyethers that represent novel, nonionic surfactants. In combination with ethylene oxide (EO), the synthetic strategies employed provide access to both amphiphilic diblock (mPEG₁₁₄-*b*-PFarGE_m) and statistical copolymers (PEG_n-*co*-PFarGE_m), featuring facile tunability of their amphiphilic and surfactant properties. The versatile application of FarGE for different polyether architectures is demonstrated by the well-controlled molecular weights in the range of 5040 to 11,170 g·mol⁻¹ and narrow molecular weight distributions ($\mathcal{D} = 1.04 - 1.11$), both for block and statistical architectures. Owing to the unexpected, nearly ideally random microstructure of the statistical EO/FarGE copolyethers, determined by *in situ* kinetics ($r_{\text{EO}} = 1.18$ and $r_{\text{FarGE}} = 0.85$), the branched alkenyl side chain impedes the crystallization of polyethylene glycol (PEG) with increasing FarGE incorporation, allowing for fine-tuning of polymer properties. Observing a low glass transition temperature (T_g) of around -70 °C for the PFarGE homopolymer, thermal analysis also unveils farnesyl side-chain control of the T_g even at low FarGE content (7.6 mol%). Detailed investigations of aqueous polymer solutions reveal self-assembly of the amphiphilic copolymers into micelles and aggregates, characterized by very low critical micelle concentrations (CMC, 10 - 53 mgL⁻¹), as well as larger clusters ($R_{\text{H,micelle}} = 17 - 35$ nm and $R_{\text{H,cluster}} = 59 - 107$ nm). The results demonstrate the enormous potential of terpenes and terpenoids for partially biobased surfactant alternatives.

Introduction

Polymeric materials are abundant in modern life and play a key role in many areas.¹ However, the dependence on fossil fuel-based raw materials and increasing environmental awareness have induced a great deal of momentum for the production of renewable, more sustainable polymer materials.^{2,3} As a consequence, the identification, further development and production of bio-derived monomers, without adversely affecting nature and avoiding competition against food production, are key for a sustainable future.^{2,4–7}

Nature provides a variety of valuable monomer building blocks such as carbohydrates, vegetable oils and terpenes.^{1,8} Terpenoids and terpenes represent a class of particularly attractive, bio-based monomer precursors that are known to follow the “isoprene rule”, referring to the $(C_5H_8)_n$ units they are composed of.⁹ Their structural and functional variety renders terpenes suitable for a plethora of polymerization techniques, ranging from catalytic to radical and anionic polymerization.^{2,10–13} Highly versatile and easy-to-functionalize synthons are accessible via manifold chemical transformations of the renewable feedstock, enabling tailor-made materials.^{2,14,15} Specifically, double bond transformation to disubstituted epoxides, predominantly limonene oxide, has enabled significant research progress in the field of terpene-derived polycarbonates and polyesters.^{2,11,16,17}

Yet, the structural scaffold of terpenes prohibits the synthesis of monosubstituted epoxides, required for polyether synthesis via classical anionic ring opening polymerization (AROP). Glycidyl ethers generally still represent an underrated class of epoxides, despite their broad functional variety for the synthesis of multifunctional PEGs (*mf*-PEGs).^{18,19}

To date, terpene-derived monomers, namely terpenyl glycidyl ethers (TGEs), have been scarcely explored in AROP, although they can be conveniently synthesized from abundant hydrophobic terpene alcohols and epichlorohydrin (ECH).^{12,20} With respect to the use of epichlorohydrin (ECH) for the TGE synthesis, TGEs can be obtained fully biosourced, as “green” ECH can be produced from glycerol as a byproduct from biomass during biofuel production (Scheme S 1). The so-called Solvay’s Epicerol™ process is more environmentally friendly and already produces 100 kilotons ECH per year.^{21–23} Moreover, increasing efforts led to potential pathways for biosourced EO – either (i) by applying “green” ethylene in the silver catalyzed epoxidation or (ii) via redox-mediated electrosynthesis from CO₂ and water (Scheme S 2).^{24–26} Johann et al. demonstrated the

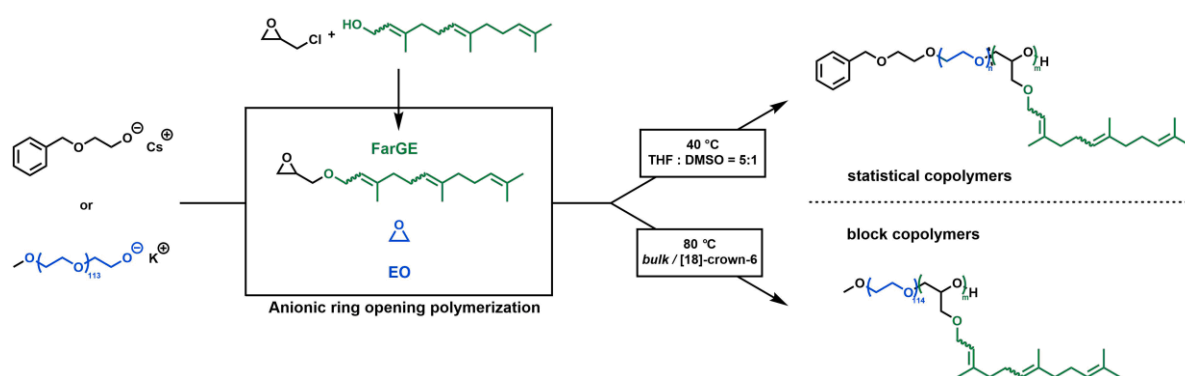
successful block copolymerization of citronellyl glycidyl ether and modified the “ene” moiety using triazolinediones (TADs).¹² In another approach, the cross metathesis of poly(terpenyl glycidyl ether)s, based on prenol and isoprenol, with small molecules has been reported, demonstrating their conjugation potential for drug delivery systems.²⁰

As poly(ethylene glycol) (PEG) exhibits extraordinary solubility in aqueous solution, it is commonly used as a water-soluble block for non-ionic surfactants. In combination with a hydrophobic monomer such as propylene oxide or alkyl glycidyl ethers (AlkGE) in block copolymers, amphiphilic polyether structures are formed.^{19,27,28} The ABA-triblock copolymers PEO-*b*-PPO-*b*-PEO, so-called poloxamers, are among the most established polymeric non-ionic surfactants both in academia and industry. This is due to the synthetic advantages and superior polyether properties, notably their biocompatibility.^{18,29} Amphiphilic polymers self-assemble in aqueous solution, leading to the formation of ordered structures like spherical, cylindrical and multi-compartment micelles as well as lamellae, vesicles and hydrogels.^{30–34} The properties of self-assembled nanostructures can be finely tuned by a variety of parameters, such as molecular weight, composition, copolymer microstructure (block, gradient, random, graft, alternating) and solvent conditions.^{31,35} Banking on the vast modification possibilities, the interest in amphiphilic nanostructures is further motivated by several application areas, varying from biomedicine, (opto-)electronics, cosmetics, emulsion polymerization and enhanced oil recovery.^{28,31,36}

TGEs with an acyclic side chain can be utilized as a hydrophobic component polyether surfactants and to the best of our knowledge have not been applied in the anionic ring opening copolymerization with ethylene oxide (EO). Applying farnesol (3,7,11-trimethyl-2,6,10-dodecatrien-1-ol) as highly hydrophobic terpenoid in glycidyl ether synthesis, novel monomer structures for amphiphilic polyethers can be obtained. Farnesol belongs to the class of bio-based sesquiterpenoids (C₁₅) and is abundant in essential oils of manifold plants.^{9,37} As a consequence of its pleasing odor and antibacterial value, its main application is in the cosmetic industry.^{38,39} Commercially, it is available as a stereoisomeric mixture with *all-trans* farnesol being the most common and easily accessible stereoisomer.³⁸ On an industrial scale, farnesol is prepared by isomerizing the considerably more abundant sesquiterpenoid *trans*-nerolidol.^{9,38} Additionally, microbial farnesol production via biosynthesis has been increasingly investigated, circumventing the production from limited natural resources.^{37,40,41} Hence, farnesyl glycidyl ether (FarGE) represents a valuable alternative to classic petroleum-

based hydrophobic epoxide monomers, such as propylene oxide and butylene oxide, commonly applied in industry.⁴²

Here we present the synthesis and AROP of EO with the terpenoid-based epoxide monomer FarGE, featuring a hydrophobic, branched alkenyl side chain (Scheme 1). The broad applicability and inertness of FarGE under different polymerization conditions allows for the design of water-soluble, amphiphilic diblock and statistical copolymers as well as PFarGE homopolymers. The hydrophilic/lipophilic balance (HLB) can be systematically tailored by the FarGE vs. EO comonomer ratio applied. The high monomer hydrophobicity of FarGE suffices to induce amphiphilicity even at a low degree of polymerization (P_n), which sets the scope of application as co-surfactants to enhance solubilization efficiency of conventional surfactants in microemulsions or as polymeric non-ionic surfactants.^{43,44}



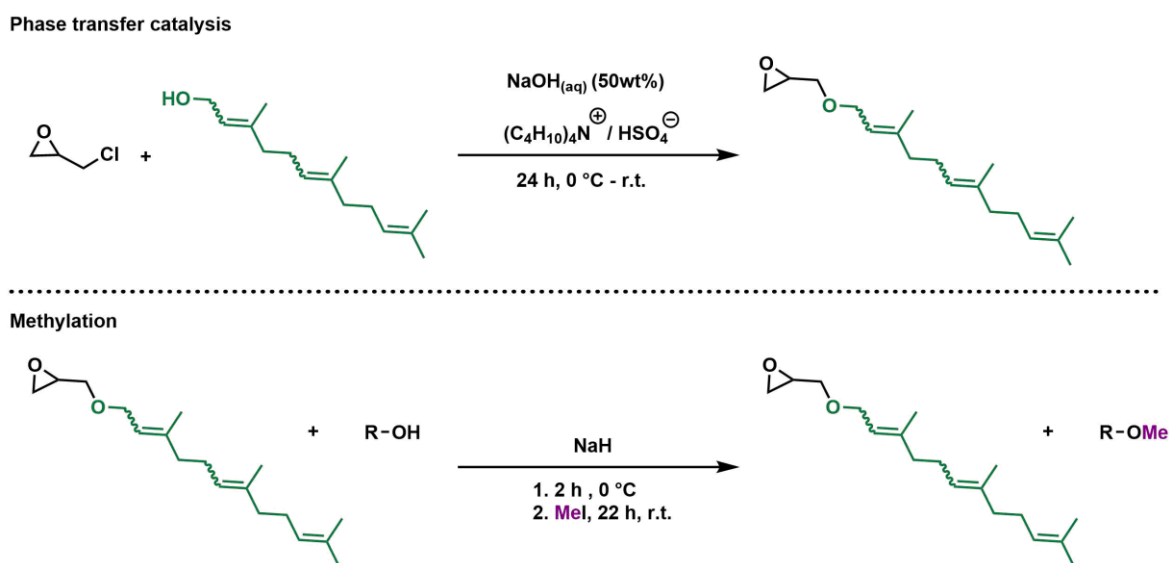
Scheme 1: Polymerization strategy of amphiphilic statistical and block copolymers via anionic ring opening (co)polymerization of EO and FarGE.

We anticipated the formation of micelles and micellar clusters with the hydrophobic FarGE blocks in the micellar core. To this end, the amphiphilic behavior in aqueous solution was studied with respect to the self-assembly and critical micelle concentration, which both depend on the respective block sizes and copolymer microstructure, respectively.²⁸

Results and Discussion

Farnesol Analysis and Monomer Synthesis

The novel glycidyl ether FarGE is characterized by its bio-derived hydrophobic side chain and allows for the facile synthesis of amphiphilic polyethers. The renewable monomer is easily accessible via phase transfer catalysis from commercially available reactants in yields of up to 85% (Scheme 2, top).⁴⁵ For this purpose, epichlorohydrin (ECH) was reacted with the terpenoid farnesol in an aqueous sodium hydroxide solution for 24 h. Farnesol is commercially available as an isomeric mixture with a purity of $\geq 95\%$, comprising *2Z,6E*-farnesol, *2E,6Z*-farnesol and *2E,6E*-farnesol at a relative ratio of 13:23:64, as indicated by GC and NMR analysis (Figures S 1 – S 4). Further, the multiplet carbon resonances approximately mirror the composition of different stereoisomers of the acyclic terpenoid (Figures S 2 and S 4). In turn, the *all-trans* configuration (*2E,6E*) represents the major component in the farnesol mixture.^{38,46,47}



Scheme 2: Synthesis pathway of the novel FarGE monomer via phase transfer catalysis (top) and subsequent deactivation of protic impurities in FarGE monomer via methylation with NaH and MeI (bottom).

The phase transfer catalysis is an efficient method for the attachment of the epoxide functionality, however, this is accompanied by the formation of an alternative epoxide structure, (3-chloroallyl) glycidyl ether (3-chloro-AGE), due to an elimination reaction of ECH under strongly basic conditions (Scheme S 3).^{48,49} Yet, the significant difference in boiling temperatures (T_b s) between FarGE and 3-chloro-AGE rendered distillation a suitable purification method, enabling the removal of undesired impurities, as confirmed via ^1H NMR analysis (Figure S 5). Nevertheless, even the presence of small amounts of protic impurities adversely impacts targeted molecular weights and molecular weight distributions, when employing oxyanionic polymerization

conditions.¹⁸ For instance, residual farnesol and water both have the capability to act as an additional initiator by forming an alkoxide due to a rapid proton exchange equilibrium (Scheme S 4, C).¹⁸ Thus, we targeted *O*-methylation as an underexplored approach to deactivate protic impurities, using sodium hydride (NaH) and methyl iodide, while simultaneously pre-drying the epoxide monomer (Scheme 2, bottom).⁵⁰ Figure S 6 compares the FT-IR spectra of farnesol and FarGE, confirming the absence of the typical OH-band of farnesol at 3311 cm⁻¹ in the final product. To determine the stereoisomeric monomer composition, FarGE was also evaluated by GC MS and ¹³C NMR spectroscopy (Figures S 7 and S 8). Although FarGE is comprised of the three stereoisomeric farnesyl side chains, the respective glycidyl ether should be presumed not to differ in reactivity of the associated epoxide functionality. Detailed NMR characterization (¹H, ¹³C, 2D analysis) is given in the Supporting Information (Figures S 9 - S 13) and further confirms the purity of the stereoisomeric FarGE monomer.

Synthesis of and Characterization of mPEG₁₁₄-*b*-PFarGE_m, P(EG_n-*co*-FarGE_m) Copolymers and PFarGE_m Homo-polymers

As a promising terpenoid-derived alternative to petroleum-based hydrophobic epoxide monomers, FarGE can be polymerized in classical AROP, enabling the synthesis of well-defined, alkene-functional polyethers. Yet, owing to the hydrophobic nature of FarGE, the design of the respective amphiphilic statistical or block-type polyether copolymers with EO required optimized polymerization conditions subject to the targeted polyether architecture (Scheme 1). Here, we first prepared a series of diblock copolymers and homopolymers in a crown ether-assisted homopolymerization at 80 °C using poly(ethylene glycol) methyl ether (mPEG₁₁₄) and 2-(benzyloxy)ethanol, respectively. According to literature, the addition of the crown ether 18-crown-6 supports the separation of the potassium ion from the active chain end and enhances chain end reactivity under solvent-free conditions while suppressing undesired chain transfer to the monomer.^{51,52} Furthermore, statistical copolymers of varying FarGE content are synthesized via copolymerization of FarGE and EO at 40 °C in solution (THF:DMSO = 5:1 (V/V)). Thus, the use of THF ensures sufficient mixing of the hydrophobic FarGE, EO and the ionic chain end, as solubilization of all polymerization components is a prerequisite to a controlled and uniform chain growth. Yet, adding the polar DMSO is important to promote the dissociation of the ion pair at the active chain end, leading to faster propagation.¹⁸ Table 1 summarizes polymer characterization data with respect to molar composition, number-averaged molecular weight M_n and

dispersity $\bar{D}$. All farnesyl-functionalized polyethers feature monomodal molecular weight distributions with low dispersities $\bar{D}$ (1.06 – 1.11) in a molecular weight range from 2800 to 7800 g·mol⁻¹, as evident from the respective SEC traces in Figure 1 and Figure S 29. Consistently, a single diffusion coefficient is observed in the DOSY NMR spectra for both the diblock and statistical architecture (Figures S 19 and S 37), translating into covalent attachment of the different blocks or comonomers, respectively. In addition, the DOSY NMR spectra evidence the absence of non-linked homopolymer blocks.

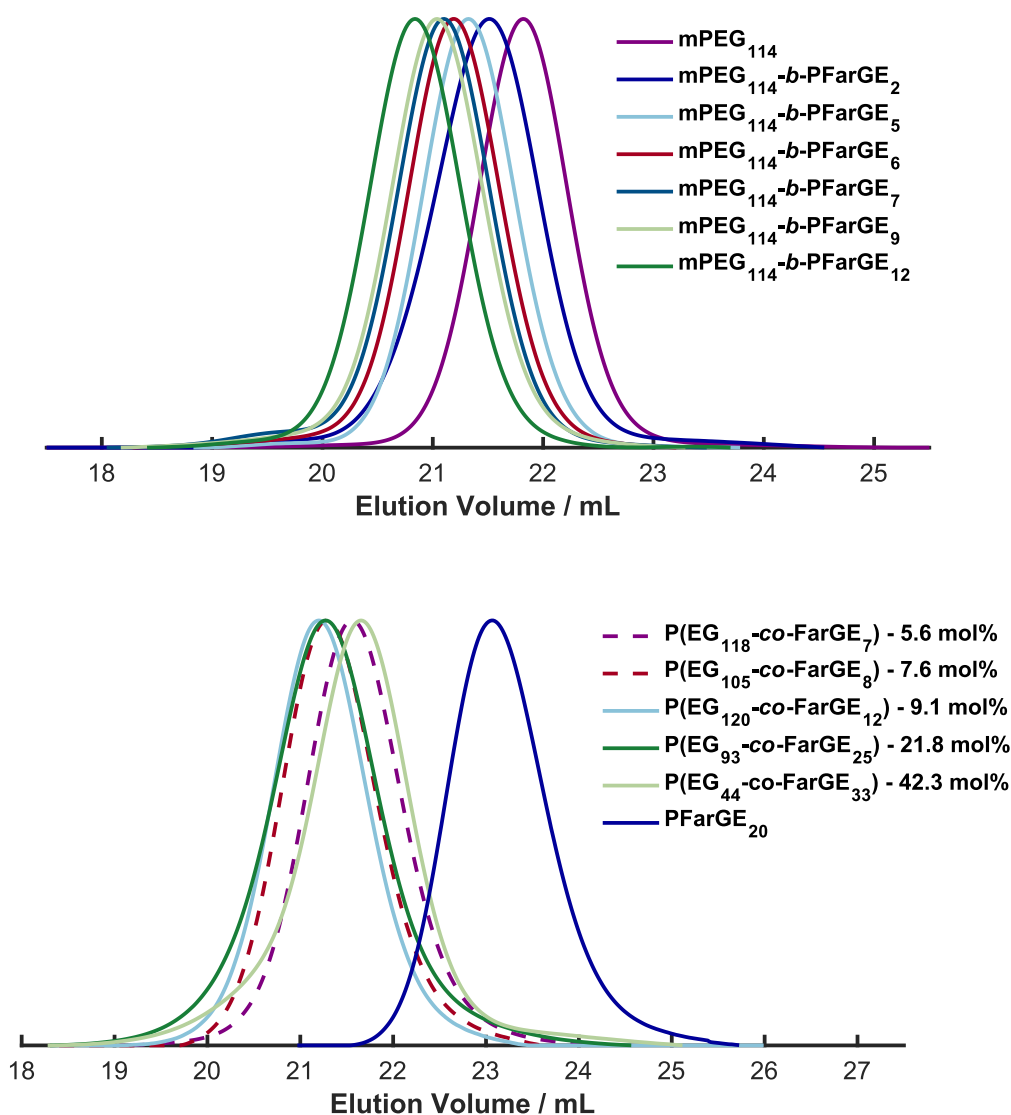


Figure 1: SEC elution traces of mPEG₁₁₄-*b*-PFarGE_m block copolymers compared to the initial mPEG₁₁₃ macroinitiator (top) and statistical P(EG_n-*co*-FarGE_m) copolymers with the PFarGE₂₀ homopolymer (bottom) (RI detector, eluent: DMF, calibration: PEG).

The polyethers' amphiphilicity is easily tunable by adjusting the FarGE comonomer feed ratio. For the block copolymers, successful variation of the FarGE content is demonstrated by the clear shift of the SEC traces towards lower elution volumes with

increasing FarGE block lengths (Figure 1 (top)). Initially, diblock copolymerizations showed a slightly lower P_n than anticipated (Table 1, entry 2, 3, 5 and 6), accompanied by the formation of homopolymer impurities (Figure S 21). The chain transfer reaction to the monomer is a well-known limitation in AROP of substituted epoxides, which is caused by proton abstraction and followed by subsequent initiation by the allylic species (Scheme S 4).^{53,54} The aforementioned established strategies to suppress the side reaction are exemplarily (i) the addition of crown ether or strongly polar solvents or (ii) application of mild polymerization conditions, by low reaction temperature and limited degree of initiator deprotonation.⁵¹⁻⁵⁵ However, neither allyl-initiated species were observable in ^1H NMR analysis, nor did a reduced polymerization temperature generate the targeted block length (Figure S 22).

Applying FarGE pretreated via methylation (Scheme 2, bottom) during the block copolymerization, we obtained the targeted block length (Table 1, entry 4 and 6 and Figure S 22). Consequently, we conclude protic impurities to be the cause the lower P_n of the FarGE block.^{44,50} In parallel, the MALDI ToF mass spectrum of the homopolymer PFarGE₂₀ not only shows minimal water-initiation, but indicates the absence of the allyl-initiated species despite the harsh polymerization conditions (Figures S 30 and S 31). These observations are in accordance with previously reported structures based on long chain AlkGE, highlighting a less acidic character of the α -methylene protons for glycidyl ethers with long alkyl chains (due to the + M-effect of the oxygen and +I-effect of long alkenyl chain).^{19,44} In addition to SEC characterization, M_n s were additionally evaluated using ^1H NMR spectroscopy ($M_{n,\text{NMR}}$) by referring the monomer signals (5.33 - 5.22 ppm) to the initiator resonance (4.53 - 4.57 ppm or 3.36 ppm), as is common for living polymerization systems (Figures S 14, S 23 and S 32).⁵⁶ The ^1H NMR spectra of the synthesized polymers show all expected signals, including the polyether backbone and the farnesyl repeating units, which confirms the successful (co)polymerization of FarGE under the varied AROP conditions. Detailed polymer characterization results are given in the Supporting Information (Figures S 14 – S 18, S 20, S 23 – S 28 and S 32 - S 36, S 38). Secondly, the comonomer ratios are in good agreement with the theoretical values and range from 2.5 to 42.3 mol% (Table 1). Yet, the concurrent (i.e., statistical) copolymerization showed slight deviations due to the challenging handling of gaseous EO and the associated errors in measured volumes at -80 °C. A deviation of M_n obtained by NMR and SEC is observed with increasing FarGE incorporation along the polyether backbone, arising more distinctly for the statistical P(EG_n-co-FarGE_m) copolymers. Equally, the molecular weights of the homopolymers (Table 1, entry 14-16) are strongly underestimated via SEC (Figure S 29). This phenomenon substantiates a decrease in

hydrodynamic radii due to the structural and polarity dissimilarity of the farnesyl side chains compared to the PEG calibration and has been commonly reported for multifunctional PEGs.^{57,58}

Table 1: Overview of polymer characterization data for the series of mPEG₁₁₄-*b*-PFarGE_m block copolymers, P(EG_n-*co*-FarGE_m) statistical copolymers as well as PFarGE_m and PEG₁₅₅ homopolymers.

Entry	Sample	$X_{\text{FarGE,theo}}^a$ (mol%)	$X_{\text{FarGE,exp}}^b$ (mol%)	$P_{n,\text{total}}^b$	$M_{n,\text{NMR}}^c$ (g·mol ⁻¹)	$M_{n,\text{SEC}}^d$ (g·mol ⁻¹)	$\bar{D}^d$
1	mPEG ₁₁₄	–	–	–	5040	5000	1.04
2 ^e	mPEG ₁₁₄ - <i>b</i> -PFarGE ₂	2.5	1.7	116	5590	5800	1.07
3 ^e	mPEG ₁₁₄ - <i>b</i> -PFarGE ₅	5.1	4.2	119	6430	6300	1.04
4	mPEG ₁₁₄ - <i>b</i> -PFarGE ₆	5.0	5.0	120	6710	6700	1.05
5 ^e	mPEG ₁₁₄ - <i>b</i> -PFarGE ₇	7.3	5.8	121	6990	7000	1.05
6	mPEG ₁₁₄ - <i>b</i> -PFarGE ₉	7.3	7.3	123	7540	7100	1.05
7 ^e	mPEG ₁₁₄ - <i>b</i> -PFarGE ₁₂	13.6	9.5	126	8380	7800	1.04
8 ^f	PEG (6K)	–	–	155	–	6800	1.09
9	P(EG ₁₁₈ - <i>co</i> -FarGE ₇)	5.2	5.6	125	7130	5500	1.07
10	P(EG ₁₀₉ - <i>co</i> -FarGE ₉)	7.5	8.0	118	7290	6100	1.06
11	P(EG ₁₂₀ - <i>co</i> -FarGE ₁₂)	10.0	9.1	132	8600	6500	1.06
12	P(EG ₉₃ - <i>co</i> -FarGE ₂₆)	20.2	21.8	119	11,330	6200	1.11
13 ^e	P(EG ₄₄ - <i>co</i> -FarGE ₃₃)	50.0	42.3	78	11,170	5400	1.11
14 ^e	PFarGE ₂₀	–	100	20	5720	2800	1.06
15 ^e	PFarGE ₃₀	–	100	30	8500	3000	1.07
16 ^e	PFarGE ₃₅	–	100	35	9890	3300	1.07

^aTheoretical monomer content. ^bExperimental monomer content determined via ¹H NMR spectroscopy. ^cNumber averaged molecular weight determined via ¹H NMR spectroscopy. ^dDetermined via SEC measurements (RI detector, eluent: DMF, calibration: PEG). ^eMonomer batch without treatment with MeI was applied. ^fThe SEC analysis of the commercial PEG (6K) was used to determine the respective P_n due to the absence of end groups.

***In situ* ^1H NMR Copolymerization Kinetics of FarGE with EO for the Determination of reactivity ratios**

A key objective of this study was to elucidate the $\text{P}(\text{EG}_n\text{-co-FarGE}_m)$ copolymer microstructure and to establish structure-property relationships regarding thermal and aqueous dissolution behavior. We performed *in situ* ^1H NMR spectroscopy to precisely monitor the copolymerization of EO and FarGE in a vacuum-sealed NMR tube under the previously optimized synthesis conditions (Cs^+ counterion, $\text{THF-}d_8\text{:DMSO-}d_6 = 5\text{:}1$, $T = 40^\circ\text{C}$), while no external manipulation was required. The resulting reactivity ratios of the EO/FarGE monomer pair are used to predict the copolymers' microstructure.⁵⁹ The SEC trace of the synthesized copolymer during the *in situ* kinetic measurement is shown in Figure S 42. Due to the absence of chain transfer and termination during AROP, it was possible to monitor the monomer consumption by the decrease of their respective monomer integrals with preceding copolymerization (Figure 2).

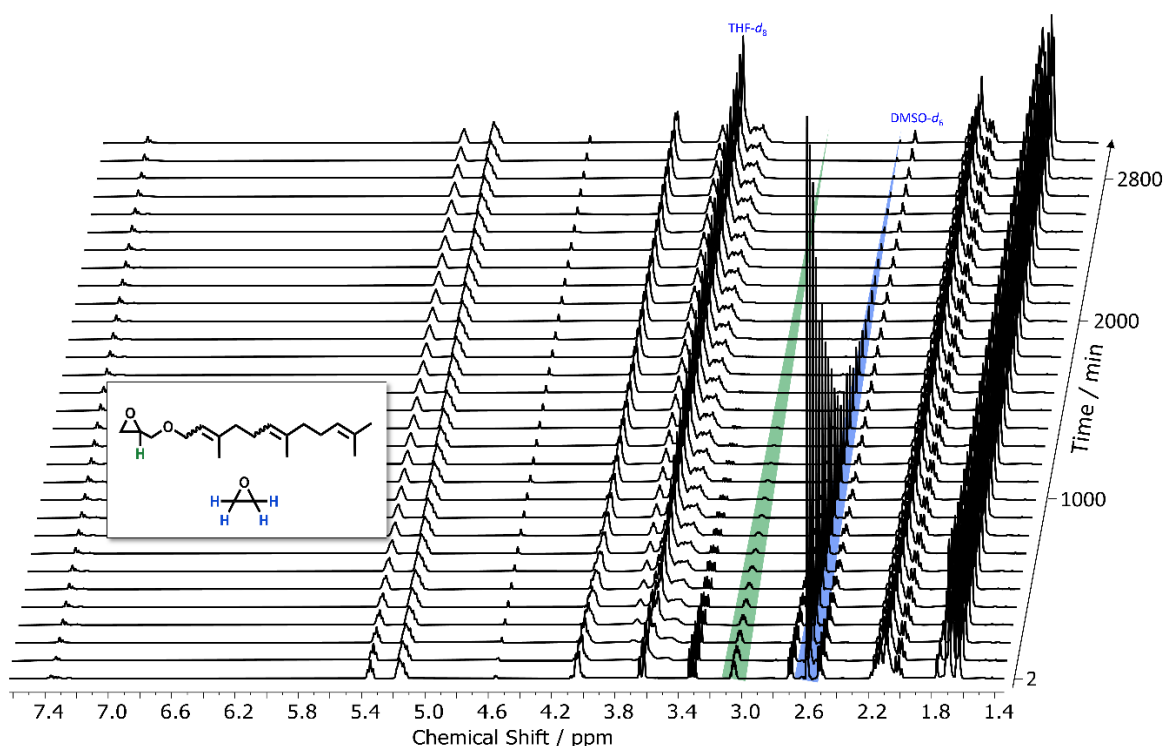


Figure 2: Selection of ^1H NMR spectra (400 MHz, $\text{THF-}d_8\text{:DMSO-}d_6=5\text{:}1$) of the *in situ* copolymerization kinetics of FarGE with EO at 40°C . Relevant proton signals are highlighted in green (FarGE) at 3.05 ppm and blue (EO) at 2.59 ppm. As spectra were collected every 2 min over a period of 51.5 h, only every 50th spectrum is displayed.

Both monomer resonances, at 3.05 ppm (FarGE, green) and at 2.59 ppm (EO, blue), show a gradual decrease up to full conversion after 51.5 h at 40°C . Figure 3 (left) depicts the individual monomer consumption with increasing total conversion and allows for the determination of the reactivity ratios, demonstrating slightly faster incorporation of EO

in comparison to FarGE. Applying the ideal, non-terminal copolymerization model, the Jaacks fit (Figure S 40) revealed reactivity ratios of $r_{\text{FarGE}}=0.85$ and $r_{\text{EO}}= 1.18$ (Table 2).^{60,61}

Table 2: Reactivity ratios for the AROP of FarGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C. The reactivity ratios presented are determined using the non-terminal Jaacks method.

Method	r_{FarGE}	r_{EO}	$r_{\text{FarGE}} \cdot r_{\text{EO}}$	R^2
Jaacks	0.85 ± 0.01	1.18 ± 0.01	1	0.999

Generally, the previously reported copolymerizations of EO with glycidyl ethers manifest an almost random copolymerization behavior, in which the glycidyl ethers commonly exhibit a slightly enhanced reactivity ($r_{\text{GE}} > r_{\text{EO}}$), which was ascribed to a transient crown ether effect and increased Lewis basicity.^{32,59,62,63} In contrast, an inversion of the reactivity ratios ($r_{\text{GE}} < r_{\text{EO}}$) has been reported for EO and bulky glycidyl ethers like catechol acetone glycidyl ether (CAGE) and 3,3-dimethoxy-2,2-dimethylpropanyl glycidyl ether (DDPGE).^{49,64} Analogously, we ascribe the surprisingly small deviation from fully random copolymerization of FarGE to its sterically hindered, bulky alkenyl side chain and its hydrophobic nature in comparison to EO. Remarkably, the resulting farnesyl chain distribution along the polymer backbone still results in an almost ideally random microstructure with a very weak gradient, despite the high steric demand of the FarGE structure. Figure 3 (right) visualizes the extent of the soft gradient microstructure, showing only a slight enrichment of FarGE segments towards the polyether terminus.

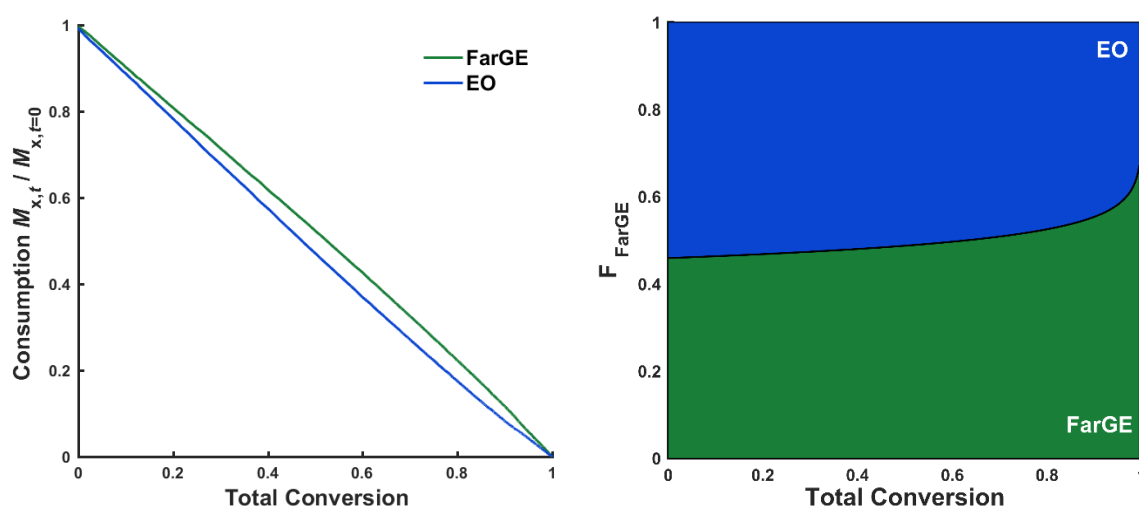


Figure 3: Individual monomer consumption plotted versus total monomer conversion (left), derived from *in situ* ^1H NMR copolymerization kinetics of FarGE (green) with EO (blue). Molar-based composition diagram of a $\text{P}(\text{EO}_n\text{-co-FarGE}_m)$ copolymer, modelled at equimolar monomer ratio, with F_{FarGE} = molar fraction of FarGE (right). Calculations are based on the reactivity ratios derived from a linear Jaacks fit ($r_{\text{FarGE}} = 0.85$, $r_{\text{EO}} = 1.18$, Figure S 40).

Thermal characterization

Based on the successful farnesyl-functionalization of PEG, the thermal properties in bulk were investigated via differential scanning calorimetry (DSC). Table 3 comprises a comprehensive overview of the thermal analysis and further reflects the distinctive structural difference between the block-like and statistical copolymer structure.^{57,58}

Table 3: Thermal characterization of mPEG₁₁₄-*b*-PFarGE diblock and P(EG_{*n*}-*co*-FarGE_{*m*}) statistical copolymers in comparison to the respective PFarGE_{*m*} and PEG₁₅₅ homopolymers.

Entry	Sample	M_n^a (g·mol ⁻¹)	X_{FarGE}^a (mol%)	X_{FarGE}^a (wt%)	T_g^b (°C)	T_m^b (°C)	ΔH_m^b (J·g ⁻¹)
1	mPEG ₁₁₄	5040	–	–	n.d.	61	217
2	mPEG ₁₁₄ - <i>b</i> -PFarGE ₂	5590	1.7	10.0	–	59	147
3	mPEG ₁₁₄ - <i>b</i> -PFarGE ₅	6430	4.2	19.9	-71	56	139
4	mPEG ₁₁₄ - <i>b</i> -PFarGE ₆	6710	5.0	24.9	-70	55	99
5	mPEG ₁₁₄ - <i>b</i> -PFarGE ₇	6990	5.8	27.9	-72	54	93
6	mPEG ₁₁₄ - <i>b</i> -PFarGE ₉	7540	7.3	33.2	-71	56	88
7	mPEG ₁₁₄ - <i>b</i> -PFarGE ₁₂	8380	9.5	39.9	-73	54	81
8	PEG ₁₅₅	–	–	–	n.d.	64	193
9	P(EG ₁₁₈ - <i>co</i> -FarGE ₇)	7130	5.6	27.1	-56	31	41
10	P(EG ₁₀₉ - <i>co</i> -FarGE ₉)	6840	8.0	33.7	-68	24	40
11	P(EG ₁₂₀ - <i>co</i> -FarGE ₁₂)	8600	9.1	38.8	-69	12	38
12	P(EG ₉₃ - <i>co</i> -FarGE ₂₆)	11,330	21.8	63.7	-70	–	–
13	P(EG ₄₄ - <i>co</i> -FarGE ₃₃)	11,170	42.3	82.2	-72	–	–
14	PFarGE ₂₀	5720	100	100	-74 ^c	–	–
15	PFarGE ₃₀	8500	100	100	-70 ^c (-73)	–	–

^aNumber averaged molecular weight and experimental monomer content determined via ¹H NMR spectroscopy.

^bDetermined from second heating cycle at a heating rate of 10 °Cmin⁻¹. ^cThe T_g s of homopolymers were determined from additional low-temperature DSC measurements for more precise values (compare Figures S 48 and S 49).

PEG itself is characterized by its high crystallinity, with a melting temperature (T_m , > 2000 g/mol) approximating 65 °C (entry 1 and 8).¹⁸ In contrast to long-chain alkyl epoxides and AlkGE, the branching of the farnesyl side chain inhibits side chain crystallization.⁵⁵ The mPEG_{*n*}-*b*-PFarGE_{*m*} diblock copolymers only feature a marginal

decrease of the T_m and melting enthalpy (ΔH_m) with increasing FarGE block length, manifesting the capability of the PEG block to crystallize (Figures S 43 and S 44). Notably, only a single T_g is displayed for block copolymers in the range of -70 to -73 °C, which is in accordance with the T_g value of -70 °C for the fully amorphous PFarGE homopolymer (Figures S 48 and S 49). This result is indicative of either poor phase separation due to the short PFarGE segments or the mere absence of the T_g of PEG due to the high PEG block crystallinity of the nano-segregated blocks.⁶⁵

In contrast, for the statistical copolymers the random incorporation of farnesyl side chain along the polyether backbone translates to regular interruptions within the crystalline PEG domains and gradually reduces the degree of crystallization with increasing FarGE content. Hence, a pronounced decrease of the T_m and ΔH_m is observed. Figure S 45 visualizes this transition from a crystalline to an amorphous polymer, displaying the respective DSC thermograms. In Figure S 47, the T_m is plotted as a function of FarGE content (mol%), which in turn allows for the interpolation to a FarGE content of 0 mol%. The linear regression entails a $T_{m,PEG,fit}$ of 61 °C and is approximately in line with the T_m of PEG (Figure S 46), thus mirroring the random copolymer structure.

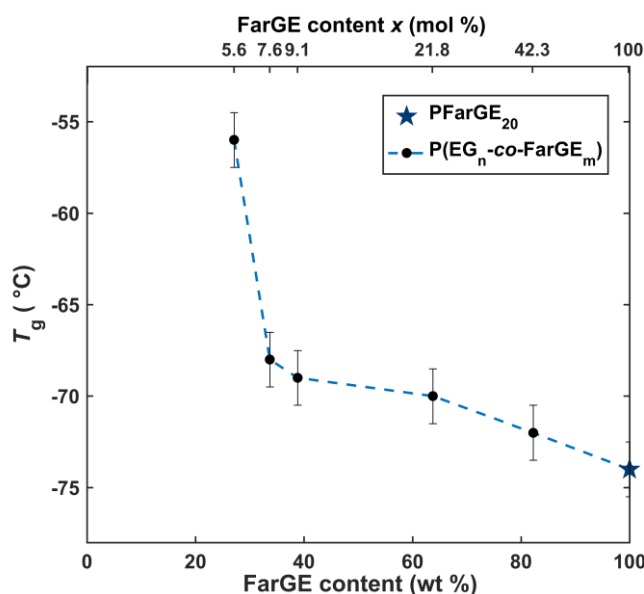


Figure 4: Glass-transition temperatures of $P(EG_n-co-FarGE_m)$ copolymers as a function of FarGE content in mol% (axis on top) and wt% (axis on bottom). Dashed line serves as a guide to the eye. Errors are estimated and error bars are set to a value of ± 1.5 °C.

Fully amorphous copolyethers are obtained at a FarGE content of 21.9 mol%, demonstrated by the DSC thermogram of $P(EG_{93}-co-FarGE_{26})$ that did not exhibit a melting endotherm. An intriguing phenomenon is observed for the T_g values, which range from -56 to -72 °C. Since the *in situ* kinetics confirmed an almost ideally random copolymerization behavior, we analyzed the linear relation between comonomer ratio and resulting T_g in consideration of the well-known Fox equation.⁶⁶ A strong, non-linear

decrease of the T_g occurs at unexpectedly low FarGE content (7.6 mol%, Figure 4), approaching the homopolymer T_g value, as it would be typically expected for strong gradient or block copolymers.⁶⁷ We propose that at higher FarGE content the onset of mobility at the T_g is predominantly controlled by the flexible farnesyl side chains (side-chain control), whereas the T_g of copolyethers at low FarGE content is mainly due to backbone reptation ($T_{g,PEG} = -56^\circ\text{C}$).⁶⁸ Conclusively, a strong influence of FarGE incorporation on the thermal properties was observed for the low- T_g statistical copolymers, whereas the block copolymers are scarcely impacted.

Amphiphilic Properties in Aqueous Solution

For potential applications as non-ionic surfactants or in the biomedical field, it is imperative to elucidate the amphiphilic properties and resulting self-assembly in aqueous solution as well as to determine the critical micelle concentration (CMC). The novel amphiphilic copolymers are water-soluble, especially for lower FarGE contents, while turbidity was observed for copolymers with larger FarGE blocks. In analogy to typical non-ionic surfactants,⁶⁹ this is most likely related to exceeding the cloud point due to increased copolymer hydrophobicity.

Determination of CMCs

Similar to conventional surfactants, amphiphilic polymers in aqueous solutions self-assemble into micelles above the critical micelle concentration (CMC). CMCs depend particularly on amphiphile hydrophobicity and can be several orders of magnitude lower for amphiphilic block copolymers than for common ionic and non-ionic surfactants.^{70,71} We employed different techniques to study micellization for selected PEG-PFarGE polymers, which were synthesized here for the first time. Surface tensiometry is a well-established method for the determination of the CMC, particularly for ordinary surfactants. Aqueous solutions of pure surfactants exhibit a strong decrease in surface tension with increasing concentration c , which remains constant for $c > \text{CMC}$. However, for aqueous solutions of amphiphilic block copolymers, the surface tension curve around the CMC shows a less pronounced kink than for surfactants. Additionally, surface tension typically continues to decrease moderately above the CMC and remains high ($> 45 \text{ mNm}^{-1}$),^{70,71} which could be related to an increasing aggregation number.⁷² Thus, the CMC determination can become inaccurate. A similar course of the surface tension curve was found here for the aqueous solution of $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_5$, from which a CMC of $43 \pm 4 \text{ mgL}^{-1}$ was obtained (see Figure S 50 in the Supporting

Information). To verify this result, we additionally determined CMCs via light scattering and fluorescence spectroscopy.

Static and dynamic light scattering (SLS/DLS).

SLS and DLS (see SI for measurement details) were performed to trace the concentration-dependent scattering of aqueous polymer solutions. In Figure 5, typical results are shown for the block copolymer mPEG₁₁₄-*b*-PFarGE₅ (data for mPEG₁₁₄-*b*-PFarGE₉ and the statistical copolymer P(EG₁₂₀-*co*-FarGE₁₂) can be found in the SI, Figure S 51). On the left side, the scattering intensity, shown as excess Rayleigh ratio R_{vv} determined with toluene as reference scatterer,⁷³ is plotted against the mPEG₁₁₄-*b*-PFarGE₅ concentration c . Given the low CMCs of amphiphilic block copolymers, the data is shown in a log-log representation. R_{vv} increases with concentration as anticipated. The scattering signal for concentrations below the CMC (gray squares/line), where only unimers are expected to be present, is weaker compared to measurements above the CMC (green circles/line), where self-aggregation of polymer molecules leads to the formation of micelles. Intersection of the trends yields a CMC = 44 ± 7 mgL⁻¹ (red star).

Further information on the presence of micelles is provided by DLS, in which intensity-time autocorrelation functions ($g^2(\tau)$) are recorded and analyzed. Figure 5, middle top, shows a $g^2(\tau)$ -1 curve obtained for an exemplary measurement above the CMC. This curve follows the typical trend of a correlation function, indicating a high-quality measurement with an intercept close to 1 and a high signal-to-noise ratio. In contrast, measurements below the CMC show significant noise and a fluctuating correlation curve over several orders of magnitude of lag time.

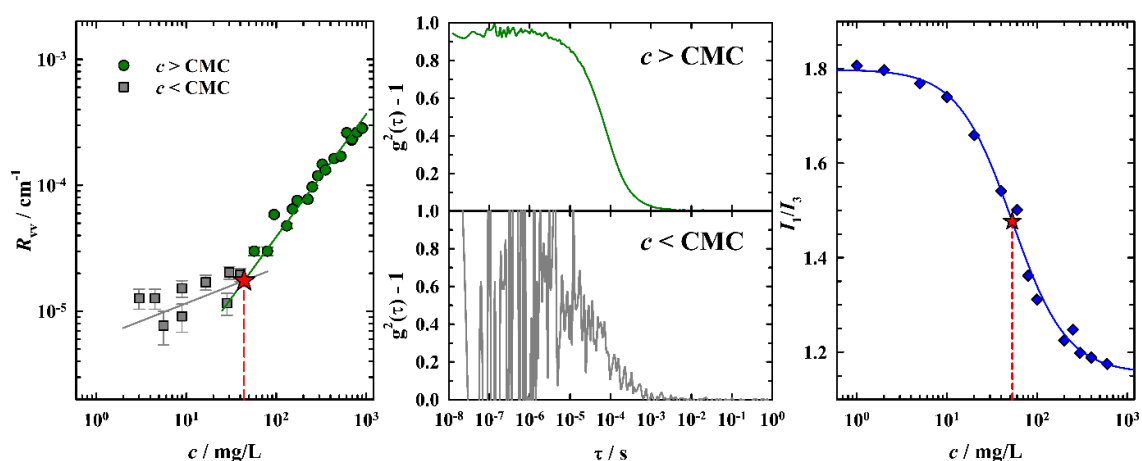


Figure 5: Micellization of the terpenoid-based polyether mPEG₁₁₄-*b*-PFarGE₅ in water, studied by concentration-dependent light scattering and fluorescence spectroscopy measurements at $T = 23 \pm 1$ °C. The CMC is denoted with a red star. Left: Excess Rayleigh ratio R_{vv} determined via SLS vs. mPEG₁₁₄-*b*-PFarGE₅ concentration c , recorded at $q = 90^\circ$. Middle: Selected DLS correlation functions $g^2(\tau)$ -1 vs. lag time τ for concentrations above (top, green) and below (bottom, gray) the CMC. Right: Pyrene I_1/I_3 ratio determined via fluorescence spectroscopy vs. polymer concentration c .

Fluorescence Spectroscopy.

In addition to the light scattering studies, we performed fluorescence spectroscopy measurements, which have been successfully used to determine the CMC of block copolymers.^{74,75} From the emission spectra of aqueous polymer solutions containing minor amounts of pyrene ($c_{\text{pyrene}} = 7 \cdot 10^{-7}$ M), we used the intensity maximum of the first and third pyrene vibronic bands to calculate the intensity ratio I_1/I_3 .^{76,77} Details are provided in the SI. Changes in the spectrum and especially in the ratio I_1/I_3 directly relate to the polarity of the pyrene environment, as pyrene is poorly soluble in water and therefore preferentially solubilized within the micellar core.⁷⁷ This allows for the determination of the CMC when plotted against polymer concentration. As evident in Figure 5, right, a typical sigmoidal trend is observed for the aqueous solution of the mPEG₁₁₄-*b*-PFarGE₅ copolymer. The exponential-based approach by Aguiar et al. is commonly used to describe the data for ordinary surfactants;⁷⁶ however, it becomes disadvantageous for very low amphiphile concentrations because minimizing χ^2 can – and indeed will for our polymers – yield negative CMCs. We therefore propose using

$$I_1/I_3 = \frac{A_1 - A_2}{1 + (c/c_0)^f} + A_2, \quad (1)$$

where A_1 and A_2 are the upper and lower limits of the sigmoid (I_1/I_3 for $c \rightarrow 0$ and $c \rightarrow \infty$, respectively), f relates to the steepness of the sigmoid, and c_0 is the concentration at the inflection point of the sigmoid, which is defined as the CMC. This more restrictive power law version is applicable solely to positive concentrations and further yields a lower χ^2 without additional constraints. At low mPEG₁₁₄-*b*-PFarGE₅ concentrations, I_1/I_3 approaches a value of $A_1 \approx 1.8$, similar to what has been found in studies using a similar excitation wavelength.^{74–76} Partitioning of pyrene into the hydrophobic micellar core decreases the magnitude of I_1/I_3 until a constant value of $A_2 \approx 1.2$ is reached (compare Figure S 52). From this analysis, we obtain CMC = 53 ± 4 mgL⁻¹ for mPEG₁₁₄-*b*-PFarGE₅ (Figure 5, right), Similar to the CMCs determined via the previous methods.

CMCs of amphiphilic polyethers

Critical micelle concentrations obtained for the block copolymers mPEG₁₁₄-*b*-PFarGE₅ and mPEG₁₁₄-*b*-PFarGE₉ as well as the statistical copolymer P(EG₁₂₀-*co*-FarGE₁₂) are compiled in Table 4. The data shows that, within measurement uncertainty, CMCs determined via surface tensiometry, light scattering and fluorescence spectroscopy are in good agreement. Due to a stronger hydrophobic effect, larger hydrophobic blocks result in significantly lower CMCs.⁷⁸ In comparison, amphiphilic copolymers such as

poly(glycidyl amine)–poly(propylene oxide)s⁷⁰, poly(ethylene glycol)–poly(propylene carbonate)s⁷¹ and –poly(styrene)s⁷⁴, which have a higher hydrophobicity than the farnesyl glycidyl ethers, exhibit even lower CMCs. In contrast, more hydrophilic poly(ethylene glycol)–poly(lactide) block copolymers⁷⁹ show higher CMCs. The low CMC of the statistical polymer suggests a hydrophobicity comparable to mPEG₁₁₄-*b*-PFarGE₉, while its high light scattering intensity (cf. Figure S 51, right) indicates that the statistical distribution of FarGE units within the PEG chain seems to result in less densely packed micelles and clusters compared to the diblock copolymers, strongly correlating with the large self-assembled structure identified by TEM measurements (Figure S 57 (bottom right)).

Table 4: Critical micelle concentrations (CMCs) for different terpenoid-based polyethers in water at $T = 23 \pm 1$ °C, obtained via static light scattering, fluorescence spectroscopy, surface tensiometry.

CMCs [mgL ⁻¹]	Static Light Scattering	Fluorescence Spectroscopy	Surface Tensiometry
mPEG ₁₁₄ - <i>b</i> -PFarGE ₅	44 ± 7	53 ± 4	43 ± 4
mPEG ₁₁₄ - <i>b</i> -PFarGE ₉	16 ± 4	15 ± 1	–
P(EG ₁₂₀ - <i>co</i> -FarGE ₁₂)	10 ± 3	14 ± 1	–

Self-assembly of farnesyl-based polyethers in water

To characterize the hydrodynamic radius of the diblock copolymers in dilute solution, dynamic light scattering experiments were carried out. The concentrations were chosen to be well above the CMC to obtain conclusive relaxation curves with high signal-to-noise ratios. Figure 6 shows representative normalized autocorrelation functions $g^{(1)}_{\text{norm}}(t)$ at a scattering angle of 90° of the homopolymer mPEG₁₁₄ (blue symbols) as well as the copolymers mPEG₁₁₄-*b*-FarGE₅ (black symbols) and mPEG₁₁₄-*b*-PFarGE₇ (green symbols). The overall relaxation shifts towards longer times with an increasing FarGE block length, implying the slow relaxation mode dominates, which in turn correlates to larger structures. The resulting DLS fit data, including the hydrodynamic radii according to the Stokes-Einstein equation, are shown in Table 5 (fitting procedure in SI, Figures S 53 – S 56). The attachment of FarGE segments leads to a significant enlargement of the hydrodynamic radius from 2 nm unimers (mPEG₁₁₄) to uniformly distributed 17 nm micelles (Table 5, entry 2 and 3, Figure 6).

The apparent diffusion coefficient $D_{\text{app,m}}$ shows no dependency on the scattering angle (Figure 6, top right and Figures S 53 and S 54). Further increasing the hydrophobic FarGE block length ($m \geq 7$), a stretching exponent β is required to fit the appearing slow relaxation mode, and its decrease indicates a cumulative heterogeneity of the formed aggregate sizes. The two modes reveal a q -dependence of the relaxation times and are assigned to micelles and clusters, respectively (Figure 6, bottom right and Figures S 55 and S 56). Evidently, from mPEG₁₁₄-*b*-PFarGE₇ on, two distinct radii were obtained that demonstrate the formation of larger clusters, as previously reported for PEG-based block copolymer systems.^{58,80} The ratio $R_{\text{H,c}}/R_{\text{H,m}}$ shows that the clusters are approximately three times larger than the micelles. The assembly of clusters is tentatively explained by hydrophobic interactions of the longer FarGE blocks, which are enhanced since the polymer concentration is far higher than the CMC. An analogous analysis of the statistical copolymers was not possible due to a strong influence of their particle form factor, resulting in q -dependent low scattering intensities and therefore low signal-to-noise ratios in the autocorrelation functions.

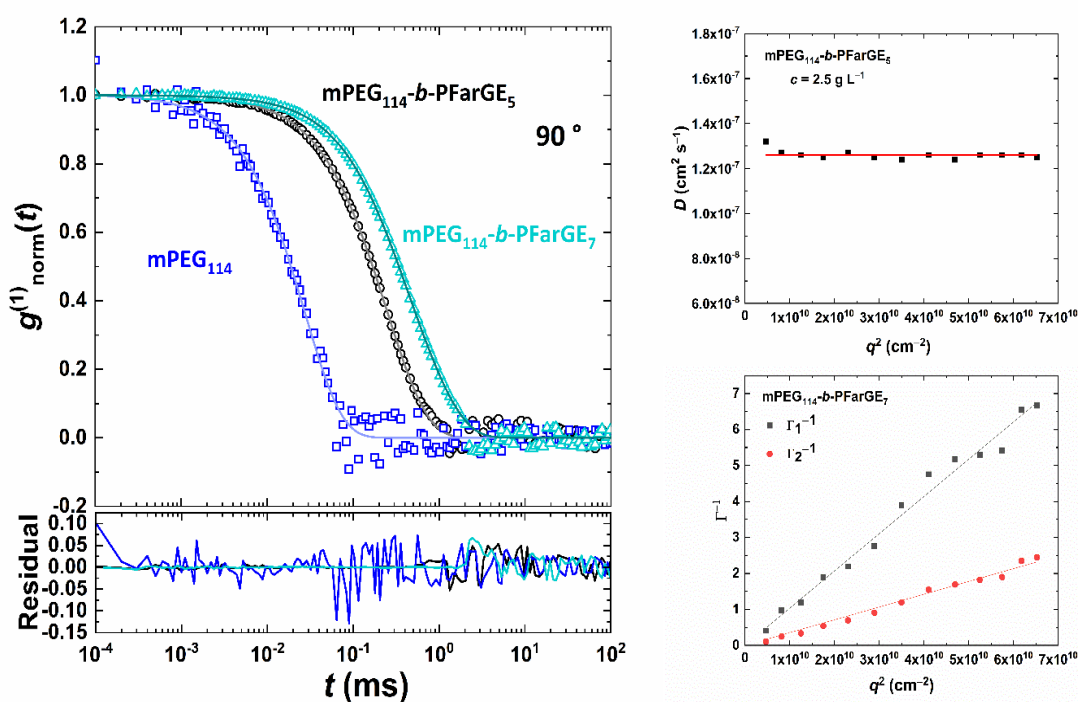


Figure 6: Normalized autocorrelation functions of a linear homopolymer mPEG₁₁₄ ($c = 15$ gL⁻¹, blue symbols), and the block copolymers mPEG₁₁₄-*b*-PFarGE₅ ($c = 2.5$ gL⁻¹, black symbols) and mPEG₁₁₄-*b*-PFarGE₇ ($c = 2.5$ gL⁻¹, green symbols) (top, left). Residuals of the data and the fits (bottom, left). Angle-independent apparent diffusion coefficient $D_{\text{app,m}}$ for mPEG₁₁₄-*b*-PFarGE₅ (top, right). Inverse relaxation times vs. q^2 to evaluate the diffusion coefficients D for mPEG₁₁₄-*b*-PFarGE₇ (bottom, right).

Table 5. Characterization data from DLS, including calculated hydrodynamic radii $R_{H,i}$, apparent diffusion coefficients $D_{app,i}$ and respective stretch factor β . The index i differentiates between micelle/ PEG unimer (i=m) and clusters (i=c).

Sample	c (g·L ⁻¹)	$R_{H,m}$ (nm)	$D_{app,m}$ (cm ² s ⁻¹)	$B_{m,\%}^a$	$R_{H,c}$ (nm)	$D_{app,c}$ (cm ² s ⁻¹)	$E_{c,\%}^a$	β_{slow}
mPEG ₁₁₄	15	2 ^b	11.09·10 ⁻⁷	1	-	-	-	-
mPEG ₁₁₄ - <i>b</i> -PFarGE ₂	2.5	17	1.27·10 ⁻⁷	1	-	-	-	-
mPEG ₁₁₄ - <i>b</i> -PFarGE ₅	2.5	17	1.27·10 ⁻⁷	1	-	-	-	-
mPEG ₁₁₄ - <i>b</i> -PFarGE ₇	1.25	21	1.04·10 ⁻⁷	0.41	59	0.36·10 ⁻⁷	0.58	0.94
mPEG ₁₁₄ - <i>b</i> -PFarGE ₉	1.25	39	0.53·10 ⁻⁷	0.28	116	0.19·10 ⁻⁷	0.72	0.87
mPEG ₁₁₄ - <i>b</i> -PFarGE ₁₂	1.25	35	0.61·10 ⁻⁷	0.23	107	0.20·10 ⁻⁷	0.77	0.86

^aDetermined using the fit amplitudes: $B_{m,\%} = B / (B + E)$ and $E_{c,\%} = E / (B + E)$. ^b $R_{H,m}$ refers to the hydrodynamic radius of the PEG₁₁₄ unimer, as no micelle is formed.

Further confirming the light scattering results, TEM micrographs (Figure S 57) display the self-assembled micellar structures of both statistical and diblock copolymers. An increasing hydrophobic FarGE block length most probably causes an aggregation of multiple spherical micelles into larger structures (Figure S 57, top and bottom left, Table 5).⁸¹ Intriguingly, only macroscopic spherical micellar structures were detected for the statistical copolymers (Figure S 57, bottom right). Figure 7 illustrates the proposed self-assembly of the detected micelles and clusters in aqueous solution, derived from TEM images and previously reported for multifunctional PEGs.⁵⁸ Nevertheless, a detailed study of the global and inner structure of the formed micelles and clusters requires further small-angle neutron or X-ray (SANS/SAXS) measurements.

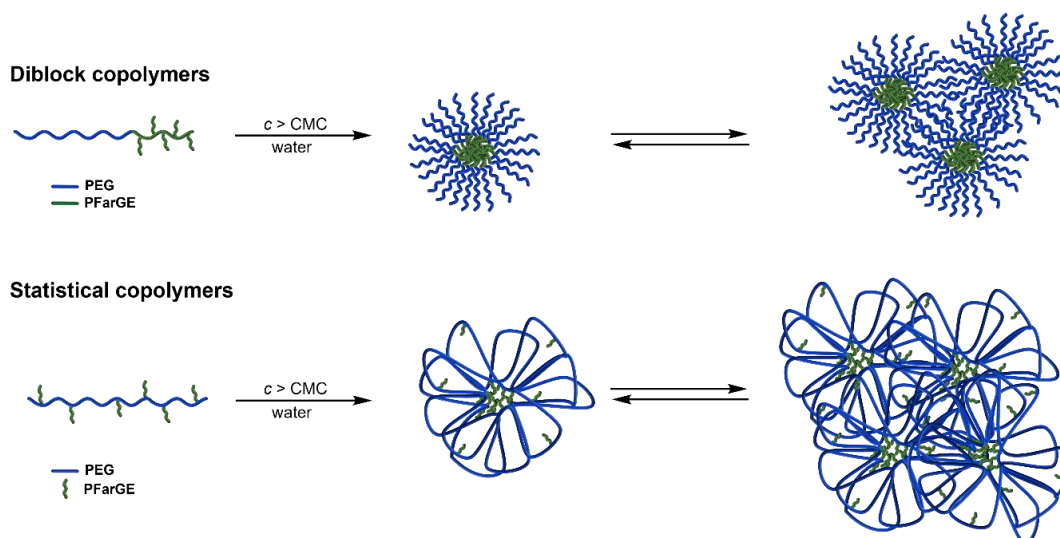


Figure 7: Schematic representation of proposed micelles and clusters of diblock and statistical copolymers in aqueous solution (Table 5 and Figure S 57).

Conclusion

Inspired by the increasing interest in bio-based materials, we present the synthesis and application of the terpenoid-derived epoxide building block FarGE for the synthesis of amphiphilic polyethers in a classical AROP. The novel monomer is synthesized by converting the terpenoid farnesol into its glycidyl ether derivative in high yields of up to 85%, with the option to be fully renewably sourced. A comprehensive investigation of its copolymerization with EO resulted in a series of well-defined statistical and diblock copolymers, demonstrating its universal applicability in oxyanionic polymerization. The copolymer amphiphilicity is conveniently tunable via FarGE comonomer feed ratio, which was varied in a range of 1.7 to 42.3 mol%. Remarkably, *in situ* ^1H NMR spectroscopy revealed an almost ideally random copolymerization behavior of EO and FarGE ($r_{\text{FarGE}} = 0.85$, $r_{\text{EO}} = 1.18$) despite the bulky, sterically demanding farnesyl side chain. The low T_g of $-70\text{ }^\circ\text{C}$ of the homopolymer is induced by the flexibility of the acyclic side chain. Despite a nearly random copolymer microstructure, farnesyl side-chain control of the T_g onset was unveiled at low FarGE content, simultaneously impeding PEG crystallization. The behavior of the amphiphilic copolymers in aqueous solution was investigated via static and dynamic light scattering, fluorescence spectroscopy and surface tensiometry, which all reveal low critical micelle concentrations ($\text{CMC} = 10 - 53\text{ mg/L}$) due to the high hydrophobicity of FarGE. Dynamic light scattering not only confirmed the self-assembly of $\text{mPEG}_{114}\text{-}b\text{-FarGE}_m$ diblock copolymers, but also that the statistical copolymers form larger spherical aggregates, which were visualized in TEM micrographs.

In summary, FarGE paves the way to a novel class of amphiphilic PEG derivatives of partially bio-based nature with a plethora of applications, ranging from co-surfactants in microemulsions^{43,44} to drug-delivery systems for hydrophobic drug encapsulation^{82,83} to the production of a variety of self-assembled nanostructures.⁸⁴

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Supporting Information

Experimental Sections

Reagents

All chemicals and solvents were purchased from commercial suppliers (Sigma-Aldrich, Fluka, Alfa Aesar, Acros, TCI) and used without prior purification, unless otherwise stated. Deuterated solvents were purchased from Deutero GmbH. Farnesol (3,7,11-Trimethyl-2,6,10-dodecatrien-1-ol) was obtained as an isomer mixture from Aldrich (95% purity) and ethylene oxide (EO) from Air Liquide. Farnesyl glycidyl ether (FarGE) was dissolved in benzene and azeotropically dried overnight under reduced pressure prior to polymerization. Tetrahydrofuran (THF) was dried over diphenylhexyllithium (adduct of sec-butyllithium and 1,1-diphenylethylene), degassed by three freeze-pump-thaw cycles and stored under vacuum until distilled into the polymerization flask. Anhydrous dimethyl sulfoxide (DMSO) stored over molecular sieves was used as purchased for the statistical copolymerizations. For *in situ* ^1H NMR kinetics, deuterated THF (THF- d_8) was stirred over calcium hydride (CaH_2) overnight and freshly distilled prior to use. Deuterated DMSO (DMSO- d_6) was utilized from an untapped bottle. Poly (ethylene glycol) monomethyl ether (mPEG₁₁₄) was purchased from Fluka and analyzed via ^1H NMR spectroscopy and size exclusion chromatography (SEC) to determine the molecular weight and dispersity $\bar{D}$ ($M_{n,\text{NMR}}$: 5050 $\text{g}\cdot\text{mol}^{-1}$, degree of polymerization (P_n) = 114, $M_{n,\text{SEC}}$: 5050 $\bar{D}$ = 1.05). Poly (ethylene glycol) (6K) (PEG (6K)) was obtained from TCI and used as a PEG reference for the thermal analysis (degree of polymerization ($P_{n,\text{SEC}}$) = 155, $M_{n,\text{SEC}}$: 6800 $\bar{D}$ = 1.09). Dialysis membranes (regenerated cellulose, $MWCO$ = 1,000 $\text{g}\cdot\text{mol}^{-1}$) were received from Orange Scientific. The uranyl acetate solution (2 wt%) for negative staining transmission electron microscopy (TEM) was obtained from Polysciences. Carbon-coated copper grids (CF400-Cu, 400 mesh) were purchased from Electron Microscopy Sciences.

Instrumentation

Nuclear Magnetic Resonance (NMR) Spectroscopy.

^1H , ^{13}C , ^1H - ^1H -COSY, ^1H - ^{13}C HSQC and ^1H - ^{13}C HMBC NMR spectra were recorded at 400 MHz (100 MHz for ^{13}C) using a Bruker Avance II HD 400 spectrometer (equipped with a 5 mm BBFO-Smartprobe (Z-gradient), an automated tuning and matching device (ATM) as well as a SampleXPress 60 auto sampler) at 23 °C.

In situ ^1H NMR copolymerization kinetics were investigated at 40 °C on a Bruker Avance III HD 400 spectrometer operated at 400 MHz (5 mm BBFO-SmartProbe (Z-gradient), an ATM and a SampleXPress 60 auto sampler). NMR spectra were recorded in 2-min-intervals. Diffusion-Ordered Spectroscopy (DOSY) measurements were also performed with the Bruker Avance III HD 400 spectrometer at 23 °C. Spectra were processed using MestReNova software 14.2.0.

All spectra were referenced internally to residual protium signals of the deuterated solvent (^1H NMR spectra) and the deuterated solvent itself (^{13}C NMR spectra). NMR spectroscopy data is reported as follows: chemical shift, multiplicity and integration. Spectra annotation uses lowercase letters for proton signals and capital letters for carbon signals. *E* (*trans*) and *Z* (*cis*) nomenclature is used for labelling of stereoisomers and an explanation is provided with the NMR assignment.

Size Exclusion Chromatography (SEC).

SEC measurements were performed using an Agilent 1100 series SEC system with a HEMA 300/100/40 Å column cascade, equipped with UV (254 nm) and RI detectors. The SEC columns were eluted with DMF, containing 1 g·mL⁻¹ lithium bromide, at 50 °C at a rate of 1 mL·min⁻¹. Toluene was used as a reference for the baseline. The SEC calibration was realized with poly(ethylene glycol) standards acquired from Polymer Standard Service (PSS). PSS WinGPC UniChrom software was employed for all data recording and processing.

Matrix-Assisted Laser Desorption Ionization Time-of-Flight (MALDI-ToF) Mass Spectrometry.

MALDI-ToF spectra were collected on a Bruker MALDI-ToF MS Autoflex Max in the linear modulus. *Trans*-2-[3-(4-*tert*-Butylphenyl)-2-methyl-2-propenyliden] malononitrile (DCTB) and KTFA were used as matrix and salt additive, respectively.

Homopolymer end groups were calculated by plotting the *m/z* ratio versus the number of FarGE ($M_{\text{FarGE}} = 278 \text{ gmol}^{-1}$) repeat units (*x*). The *m/z*-intercept M_{end} of the linear fit:

$$m/z = M_{\text{FarGE}} X + M_{\text{M}} + M_{\text{end}} = 278x + 39.10 + M_{\text{end}} \quad (1)$$

depicts the molar mass of the initiating species, while M_{M} equals 39.10 gmol⁻¹ when using potassium for ionization.

Fourier-Transformations-Infrared (FT-IR) Spectroscopy.

FT-IR spectra were recorded on a *Nicolet* iS10 FT-IR spectrometer (Thermo Scientific, Waltham, MA, USA) equipped with a diamond ATR unit in a frequency range of 650–3500 cm^{-1} .

Gas Chromatography-Mass Spectrometry (GC-MS).

Gas chromatography (GC) was performed on a Shimadzu GC-2010 (Shimadzu, Japan) using a quartz capillary column HI-5 MS column (VWR, Avantor, USA; length: 30 m, inner diameter: 0.25 mm, film: 0.25 μm , carrier gas: He, injection temperature: 250 $^{\circ}\text{C}$) combined with a GCMS-QP2010 (Shimadzu, Japan) with an ion source (EI) at 200 $^{\circ}\text{C}$. The starting temperature of 50 $^{\circ}\text{C}$ was maintained for 1 min, followed by a temperature gradient of 15 $^{\circ}\text{C}/\text{min}$ to 290 $^{\circ}\text{C}$. The final temperature was maintained for 8 min.

Differential Scanning Calorimetry (DSC).

Thermal properties of the polymers were studied by DSC on a DSC 250, TA Instrument, utilizing indium and *n*-octane as calibration standard. All samples were dried azeotropically, hermetically sealed in an aluminium pan and measured against an empty pan as reference. The temperature protocol consisted of two heating and two cooling cycles in a temperature range of -90 $^{\circ}\text{C}$ to 100 $^{\circ}\text{C}$ at a heating rate of 10 $^{\circ}\text{C}\cdot\text{min}^{-1}$ under a nitrogen atmosphere. The thermal analysis of the diblock copolymers included an additional temperature plateau after each cycle for 5 min. All melting temperature (T_{m}) and glass transition temperature (T_{g}) values were determined from the second heating cycle after the removal of the thermal history. Additional low temperature measurements in a range of -130 $^{\circ}\text{C}$ to 100 $^{\circ}\text{C}$ using a Mettler Toledo DSC 823 (indium, zinc and *n*-octane as calibration standard) enabled a more accurate extrapolation of the low temperature plateau and allowed for the determination of the homopolymer T_{g} .

Dynamic Light Scattering (DLS).

All measurements were carried out on an ALV-SP125-Goniometer, equipped with an ALV/High-QE APD-Avalanche photo diode with fiber optical detection in pseudo cross correlation mode, an ALV 5000/E/PCI correlator, and a JDSU (USA, CA) He/Ne laser (632.8 nm, 35 mW). Angular dependent measurements were performed in a range of $30^{\circ} < \theta < 150^{\circ}$ corresponding to wave vectors of $q = (4\pi n \sin(\theta/2)) / \lambda$ with the scattering angle θ , the wavelength λ , and the refractive index $n = 1.332$ for water.

Temperature control (± 0.1 °C) during measurements was assured by a Lauda ultrathermostat RKS C6 (Lauda Dr. Worbser GmbH, Lauda, Königshofen, Germany). After using the Siegert relation $F(q,t) = g^{(1)}(q,\tau) = \sqrt{g^{(2)}(\tau) - 1}$ on the measured intensity correlation functions $g^{(2)}(\tau)$, the normalized field autocorrelations $g^{(1)}(\tau)$ were fitted either by biexponential or stretched biexponential relaxation functions of the type

$$g^{(1)}(\tau) = A + B \cdot \exp\left(-\frac{\tau}{\tau_1}\right) + E \cdot \exp\left(-\left(\frac{\tau}{\tau_{2(\text{slow})}}\right)^\beta\right) \quad (2)$$

with the stretching exponent b , the fast relaxation time τ_1 , and the slow relaxation time τ_2 . For instance, a stretching exponent $b = 1$ reflects a monodisperse relaxation time. It is assumed that free and clustered micelles are present, whereby the slow mode and slow relaxation time $\tau_{2(\text{slow})}$ are ascribed to the latter. B and E refer to the amplitudes of the fast (micelles) and slow mode (clusters), allowing for the calculation of the relative compositions, $B_{m,\%}$ and $E_{c,\%}$, by applying $B_{m,\%} = B / (B + E)$ and $E_{c,\%} = E / (B + E)$. Considering a distribution of relaxation times $\tau_{2(\text{slow})}$, which are in general indicated by stretching exponents smaller than 1, the average slow relaxation time $\langle \tau_{2(\text{slow})} \rangle$ is calculated by $\langle \tau_{2(\text{slow})} \rangle = \frac{\tau_{2(\text{slow})}}{\beta} \cdot \Gamma\left(\frac{1}{\beta}\right)$ with the gamma function Γ . The fast and slow diffusion coefficients $D_{\text{app},i}$ were obtained using $D_{\text{app},i} = \frac{1}{q^2 \tau_i}$, and the hydrodynamic radii via Stokes-Einstein formula $R_{H,i} = \frac{k_B T}{6\pi\eta D_{\text{app},i}}$ with the Boltzmann constant k_B , the temperature T , and the viscosity η of the solvent. The index i differentiates between micelle ($i=m$) and clusters ($i=c$).

Static and Dynamic Light Scattering (SLS/DLS) for CMC determination.

For the determination of the critical micelle concentration (CMC) via light scattering, a 3D LS Spectrometer (LS Instruments, Switzerland) equipped with a diode-pumped laser with a wavelength of $\lambda = 561$ nm (Cobolt, Sweden) was employed. A combination of dynamic (DLS) and static light scattering (SLS) was performed at a scattering angle of $\theta = 90^\circ$ and a maximum incident laser intensity of $I_0 \approx 82$ mW. A temperature of $T = (23.0 \pm 0.1)$ °C was set using a decalin bath connected to a thermostat (Julabo, Germany). Polymer solutions with concentrations between $0.003 \text{ g}\cdot\text{L}^{-1}$ and $1 \text{ g}\cdot\text{L}^{-1}$ were prepared in 10 mL volumetric flasks, from which a sample volume of 1 mL was filled into borosilicate test tubes (Fisher Scientific, USA) that were cleaned in advance with

acetone and filtered double-distilled water. Measurement setup was 60 repetitions of 5 s each for all polymer concentrations. All measurements were run in 2D Pseudo Cross Correlation mode to avoid errors in the correlation function at short lag times, which result from after-pulsing of the detectors. Details of DLS theory are provided above. The static light scattering intensity was determined as the mean count rate (*meanCR* in kHz), calculated via the geometric mean of the count rates recorded at the two detectors (CR_A and CR_B), with $meanCR = \sqrt{CR_A * CR_B} * \sin(\theta) \equiv C$. All values were further corrected by considering the scattering intensity of a polymer-free water sample (see below).

Count rates were converted to absolute units (1/cm) via the scattering intensity of a known scatterer, toluene. To obtain the reference Rayleigh ratio for our setup, we followed the procedure outlined by Wu.¹ For toluene measured at $\theta = 90^\circ$, the Rayleigh ratio with unpolarized incident light and detection without a polarizer at $T = 25^\circ\text{C}$, $R_{u,25}$, is

$$R_{u,25} = 4.9 * 10^6 * \lambda^{-4.17} \left[\frac{1}{\text{cm}} \right] \quad (3)$$

Since we used vertically polarized incident light and detected the signal with a vertical polarizer, we convert R_u to R_{vv} via the depolarization factor ρ_u and the relation

$$R_{vv} = R_u(2 - \rho_u)/(1 + \rho_u) \left[\frac{1}{\text{cm}} \right]. \quad (4)$$

As found by Kaye and McDaniel for $T = 23^\circ\text{C}$, which is our measurement temperature, we used $\rho_u = 0.491$.² This is in good agreement with the value suggested by Wu at $T = 25^\circ\text{C}$, $\rho_u = 0.492$.¹ The temperature dependence of the Rayleigh ratio of toluene is similar to that of benzene and can be incorporated via

$$R_{vv,T} = R_{vv,25} (1 + 0.00368(T - 25^\circ\text{C})) \left[\frac{1}{\text{cm}} \right]. \quad (5)$$

From this, it is possible to determine the excess Rayleigh ratio via

$$R_{vv,T,sample} = \left(\frac{C_{sample}}{I_{0,sample}} - \frac{C_{water}}{I_{0,water}} \right) * \left(\frac{I_{0,toluene}}{C_{toluene}} \right) R_{vv,T,toluene}, \quad (6)$$

where $I_{0,x}$ is the incident laser beam intensity used for measurements of water, toluene, and the sample. At our setup conditions ($\lambda = 561 \text{ nm}$, $T = 23^\circ\text{C}$, $\theta = 90^\circ$),

$$R_{vv,T,toluene} = 1.694 * 10^{-5} \frac{1}{\text{cm}}.$$

Fluorescence Spectroscopy (FS) for CMC determination.

The fluorometric determination of the CMC by employing pyrene as a hydrophobic fluorescence dye has been widely established.³⁻⁶ Firstly, aqueous polymer stock solutions (1.00 g·L⁻¹, 0.10 g·L⁻¹, 0.01 g·L⁻¹) were prepared and equilibrated overnight (Milli-Q water). For sample preparation, an aliquot of an ethanolic pyrene solution (0.7 mM) was added to a volumetric flask. After solvent evaporation, a calculated amount of polymeric stock solution and distilled water (Milli-Q) were added, resulting in a final pyrene concentration (c_{pyrene}) of $7 \cdot 10^{-7}$ M. All samples were gently shaken at r.t. overnight to allow for micelle equilibration as well as solubilization of pyrene inside the micelles. For each polymer, a series of sample solutions were prepared in the polymer concentration range of 0.0005 to 0.60 g·L⁻¹. Pyrene emission spectra were collected on a Jasco FP-8200 spectrofluorometer through a quartz cell at $T = (23 \pm 1)$ °C in a wavelength range of 350-450 nm. Quartz cells were washed once with the corresponding polymer solution prior to the measurement. Selected instrument parameters were as follows: excitation wavelength $\lambda_{\text{ex}} = 334$ nm, slit_{em} = 2.5 nm, slit_{ex} = 2.5 nm, scan speed: 20 nm·min⁻¹, data interval = 0.5 nm, response = 0.5 sec. The intensity ratio I_1/I_3 , referring to the first ($\lambda_{\text{peak}} = 372\text{-}373$ nm) and third ($\lambda_{\text{peak}} = 383\text{-}384$ nm) vibronic bands in the pyrene fluorescence spectrum,^{6,7} is extremely sensitive to the polarity of the medium surrounding pyrene molecules. In an aqueous solutions of amphiphilic polymers, a ratio change of I_1/I_3 hence reflects the pyrene location in the polar aqueous solution or a non-polar micellar core.^{3,8} Plotting I_1/I_3 against polymer concentration is a convenient approach to estimate the CMC of the respective polymer.

Surface Tensiometry for CMC determination.

We used a Du Noüy ring STA-1 tensiometer (SINTERFACE, Germany) combined with a scale (CP64, Sartorius, Germany) to determine the CMC of mPEG₁₁₄-*b*-PFarGE₅ in aqueous solution at $T = (22 \pm 1)$ °C. Polymer was weighed into a 100 mL volumetric flask, which was subsequently filled with double-distilled water, setting a starting concentration of 0.15 g·L⁻¹. A volume of 5 mL was removed from the flask with a syringe and used to clean a Petri dish, after which another 15 mL of sample was deposited into the Petri dish, which was then placed inside the tensiometer. The ring was annealed in the flame of a gas burner before each measurement. Surface tension was recorded as a function of time by a connected computer. Note that the surface tension of conventional

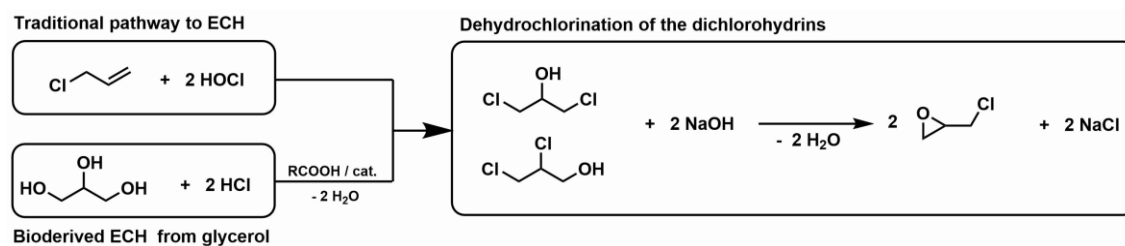
surfactants typically reaches a constant value rather quickly, whereas it takes significantly longer for amphiphilic polymers. Given the longer equilibration time and the fluctuations in surface tension, we paused for 45 minutes until only minor deviations in surface tension were observed. After each measurement, the missing volume in the volumetric flask was refilled with double-distilled water and the procedure was repeated with the diluted polymer solution down to a concentration of $0.0018 \text{ g}\cdot\text{L}^{-1}$.

Transmission Electron Microscopy (TEM).

Negative stain TEM was conducted on a Tecnai G2/ F12 Bio-Twin, equipped with a LaB6 cathode operating at 120 kV acceleration voltage. Images were acquired with a side entry MegasYS 1kx1k CCD camera. Negative staining TEM was undertaken as previously described in literature, using carbon grids and 2% uranyl acetate with a polymer solution concentration of 0.1 g/mL .⁹ Glow-discharge treatment of carbon grids was performed prior to use. For each sample, a $5 \text{ }\mu\text{L}$ volume polymer solution was adsorbed on the grid for 1 min, followed by blotting with filter paper. The grid was subsequently stained with a droplet of aqueous uranyl acetate solution (2 wt%) for 1 min before blotting with filter paper again.

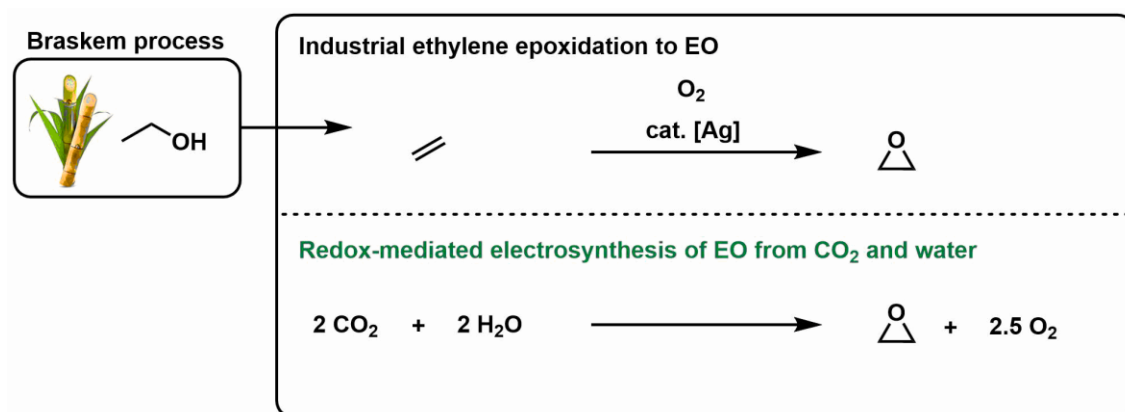
Alternative Production Pathways for Oxirane Commodity Chemicals

Industrial epichlorohydrin production



Scheme S 1: Industrial production pathways for epichlorohydrin (ECH).¹⁰⁻¹²

Ethylene oxide synthesis pathways



Scheme S 2: Industrial and potentially bio-renewables production pathway for the commodity chemical EO.¹³⁻¹⁵

Monomer Synthesis

Stereoisomeric farnesol mixture

Farnesol (3,7,11-Trimethyl-2,6,10-dodecatrien-1-ol) varies in its stereochemistry at the C-2 and C-6 position in the acyclic chain, resulting in four stereoisomeric farnesol derivatives (Figure S 1).¹⁶ As farnesol is only commercially available as an isomeric mixture with a purity of 95%, a detailed characterization is conducted in the following.

Bradesi et al. conducted an in-depth ¹³C NMR study of farnesol, facilitating the identification and assignment of the existing stereoisomers, specifically 2*E*,6*Z*-farnesol, 2*Z*,6*E*-farnesol and 2*E*,6*E*-farnesol. The composition of the stereoisomeric mixture is significantly reflected in the ¹³C signal intensities of the respective stereoisomers (Figure S 2).¹⁷ To resolve the stereoisomeric ratio at the C2 position, we analyzed the shift of the methylene protons of the C-1 (d) carbon via ¹H NMR analysis, revealing a *Z*:*E* ratio of 13:87 (2*Z*,6*E*-farnesol : [2*E*,6*E*-farnesol + 2*E*,6*Z*-farnesol]) (Figure S 3). The GC-MS analysis of the commercial farnesol is shown in Figure S 4 and confirms three major peaks. The peaks were identified using literature data to be 2*Z*,6*E*-farnesol and 2*E*,6*Z*-farnesol (two overlapping peaks, *t* = 11.280 min) and 2*E*,6*E*-farnesol (*t* = 11.447 min), resulting in an overall approximate stereoisomeric ratio of 13:24:64, respectively.^{16,18} Ratio calculations derive by combining the results from NMR and GC MS analysis. Note that we labelled the carbon shifts according to the respective farnesol stereoisomers they are assigned to. Using *E* (*trans*) and *Z* (*cis*) nomenclature for the C-2 and C-6 carbon in lower cases, the stereochemistry-induced carbon shifts of the same carbon are distinguished as *X_{EE}* (2*E*,6*E*-farnesol), *X_{EZ}* (2*E*,6*Z*-farnesol) and *X_{ZE}* (2*Z*,6*E*-farnesol) in all following analyses.

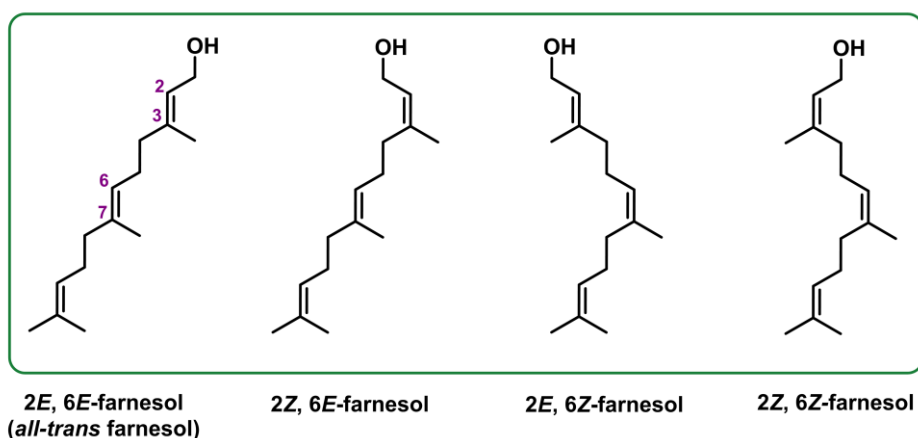


Figure S 1: Overview of stereoisomeric farnesol derivatives.

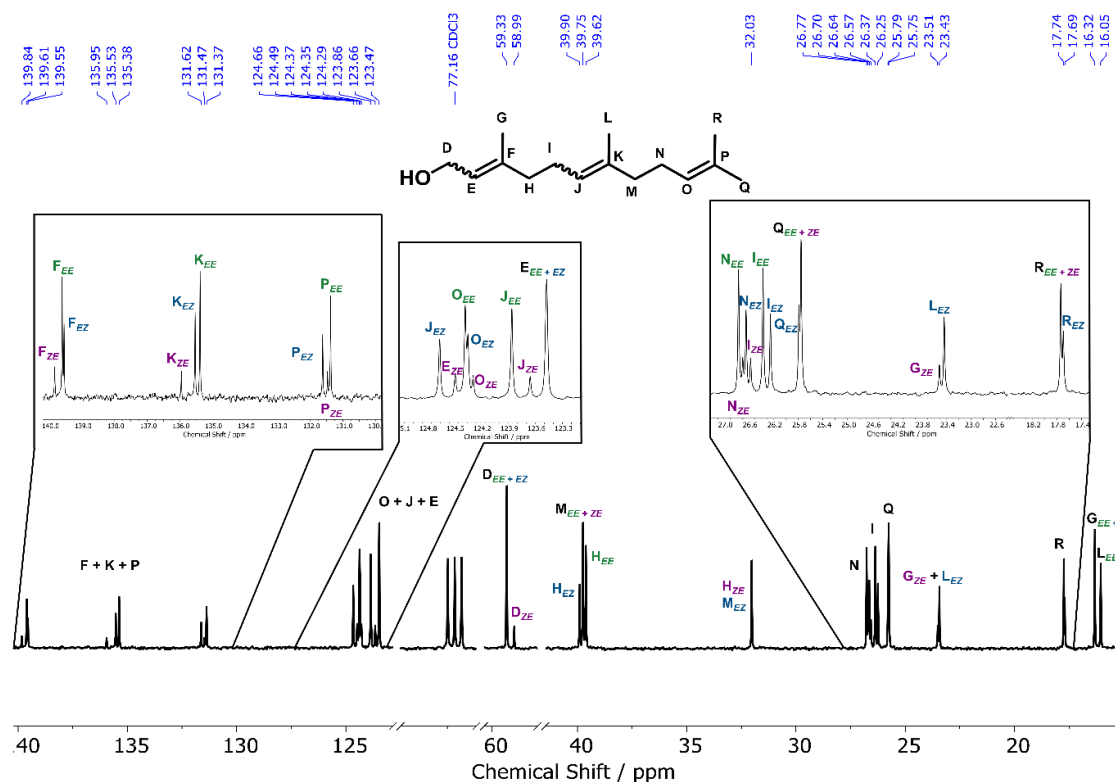


Figure S 2: ^{13}C NMR spectrum (100 MHz, CDCl_3) of the commercial farnesol mixture, including a detailed assignment of the stereoisomeric carbon atoms.¹⁷ To indicate the stereoisomeric nature of the assigned carbons, we referred to the isomers in lower case as *EE* (2*E*,6*E*-farnesol), *EZ* (2*E*,6*Z*-farnesol) and *ZE* (2*Z*,6*E*-farnesol). The composition of the stereoisomeric mixture is significantly reflected in the signal intensities of the respective stereoisomers.

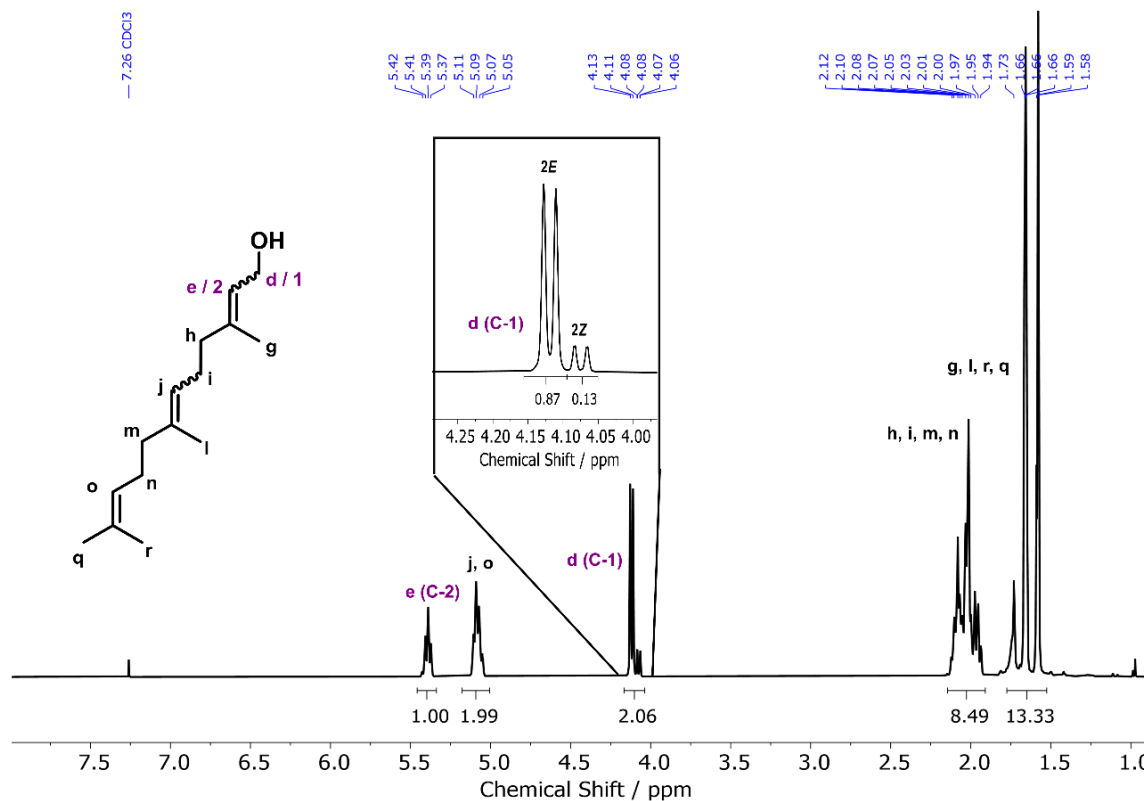


Figure S 3: ^1H NMR spectrum (400 MHz, CDCl_3) of stereoisomeric farnesol, indicating a variation of *E* and *Z* stereochemistry of the double bond in C-2 position. The resulting shift of the methylene protons of the C-1 carbon shows an *E:Z* ratio of 13:87 for the C-2 double bond.

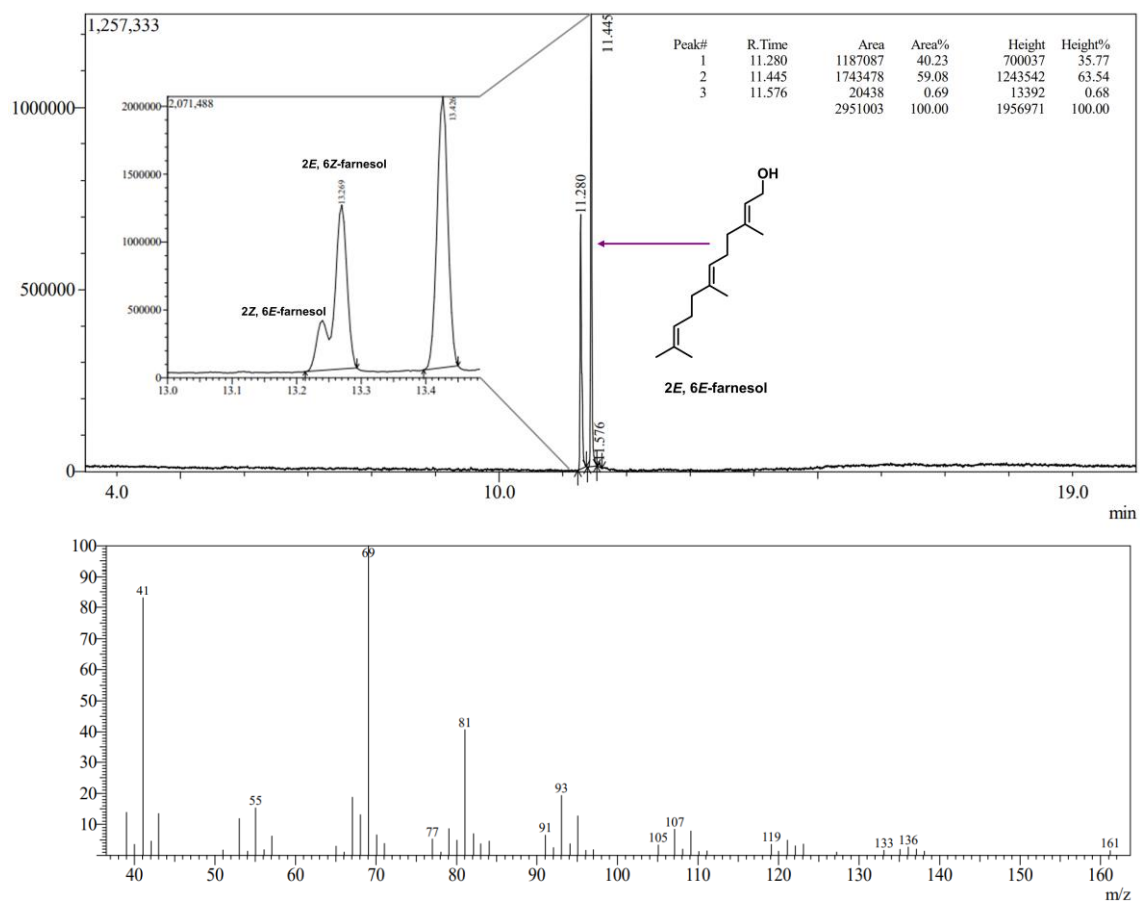


Figure S 4: GC-MS analysis of the commercial farnesol, confirming a mixture of stereoisomers, namely 2E,6Z-farnesol, 2Z,6E-farnesol and 2E,6E-farnesol, at an approximate ratio of 13:23:64 (36:64 of (2E,6Z + 2Z,6E) : 2E,6E according to GC MS), respectively (top). The MS spectrum illustrates the identical fragmentation pattern of all stereoisomeric farnesols (bottom).

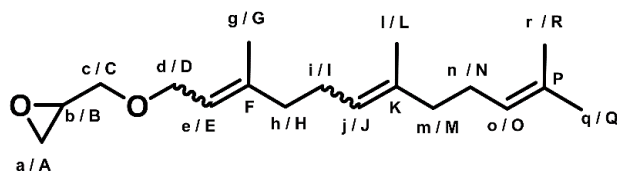
Phase transfer catalysis.

Farnesyl glycidyl ether (FarGE) was synthesized via aqueous phase transfer catalysis of epichlorohydrin (ECH) and farnesol according to a modified literature procedure by Mouzin et al.¹⁹

A mixture of a 50wt% aqueous sodium hydroxide solution ($V_{\text{solution}} = 68.5$ mL, NaOH: 34.25 g, 0.85 mol, 12.7 equiv.), ECH (56.1 mL, 66.15 g, 0.715 mol, 5.30 equiv.) and tetrabutylammonium hydrogen sulfate (TBAHS, 1.83 g, 0.005 mol, 0.04 equiv.) was added to a 250 mL three-neck round bottom flask, equipped with a mechanical stirrer and a dropping funnel. After the reaction mixture was cooled to 0 °C with an ice bath, farnesol (34.1 mL, 30.00 g, 0.135 mol, 1.00 equiv.) was added dropwise within 30 min under continuous cooling ($T < 20$ °C). Subsequently, the reaction mixture was vigorously stirred at room temperature (r.t.) until complete consumption of farnesol ($t = 24$ h) and the reaction was quenched by the addition of ice. After separating the organic layer, the aqueous phase was extracted with diethyl ether (DEE, three times: 30 mL) and the combined organic phases were washed with saturated sodium hydrogen carbonate (seven times: 30 mL) and water (three times: 30 mL) until a neutral pH value was obtained. The organic phase was dried over magnesium sulfate and DEE was removed using rotary evaporation. Crude FarGE was further purified by removal of an accrued side product, 3-Chloroallyl glycidyl ether (3-Chloro-AGE), via high vacuum distillation at 180 °C ($p = 5 \cdot 10^{-3}$ mbar, $T_{\text{b,3-Chloro-AGE}} = 30$ °C).²⁰ Utilizing Kugelrohr distillation in a final purification step, high-boiling FarGE ($p = 5 \cdot 10^{-3}$ mbar, $T_{\text{b,FarGE}} = 170$ °C) was isolated as a colorless liquid in high purity and yields of up to 85%. To prevent crosslinking and oxidation of the side chain double bonds, FarGE was stored at 20 °C under an argon atmosphere.

Methylation of protic impurities in the FarGE monomer.

Potential protic impurities in the FarGE monomer were masked using methyl iodide (MeI) according to a protocol by Greiner et al. (Scheme 1, bottom).²¹ A flame-dried Schlenk flask, charged with sodium hydride (NaH, 0.377 g, 16.0 mmol, 0.22 equiv.), was cooled to 0 °C and FarGE (15.0 g, 71.3 mmol, 1.00 equiv.) was added. After 2 h of stirring, hydrogen gas formation seized and MeI (1.01 g, 7.0 mmol, 0.10 equiv.) was added. The reaction was allowed to warm up to r.t. and stirred for 22 h. Subsequently, the suspension was diluted with hexane and filtered to remove sodium iodide formed during the methylation process. After a Kugelrohr distillation ($p = 5 \cdot 10^{-3}$ mbar, $T_{\text{b,FarGE}} = 170$ °C), FarGE was received in quantitative yields.



^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 5.36–5.29 (m, 1H, H_e), 5.11–5.03 (m, 2H, H_j , H_o),

4.09–3.97 (m, 2H, H_d), 3.71–3.60 (m, 1H, H_c), 3.39–3.32 (m, 1H, H_c), 3.17–3.08 (m, 1H, H_b), 2.79–2.70 (m, 1H, H_a), 2.62–2.51 (m, 1H, H_a), 2.18–1.88 (m, 8H, H_h , H_i , H_m , H_n), 1.73+1.85+1.57 (s, 12H, H_g , H_l , H_r , H_q , $J = 5.0, 4.2$ Hz).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.93 ($\text{C}_{\text{F}(\text{ZE})}$), 140.68 ($\text{C}_{\text{F}(\text{EE})}$), 140.64 ($\text{C}_{\text{F}(\text{EZ})}$), 135.61 ($\text{C}_{\text{K}(\text{ZE})}$), 135.46 ($\text{C}_{\text{K}(\text{EZ})}$), 135.31 ($\text{C}_{\text{K}(\text{EE})}$), 131.54 ($\text{C}_{\text{P}(\text{EZ})}$), 131.34 ($\text{C}_{\text{P}(\text{ZE})}$), 131.29 ($\text{C}_{\text{P}(\text{EE})}$), 124.67 ($\text{C}_{\text{J}(\text{EZ})}$), 124.37 + 124.34 ($\text{C}_{\text{O}(\text{EE}, \text{EZ}, \text{ZE})}$), 123.86 ($\text{C}_{\text{J}(\text{EE})}$), 123.66 ($\text{C}_{\text{J}(\text{ZE})}$), 121.53 ($\text{C}_{\text{E}(\text{ZE})}$), 120.55 ($\text{C}_{\text{E}(\text{EE}, \text{EZ})}$), 70.73 ($\text{C}_{\text{C}(\text{ZE})}$), 70.66 ($\text{C}_{\text{C}(\text{EE}, \text{EZ})}$), 67.79 ($\text{C}_{\text{D}(\text{EE}, \text{EZ})}$), 67.54 ($\text{C}_{\text{D}(\text{ZE})}$), 50.90 (C_B), 44.44 (C_A), 39.92 ($\text{C}_{\text{H}(\text{EZ})}$), 39.74 ($\text{C}_{\text{M}(\text{EE}, \text{ZE})}$), 39.63 ($\text{C}_{\text{H}(\text{EE})}$), 32.27 ($\text{C}_{\text{H}(\text{ZE})}$), 32.01 ($\text{C}_{\text{M}(\text{EZ})}$), 26.76 ($\text{C}_{\text{N}(\text{EE})}$), 26.71 ($\text{C}_{\text{N}(\text{ZE})}$), 26.63 ($\text{C}_{\text{N}(\text{EZ})}$), ($\text{C}_{\text{I}(\text{ZE})}$), 26.31 ($\text{C}_{\text{I}(\text{EE})}$), 26.18 ($\text{C}_{\text{I}(\text{EZ})}$), 25.76 ($\text{C}_{\text{Q}(\text{EZ})}$), 25.73 ($\text{C}_{\text{Q}(\text{EE}, \text{ZE})}$), 23.55 ($\text{C}_{\text{G}(\text{ZE})}$), 23.41 ($\text{C}_{\text{L}(\text{EZ})}$), 17.71 ($\text{C}_{\text{R}(\text{EE}, \text{ZE})}$), 17.67 ($\text{C}_{\text{R}(\text{EZ})}$), 16.52 ($\text{C}_{\text{G}(\text{EE}, \text{EZ})}$), 16.03 ($\text{C}_{\text{L}(\text{EE}, \text{ZE})}$).

Note that stereoisomeric carbon resonances of FarGE show no significant shifts after the etherification of farnesol (overlay for facile comparison, Figure S 7), resulting in a similar stereochemistry assignment.

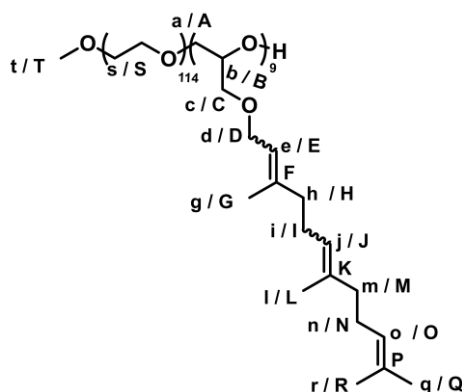
Polymerization Procedures

To maintain clarity, we refrain from specifying the isomeric farnesyl side chain for each carbon signal for all polymer characterizations. In general, the comparison of the monomer and polymers' ^{13}C NMR spectra (Figures S 10, S 15, S 24 and S 33) assisted in the assignment of the carbon signals, combined with detailed 2D NMR analyses (Figures S 16 – S 18, S 25 - S 27 and S 34 - S 36), and shows that the stereoisomeric carbon resonances of the farnesyl side chain are still visible in high resolution after polymerization. Table S 1 provides an overview of all polymer synthesis data.

Synthesis procedure for diblock copolymerization of mPEG₁₁₄ and FarGE

A series of mPEG₁₁₄-*b*-FarGE_m diblock copolymers were prepared from mPEG₁₁₄ as macroinitiator varying the length of the hydrophobic FarGE block ($n = 2\text{-}12$) in accordance with a modified, literature-known protocol.²² FarGE was pretreated with methyl iodide (MeI) for several of the synthesized diblock copolymers as noted in Table 1.²¹

In the following, the general synthesis is exemplified for mPEG₁₁₄-*b*-FarGE₉ (Table 1 and 2, entry 5). A dry 50 ml Schlenk flask was charged with mPEG₁₁₄ (0.500 g, 0.10 mmol, 1.0 equiv.), potassium *tert*-butoxide (KO^tBu, 0.009 g, 0.08 mmol, 0.8 equiv.) and 18-crown-6 (0.042 g, 0.16 mmol, 2.0 equiv.) under positive nitrogen flow. The mixture was suspended in 8 mL benzene and stirred for 1 h at 80 °C under reduced pressure. Evacuating the flask overnight at 80 °C afforded the dry potassium alkoxide initiator. Accordingly, the dried FarGE (0.27 mL, 0.250 g, 0.90 mmol, 9.0 equiv.) was added via syringe and the reaction mixture was stirred for 24 - 72 h at 80 °C. After cooling the polymerization mixture to r.t., it was terminated by adding 1 mL of methanol (MeOH) and dissolved in 2 mL dichloromethane (DCM). Three-fold precipitation in cold diethyl ether (-20 °C) yields the block copolymers in quantitative amounts (> 70%). Dialysis (MWCO = 1000 g·mol⁻¹) in Milli-Q® water allowed for the full removal of traces of 18-crown-6 and potassium salts.



^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 5.39 – 5.22 (m, H_e), 5.20 – 4.98 (m, H_j , H_o), 4.04 – 3.86 (m, H_d), 3.83 – 3.38 (m, H_a , H_b , H_c , H_s), 3.36 (s, H_t), 2.13 – 1.84 (m, H_h , H_i , H_m , H_n), 1.75 – 1.41 (m, H_g , H_l , H_r , H_q).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.01, 139.83, 139.71 (C_F), 135.51, 135.40, 135.25 (C_K),

131.54, 131.31 (C_P), 124.74, 124.40, 123.95, 123.73 (C_O , C_J), 121.24, 121.14, 121.07, 120.75 (C_E), 78.87, 78.68, 78.37 (C_B), 71.98, 71.20, 71.07, 70.82, 70.61, 70.14, 69.87, 69.70 (C_A , C_C , C_S), 67.93, 67.62 (C_D), 59.09 (C_T), 40.01, 39.76, 39.73, 32.34, 32.01 (C_H , C_M), 26.78, 26.64, 26.53, 26.46, 26.43, 26.27, 26.21 (C_N , C_I), 25.80, 25.76 (C_Q), 23.62, 23.59, 23.45 (C_G , C_L), 17.75, 17.71 (C_R), 16.59, 16.51 (C_G), 16.06 (C_L).

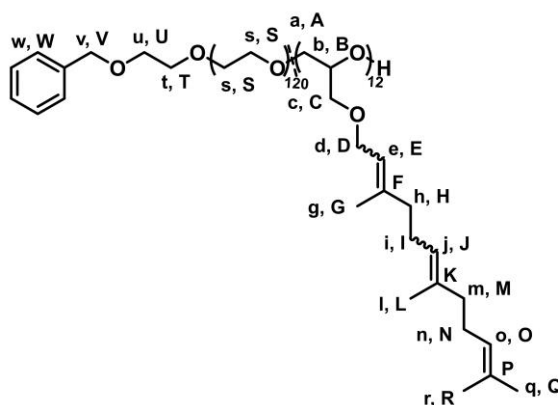
SEC analysis (RI detector, eluent: DMF, standard: PEG): $M_n = 7100 \text{ g}\cdot\text{mol}^{-1}$; $D = 1.05$

$T_g = -71\text{ }^\circ\text{C}$ $T_m = 56\text{ }^\circ\text{C}$

Synthesis procedure for statistical copolymerization of FarGE and EO

The statistical copolymerization of FarGE and EO is described exemplarily for P(EG_{120-co}-FarGE₁₂) according to a literature-known procedure (Table 1 and 2, entry 10).²³ Cesium hydroxide monohydrate (41.7 mg, 0.25 mmol, 0.9 equiv.) and 2-(benzyloxy)ethanol (42.0 mg, 0.28 mmol, 1.0 equiv., BzEtOH) were suspended in benzene (10 mL) in a dry Schlenk flask under argon atmosphere. The cesium alkoxide initiator was generated by stirring the initiator mixture at 60 °C in vacuo for 1 h, followed by the azeotropic removal of benzene and traces of water at 60 °C under reduced pressure overnight. The next day, the initiator was dissolved in DMSO (0.80 mL) and tetrahydrofuran (THF, 4.2 mL) was added via cryo-transfer, resulting in a solvent mixture of THF/DMSO ($V_{\text{THF}}/V_{\text{DMSO}}=5/1$). After stirring for 20 min at r.t., the

reaction mixture was cooled to $-82\text{ }^{\circ}\text{C}$ with an ethanol/liquid nitrogen bath and dried FarGE (0.94 mL, 0.87 g, 3.15 mmol, 11.4 equiv.) was added via syringe. The targeted volume of EO (1.30 mL, 1.25 g, 28.3 mmol, 102.6 equiv.) was distilled into a graduated ampule under vacuum and subsequently cryo-transferred into the cooled polymerization flask. The polymerization was performed at $40\text{ }^{\circ}\text{C}$ for 24 h up to completion and quenched with an excess of MeOH. THF and MeOH were removed under reduced pressure and dialysis ($\text{MWCO} = 1000\text{ g}\cdot\text{mol}^{-1}$) against a Milli-Q® water/MeOH mixture ($V_{\text{MeOH}}/V_{\text{water}}=5/1$) allowed for the removal of salt impurities and DMSO traces. The lyophilized copolymer was received as a brown, viscous liquid in yields of 77%.



^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 7.33 – 7.28 (m, H_w), 5.33 – 5.24 (m, H_e), 5.13 – 5.00 (m, H_j , H_o), 4.53 (s, H_v), 4.01 – 3.90 (m, H_d), 3.80 – 3.31 (m, H_a , H_b , H_c , H_s , H_t , H_u), 2.13 – 1.88 (m, H_h , H_i , H_m , H_n), 1.75 – 1.50 (m, H_g , H_l , H_r , H_q).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.23, 140.08, 139.99, 139.94, 139.91, 138.30 (C_f), 135.57, 135.43, 135.29 (C_k), 131.57, 131.38, 131.32 (C_p), 128.40, 128.37, 127.79, 127.73, 127.63, (C_w), 124.71, 124.38, 123.91, 123.72 (C_o , C_j), 121.96, 121.10, 120.99, 120.93 (C_e), 78.69, 78.48 (C_b), 73.28, 72.69 (C_v), 71.48, 71.01, 70.84, 70.79, 70.60, 70.31, 70.08, 69.95, 69.73, 69.66, 69.46, 67.91, 67.63, 61.71 (C_a , C_c , C_s , C_t , C_u), 67.91, 67.63, (C_d), 39.95, 39.75, 39.67, 32.30, 32.01 (C_h , C_m), 26.76, 26.73, 26.69, 26.63, 26.41, 26.22 (C_n , C_l), 25.80, 25.77 (C_q), 23.61, 23.45 (C_g , C_l), 17.76, 17.72 (C_r), 16.58, 16.54 (C_g), 16.07 (C_l).

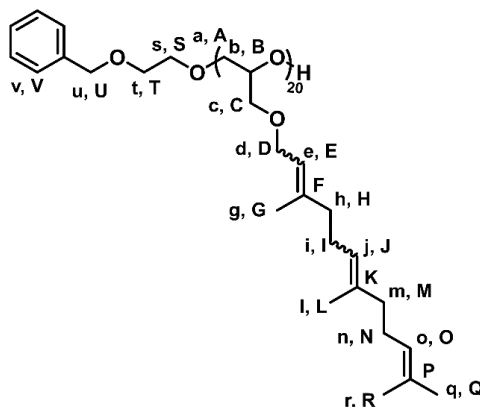
SEC analysis (RI detector, eluent: DMF, standard: PEG): $M_n = 6500\text{ g}\cdot\text{mol}^{-1}$; $D = 1.06$

$T_g = -69\text{ }^{\circ}\text{C}$ $T_m = 12\text{ }^{\circ}\text{C}$

Synthesis procedure for PFarGE homopolymers

The homopolymerization procedure was performed starting from BzEtOH and is otherwise in accordance with the block copolymer synthesis. The homopolymer was purified via precipitation in cold methanol (-20 °C) and was yielded quantitatively after drying under reduced pressure overnight.

PFarGE₂₀ served for an exemplary homopolymer characterization in the following (Table 1 and 2, entry 13).



¹H NMR (400 MHz, chloroform-*d*₁): δ (ppm) = 7.38 – 7.27 (m, H_v), 5.45 – 5.22 (m, H_e), 5.21 – 5.03 (m, H_j, H_o), 4.57 (s, H_u), 4.09 – 3.86 (m, H_d), 3.86 – 3.32 (m, H_a, H_b, H_c, H_s, H_t), 2.18 – 1.82 (m, H_h, H_i, H_m, H_n), 1.82 – 1.47 (m, H_g, H_l, H_r, H_q).

¹³C NMR (100 MHz, chloroform-*d*₁): δ (ppm) = 140.06, 139.95, 139.88, 139.76, 139.65 (C_F), 135.58, 135.47, 135.39, 135.34, 135.30 (C_K), 131.57, 131.38 (C_P), 128.45, 127.78, 127.66 (C_V), 124.84, 124.82, 124.48, 124.45, 124.05, 124.00 (C_o, C_j), 122.38, 121.38, 121.24, 121.14, 121.07, 121.01, 120.92, 120.81 (C_E), 79.07, 78.96, 78.79 (C_B), 73.31 (C_U), 71.38, 71.29, 71.20, 71.01, 70.21, 69.92, 69.79, 69.55 (C_A, C_C, C_S, C_T), 68.03, 67.69 (C_D), 40.09, 40.03, 39.84, 39.80, 39.76, 32.42, 32.39, 32.09 (C_H, C_M), 26.86, 26.62, 26.58, 26.56, 26.35, 26.31, 26.29 (C_N, C_I), 25.86, 25.82 (C_Q), 23.68, 23.52 (C_G, C_L), 17.81, 17.77 (C_R), 16.66, 16.57 (C_G), 16.12 (C_L).

SEC analysis (RI detector, eluent: DMF, standard: PEG): *M*_n = 2800 g·mol⁻¹; *Đ* = 1.06

*T*_g = -74 °C

Table S 1: Overview of polymer synthesis data for the series of mPEG₁₁₄-*b*-PFarGE_m block copolymers, P(EG_n-*co*-FarGE_m) statistical copolymers as well as PFarGE_m and PEG₁₅₅ homopolymers. All polymerizations were run to full conversion.

Entry	Sample	<i>t</i> / h	Yields / %
1	mPEG ₁₁₄ ^c	-	-
2 ^a	mPEG ₁₁₄ - <i>b</i> -PFarGE ₂	101	86
3 ^a	mPEG ₁₁₄ - <i>b</i> -PFarGE ₅	96	84
4	mPEG ₁₁₄ - <i>b</i> -PFarGE ₆	56	74
5 ^a	mPEG ₁₁₄ - <i>b</i> -PFarGE ₇	28	77
6	mPEG ₁₁₄ - <i>b</i> -PFarGE ₉	56	80
7 ^a	mPEG ₁₁₄ - <i>b</i> -PFarGE ₁₂	23	70
8	PEG (6K) ^c	-	-
9	P(EG ₁₁₈ - <i>co</i> -FarGE ₇)	67	80
10	P(EG ₁₀₉ - <i>co</i> -FarGE ₉)	24	73
11	P(EG ₁₂₀ - <i>co</i> -FarGE ₁₂)	24	77
12	P(EG ₉₃ - <i>co</i> -FarGE ₂₆)	23	70
13 ^a	P(EG ₄₄ - <i>co</i> -FarGE ₃₃)	70	53 ^b
14 ^a	PFarGE ₂₀	90	74
15 ^a	PFarGE ₃₀	29	80
16 ^a	PFarGE ₃₅	54	76

^aMonomer batch without treatment with MeI was applied. ^bSome polymer was lost due to spillage. ^cCommercial product.

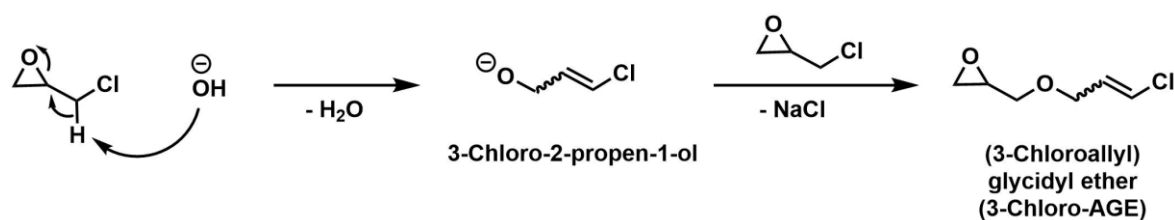
***In situ* ^1H NMR kinetic study of a statistical copolymerization of FarGE and EO**

A statistical copolymerization of FarGE and EO was conducted in a sealable Norell S-500-VT-7 NMR tube according to a procedure by Herzberger et al.²⁴ Thus, 35 mg partially deprotonated 2-(benzyloxy)ethanol (degree of deprotonation: 95%) was generated and dried according to the statistical copolymerization protocol stated above, followed by the dissolution of the initiator salt in 0.63 mL of anhydrous $\text{DMSO-}d_6$ under stirring (initiator salt stock solution). The oven-dried NMR tube, equipped with a Teflon stopcock, was evacuated via Schlenk-line and cooled with an acetone/nitrogen bath. Subsequently, 21 equiv. of EO (~ 0.025 mL) were transferred into the cooled NMR tube under static vacuum. Maintaining cooling of the NMR tube, 0.063 mL of the initiator stock solution (3.5 mg, 1 equiv.), 17 equiv. of FarGE (0.12 mL) and 0.31 mL of anhydrous $\text{THF-}d_8$ were syringed into the tube under argon atmosphere. After a final evacuation cycle of the frozen tube, it was sealed and warmed up to r.t.. To homogenize the solution, it was shaken vigorously before transferring in the preheated NMR spectrometer (40 °C). The first spectrum was recorded when the temperature in the probe head was stable (~ 10 min, $\Delta T = 0.1$ K). The sample rotation was turned off and ^1H NMR spectra with 1 scan per spectrum were collected every 2 min over a period of 51.5 h. Monitoring the decrease of the highlighted proton integrals of the epoxide ring (FarGE: green, 1H, 3.05 ppm; EO: blue, 4H, 2.59 ppm; Figure 2) displays the monomer consumption with preceding copolymerization (time-conversion plot, Figure S 41) as well as the monomer concentrations in each spectrum. The evaluation of the reactivity ratios of the comonomer pair was performed by employing the NIREVAL software from Johann et al.²⁵ The Jaacks equation was applied for a FarGE conversion of 90% to ensure a significant signal-to-noise ratio.

After the kinetics study, the copolymerization sample was terminated with acidic MeOH and the resulting $\text{P(EO}_{21}\text{-co-FarGE}_{17})$ copolymer was characterized via SEC to confirm the copolymerization reproducibility on a small scale (M_n : 3100 $\text{g}\cdot\text{mol}^{-1}$, $\bar{D}$: 1.09, Figure S 42).

Note: EO is a flammable, highly toxic gas, which requires careful handling. Although very small volumes of EO are added to the NMR tube, the copolymerization is conducted in a reproducible manner. Yet, as it is challenging to measure such small volumes as needed for the kinetic copolymerization, the comonomer ratios and molecular weights can vary to a small extent.

Characterization Data of Farnesyl glycidyl ether, Farnesol and Reaction Side Products



Scheme S 3: Elimination reaction of excess ECH under basic conditions during phase transfer catalysis. After the formation of 3-chloro-2-propen-1-ol, this side reactions results in the formation of the undesired 3-Chloro-AGE monomer structure.²⁰

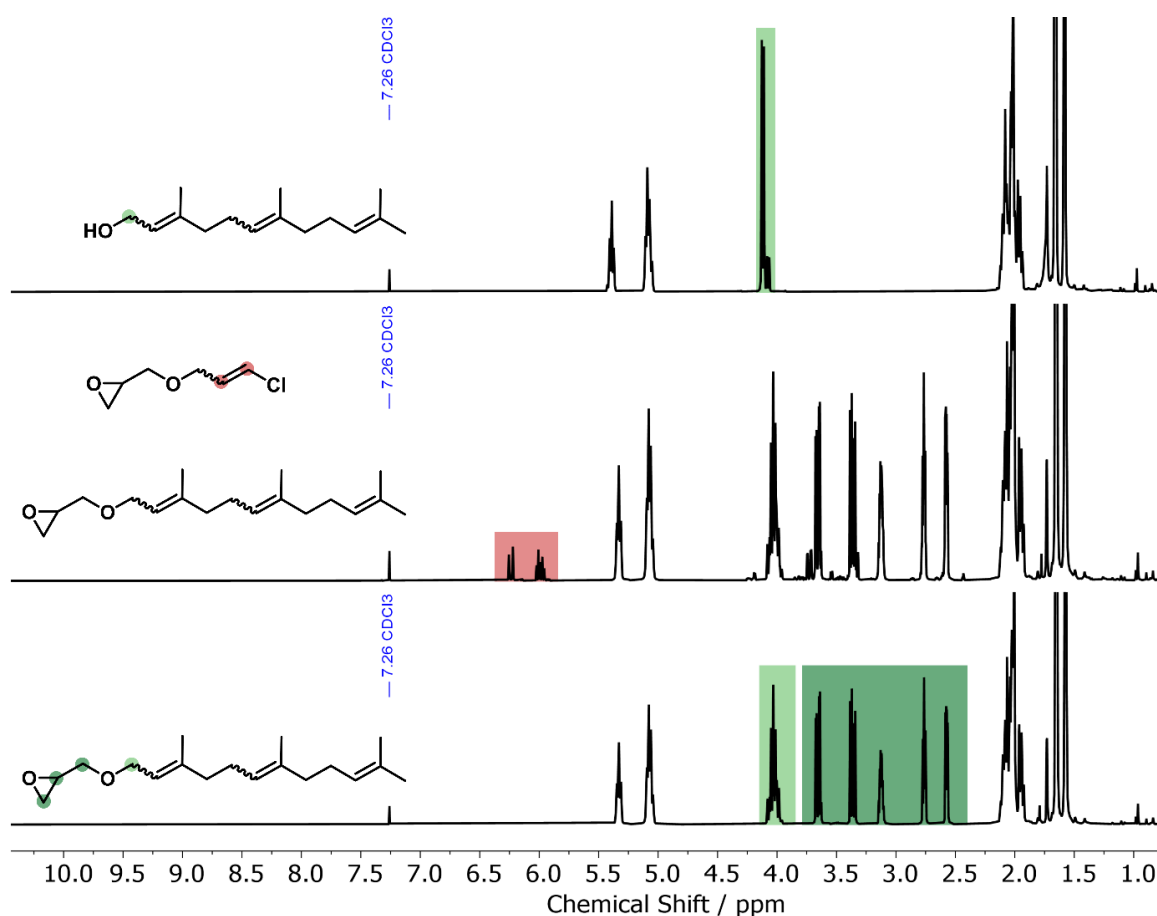


Figure S 5: Overlay of ¹H NMR spectra (400 MHz, CDCl₃) of Farnesol, crude FarGE before distillation and purified FarGE (top to bottom).

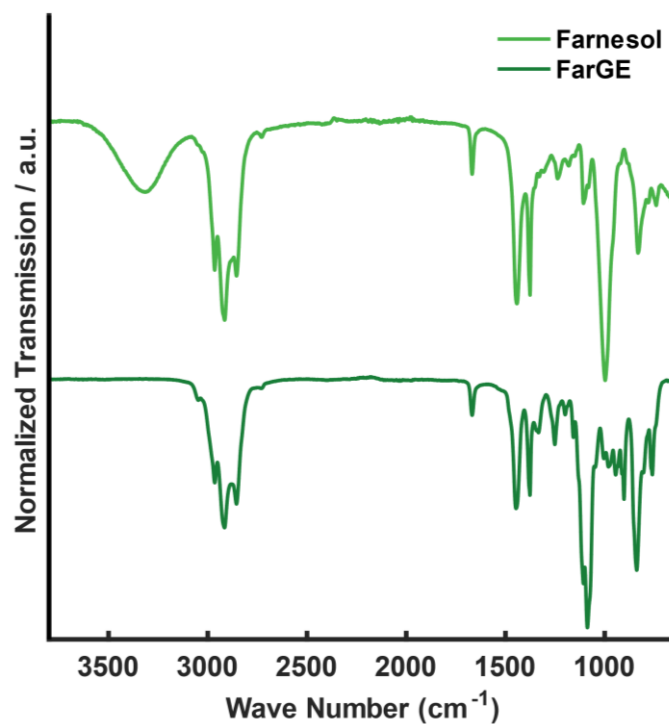


Figure S 6: Normalized IR spectra of farnesol and FarGE, displaying the disappearance of OH band (3311cm⁻¹) of farnesol after the phase transfer catalysis.

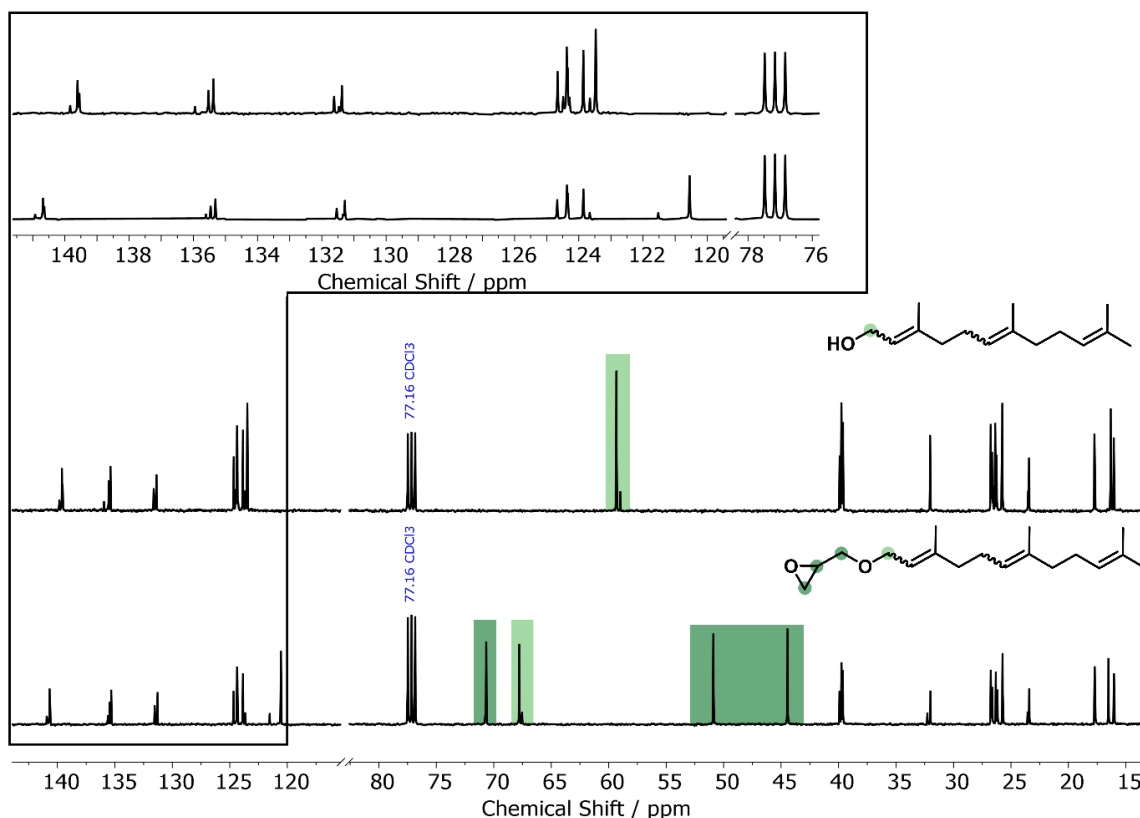
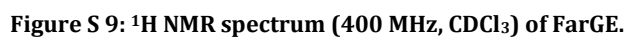
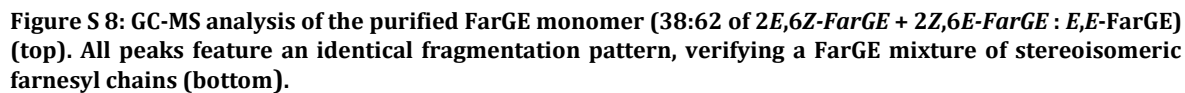


Figure S 7: Stacked ¹³C NMR spectra sections (100 MHz, CDCl₃) of Farnesol and FarGE, validating the successful synthesis by the appearance of terminal epoxide signals (dark green). The multiplett carbon resonances for the farnesyl chain (exemplary zoom-in area) agree with the farnesol spectrum and therefore are ascribed to the three identified stereoisomers of the acyclic chain (Figures S2 and S 4).



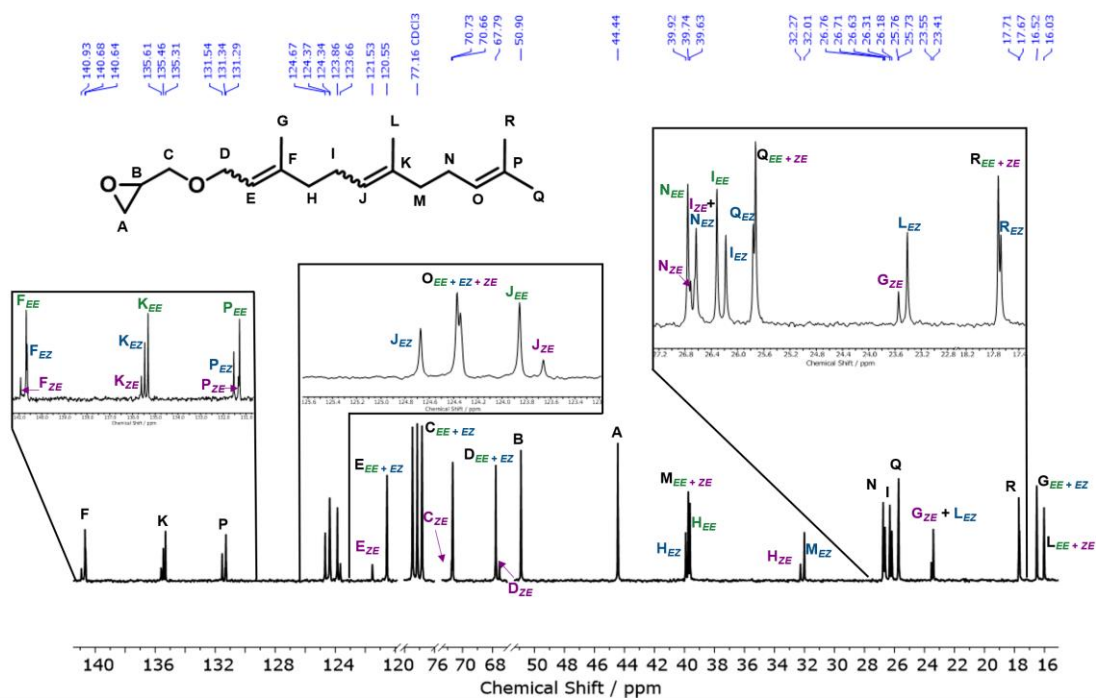


Figure S 10: ^{13}C NMR spectrum (100 MHz, CDCl_3) of FarGE. The multiplet carbon resonances result from the presence of different stereoisomers of the acyclic side chain while the *all-trans*-FarGE represents the major component (see Figure S 1 + Figure S 4).¹⁷

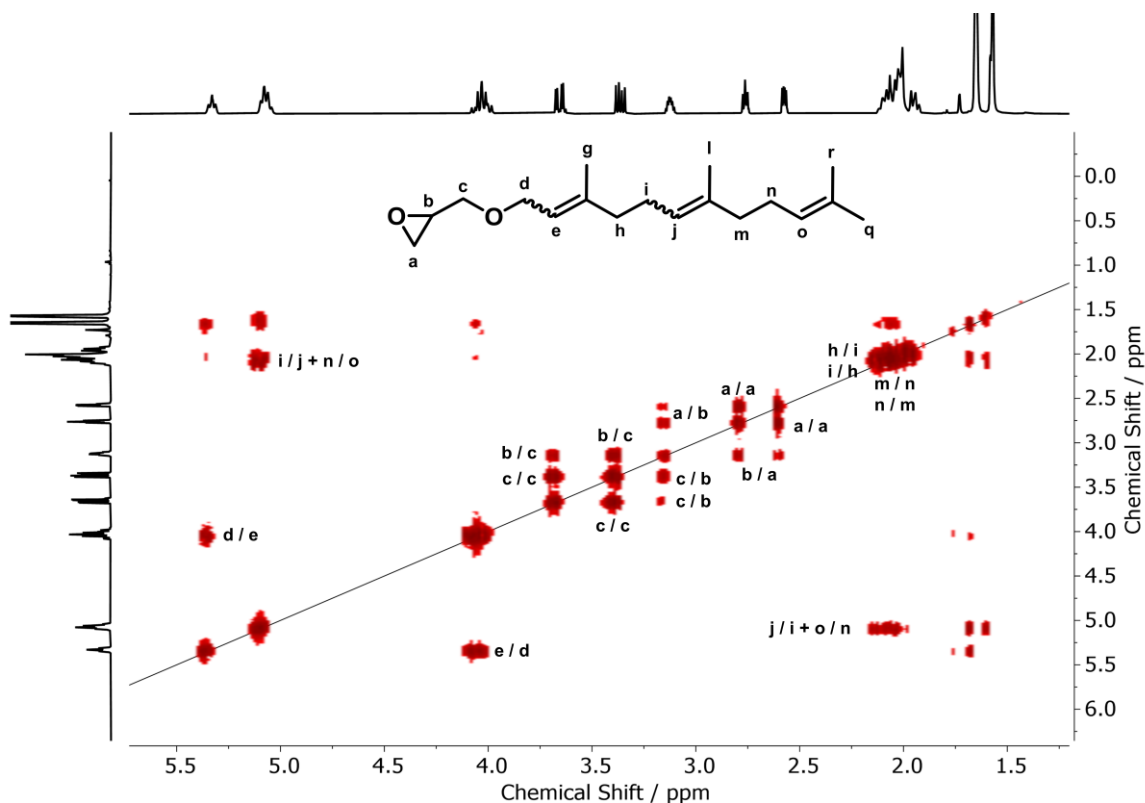
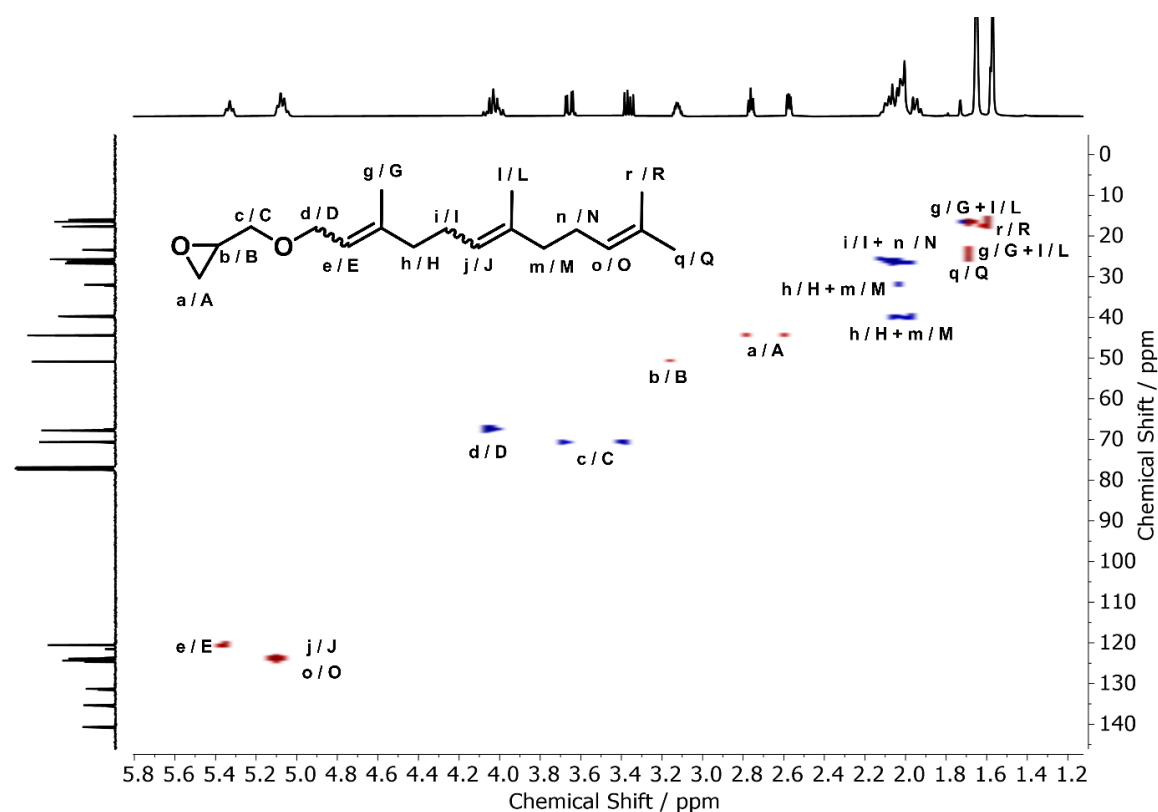
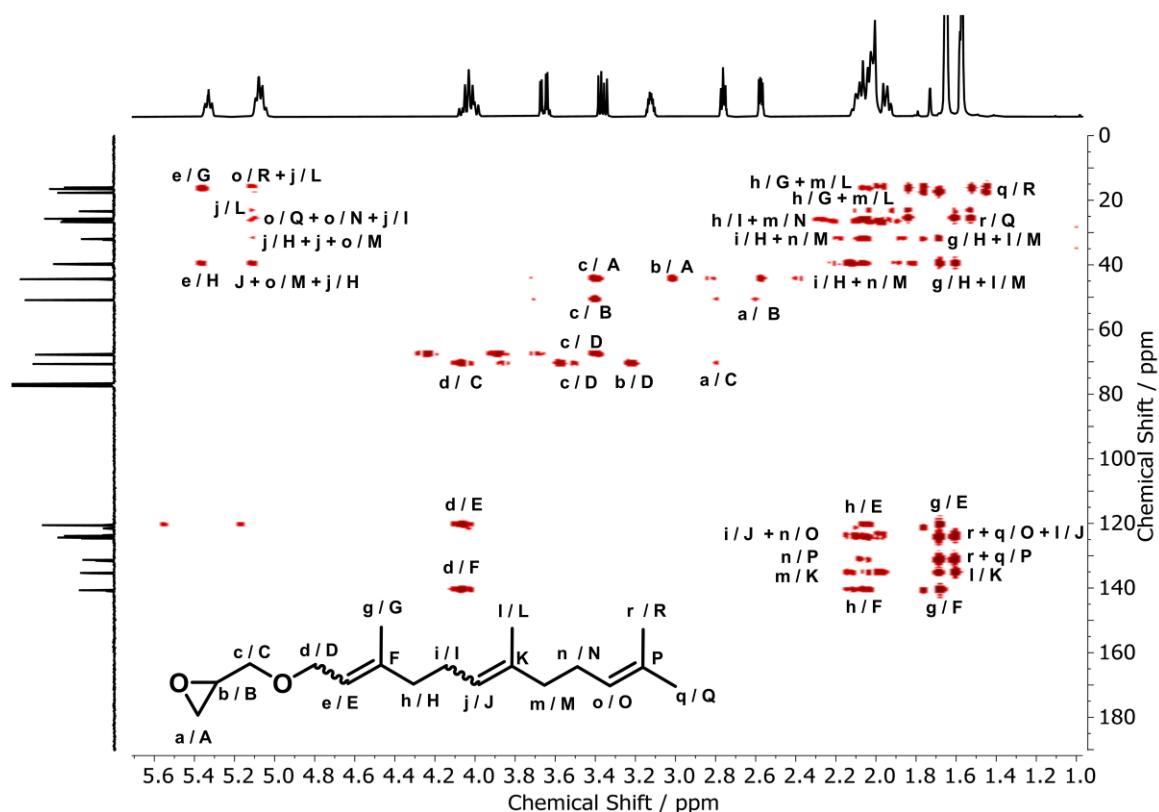
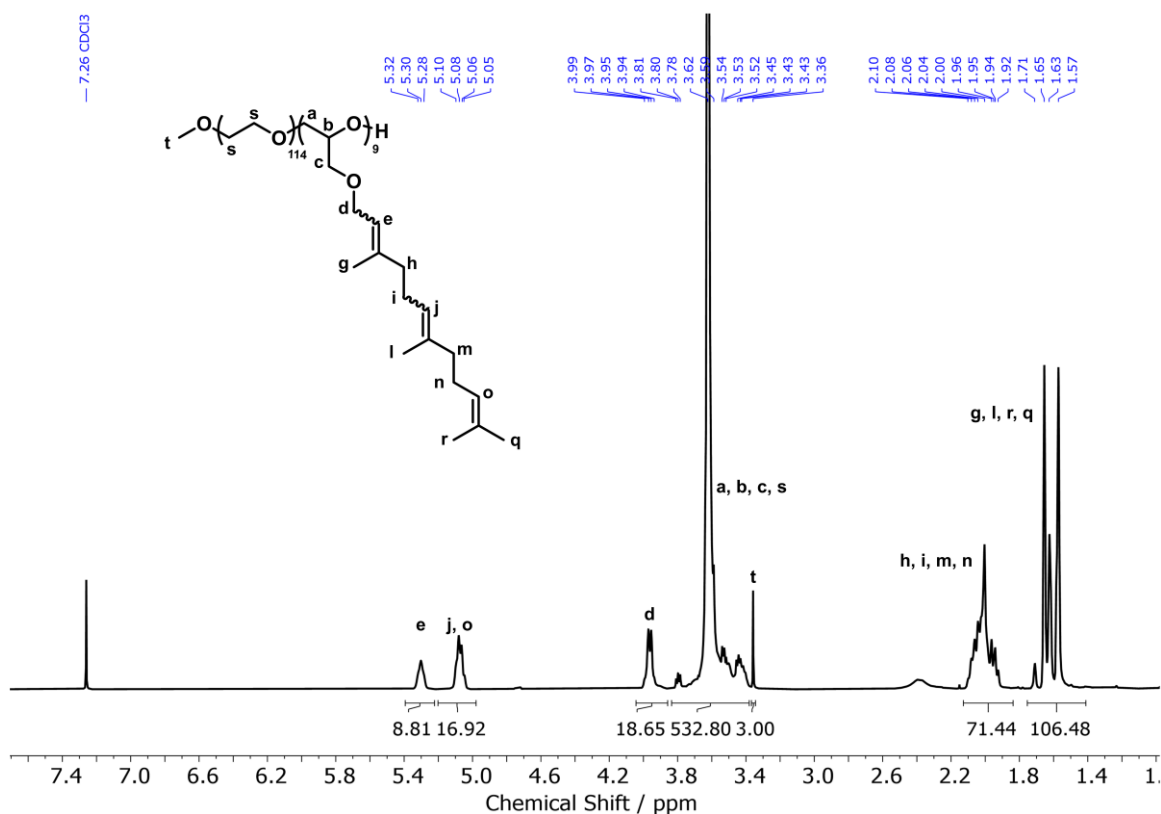
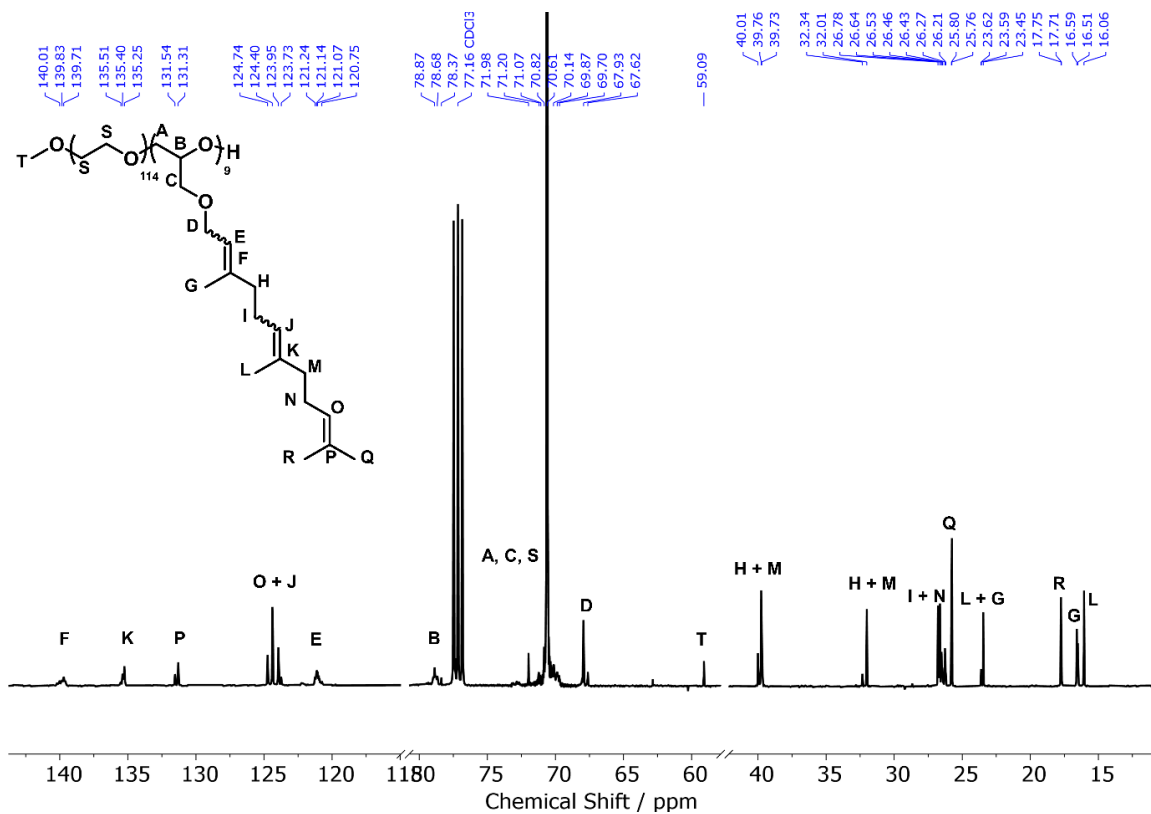


Figure S 11: ^1H - ^1H COSY NMR spectrum (400 MHz, CDCl_3) of FarGE.

Figure S 12: ^1H - ^{13}C HSQC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of FarGE.Figure S 13: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of FarGE.

Characterization of Diblock Copolymers of FarGE with mPEG₁₁₄Figure S 14: ¹H NMR spectrum (400 MHz, CDCl₃) of mPEG₁₁₄-b-PFarGE₉.Figure S 15: ¹³C NMR spectrum (100 MHz, CDCl₃) of mPEG₁₁₄-b-PFarGE₉.

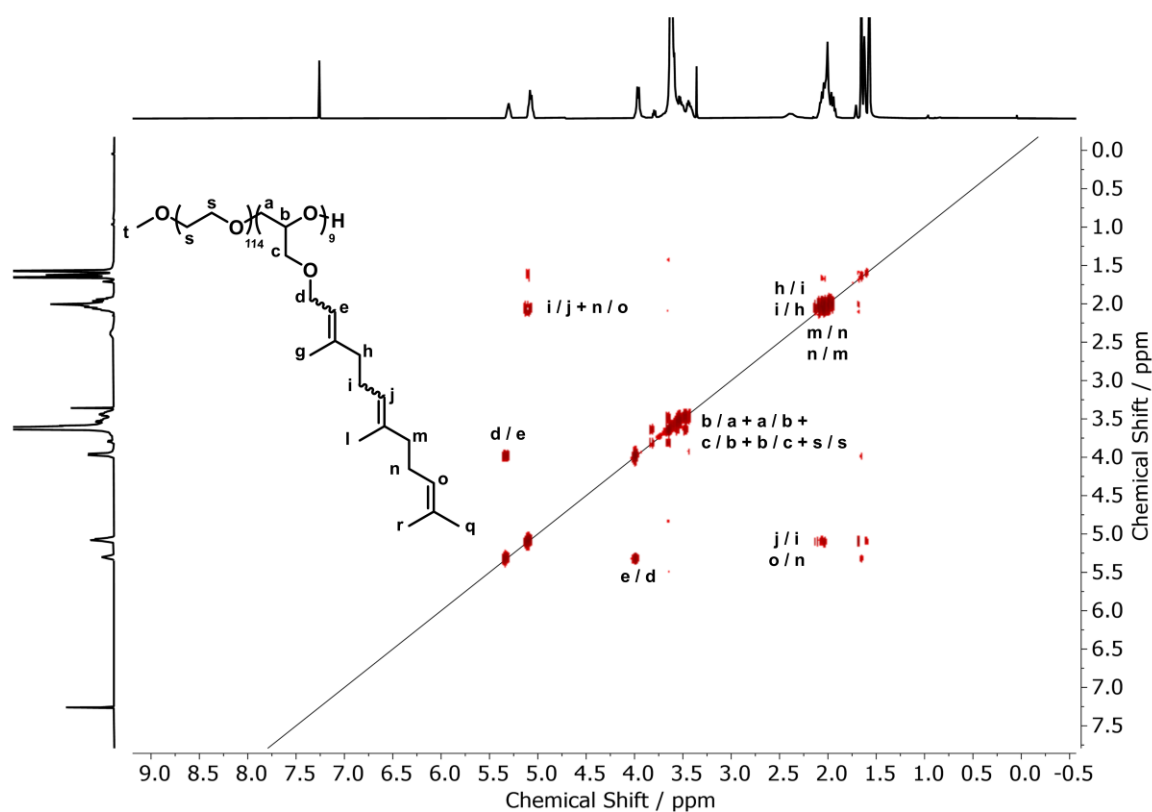


Figure S 16: ^1H - ^1H COSY NMR spectrum (400 MHz, CDCl_3) of $\text{mPEG}_{114}\text{-b-PFarGE}_9$.

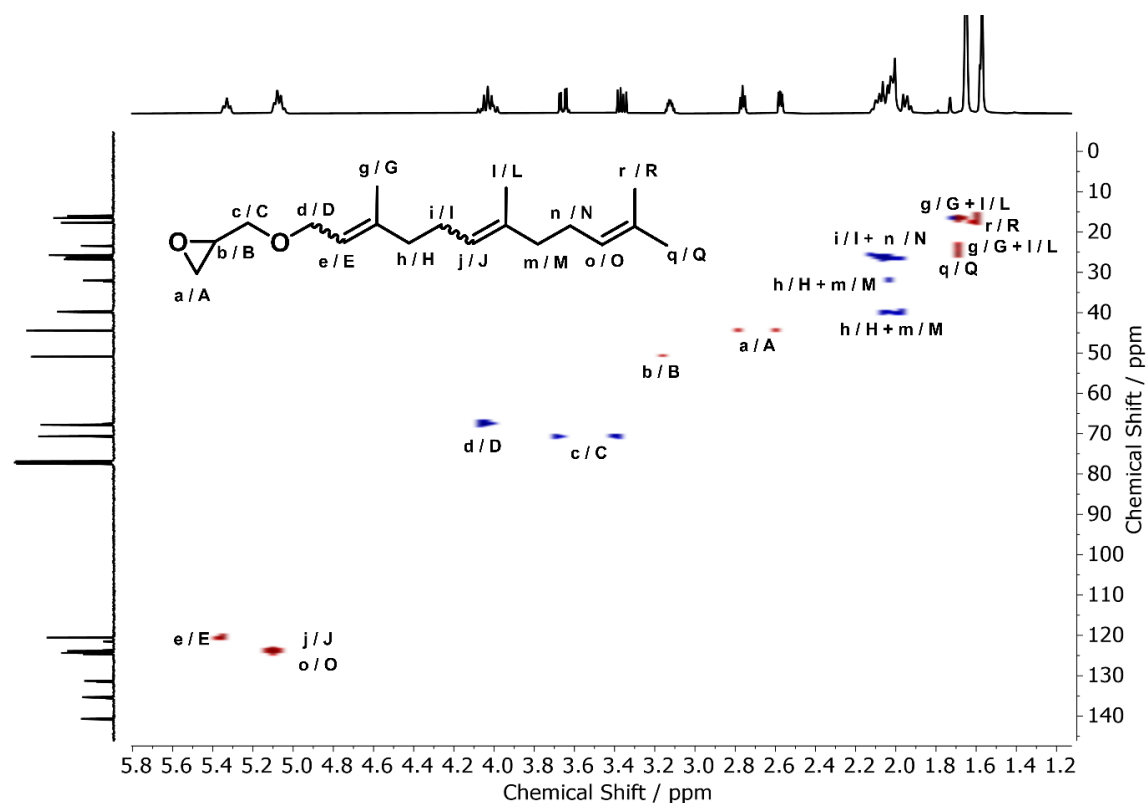


Figure S 17: ^1H - ^{13}C HSQC NMR spectrum (400 MHz/100 MHz, CDCl_3) of $\text{mPEG}_{114}\text{-b-PFarGE}_9$.

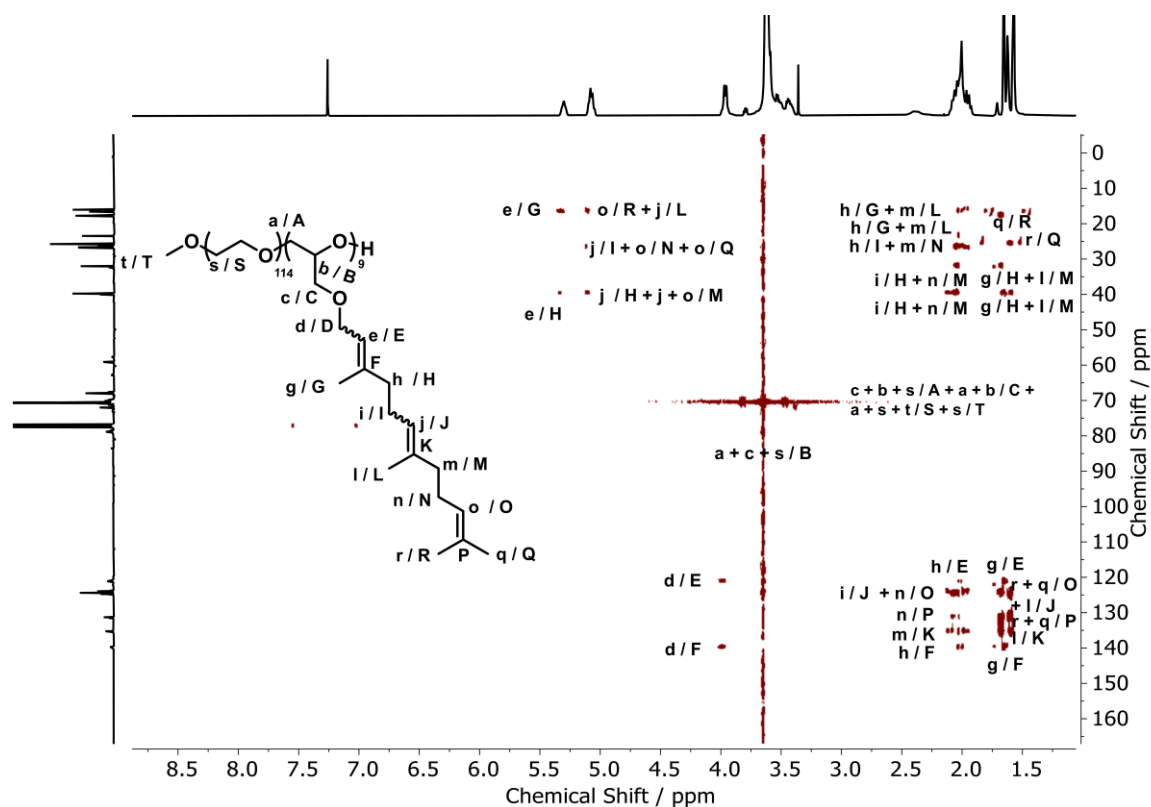


Figure S 18: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_9$.

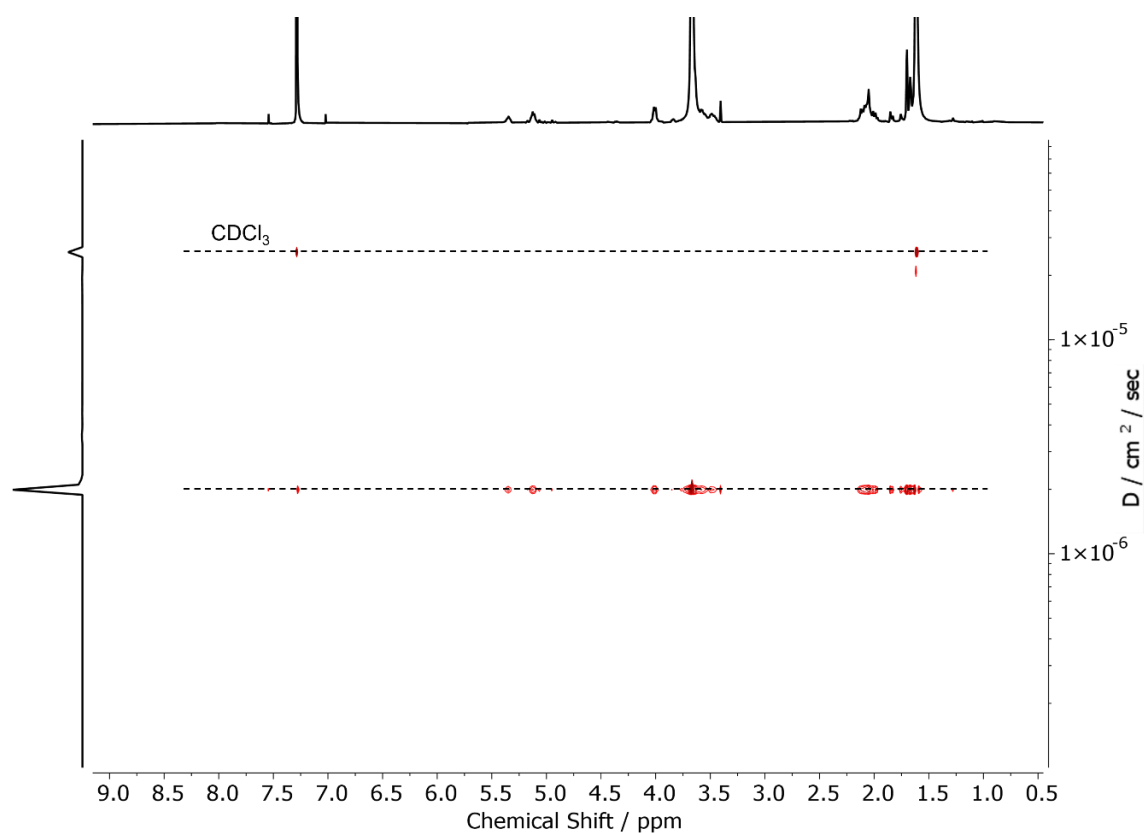


Figure S 19: DOSY NMR spectrum (400 MHz, CDCl_3) of $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_9$, featuring only one diffusion coefficient for the block copolymer. The signal at 7.26 ppm and 1.60 ppm with a higher diffusion coefficient belong to the CDCl_3 solvent and water respectively.

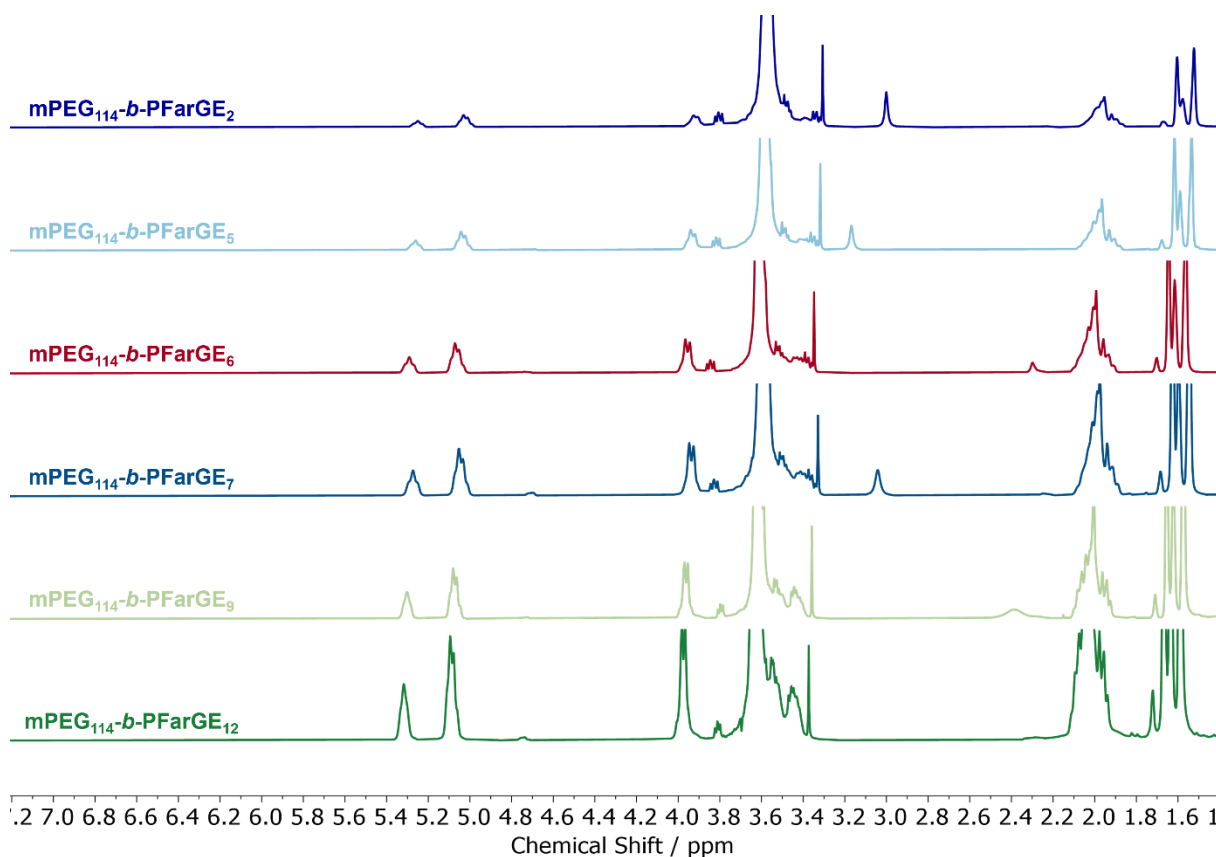
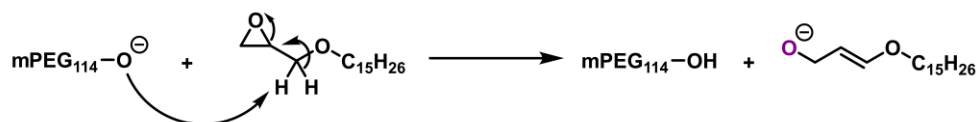
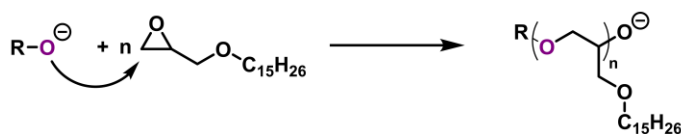


Figure S 20: Stacked NMR spectra (400 MHz, CDCl_3) of all $\text{mP}(\text{EG}_{114}\text{-}b\text{-FarGE}_m)$ block copolymer, normalized to the initiator peak intensity at 3.36 ppm.

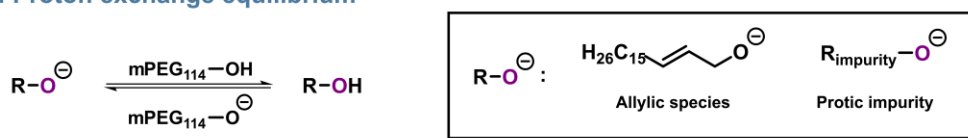
A: Potential proton abstraction by polymer alkoxide generating allylic species



B: Homopolymerization initiated by allylic species or protic impurity



C: Proton exchange equilibrium



Scheme S 4: Potential reaction cascade in anionic ring opening polymerization (AROP). (A) Proton abstraction of substituted epoxides under basic conditions results in a chain transfer reaction to the FarGE monomer. (B) Homopolymer formation is either initiated by allylic monomer species or protic impurities. (C) Protic impurities form alkoxide due to a very fast proton exchange equilibrium.²⁶

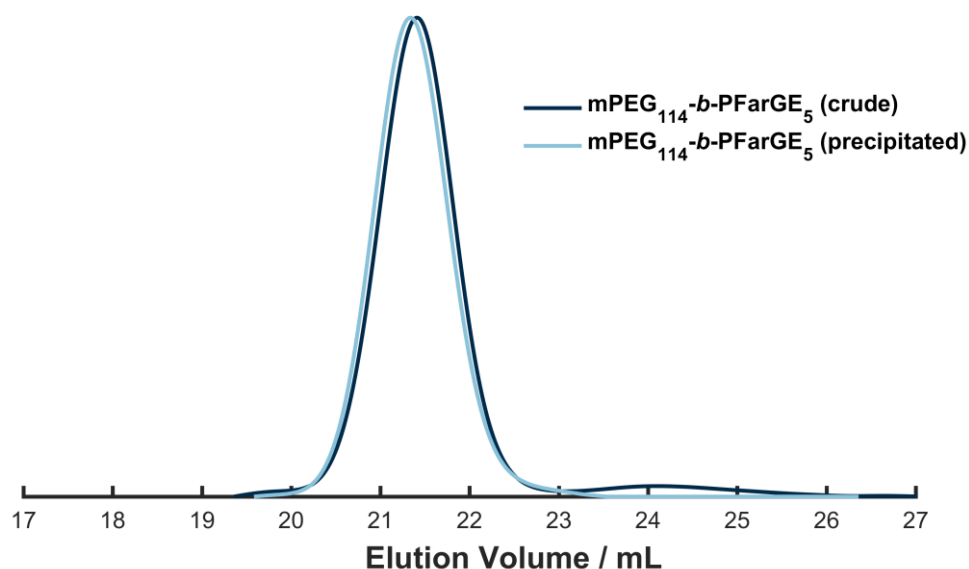


Figure S 21: SEC elution traces (RI detector, eluent: DMF, standard: PEG) of crude and precipitated mPEG₁₁₄-b-PFarGE₇ diblock copolymer ($T = 80\text{ }^{\circ}\text{C}$), targeting a $P_{n,\text{targeted}} = 9$. The trace of the crude polymer contains a lower molecular weight mode at higher elution volumes, which we attribute to homopolymer formation due to water initiation.

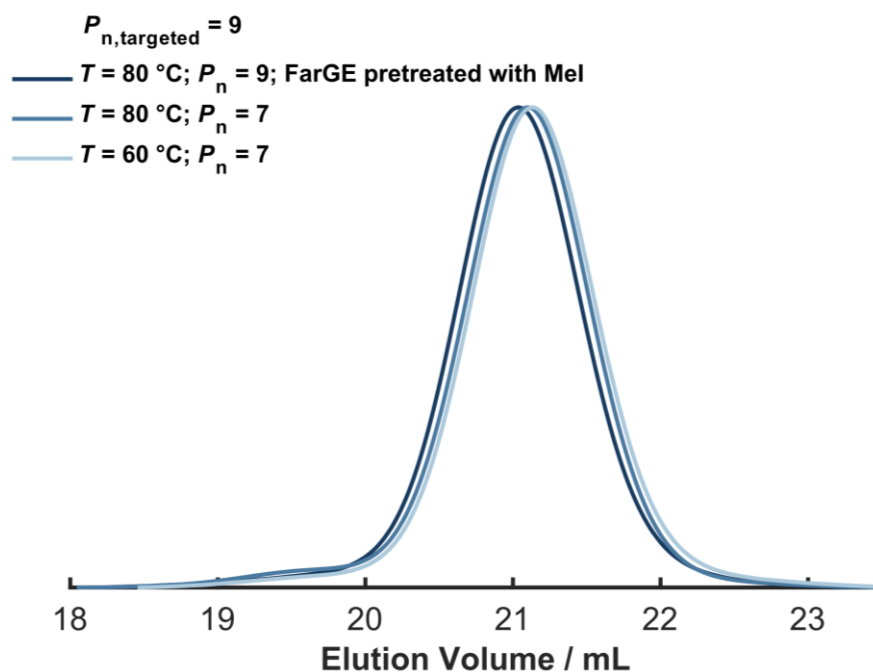
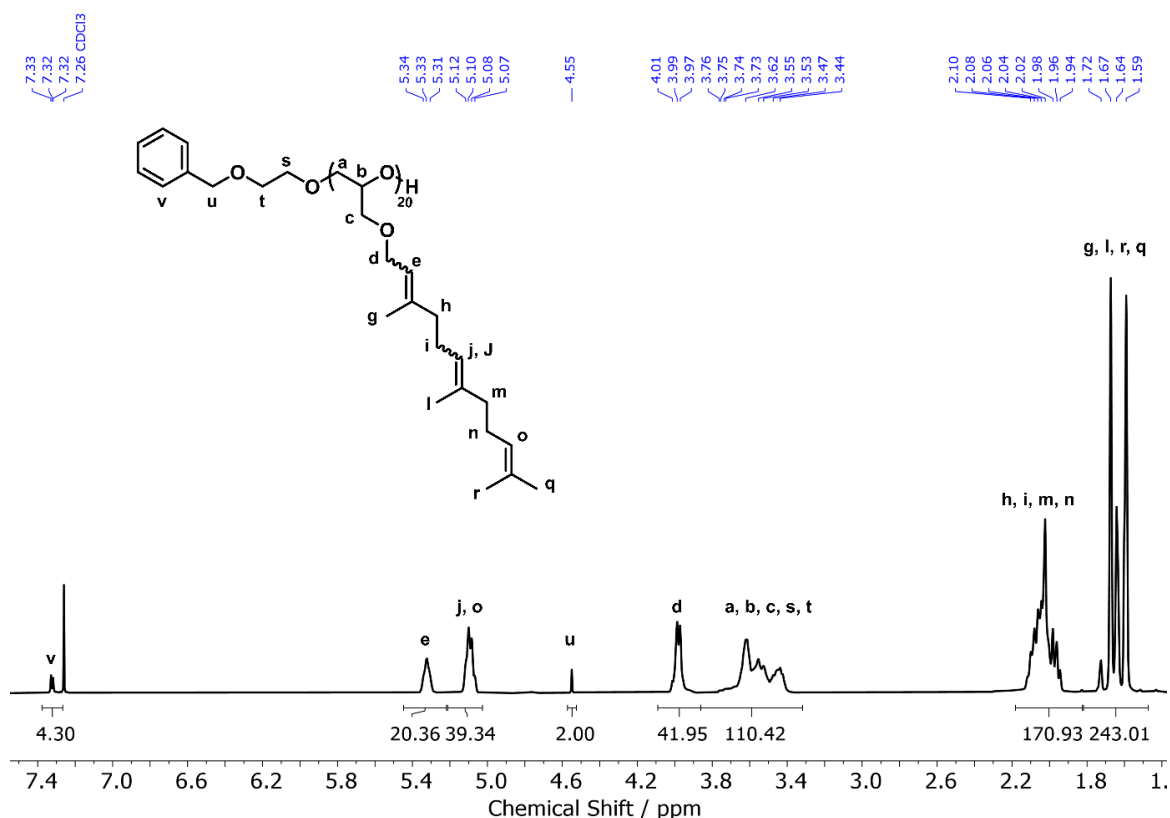
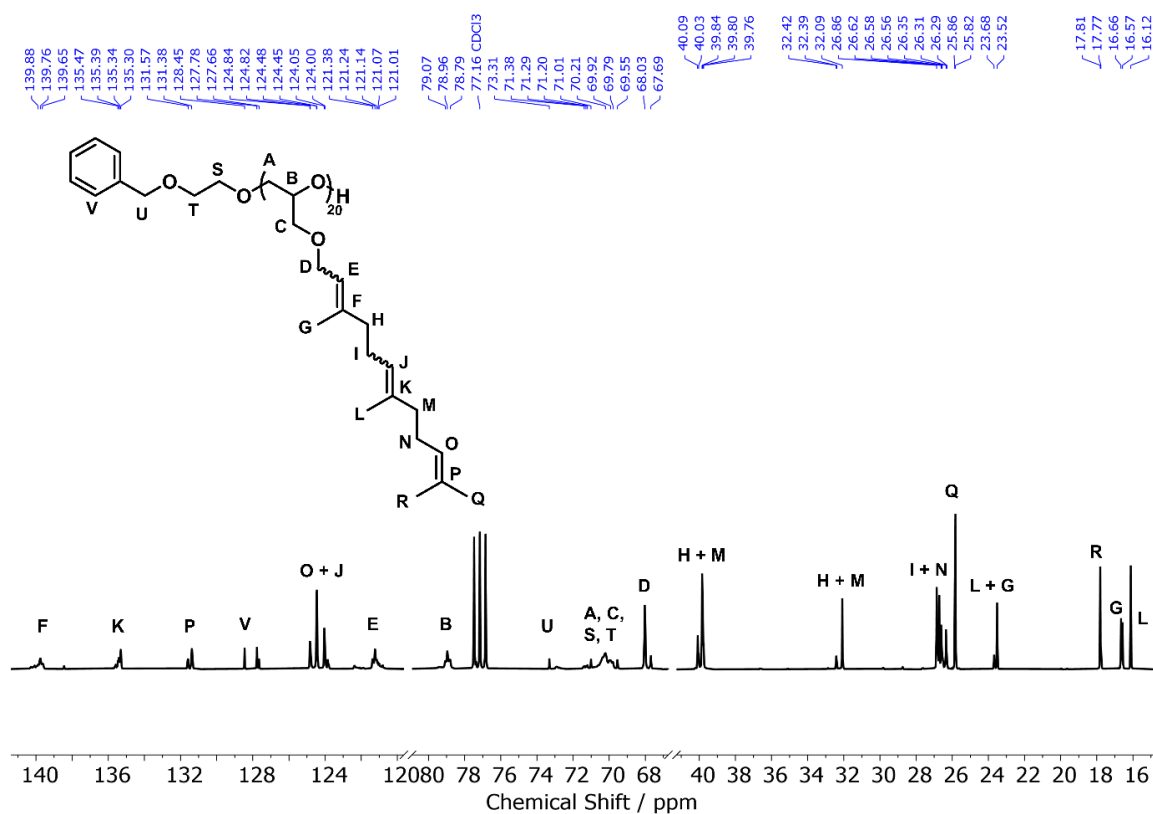
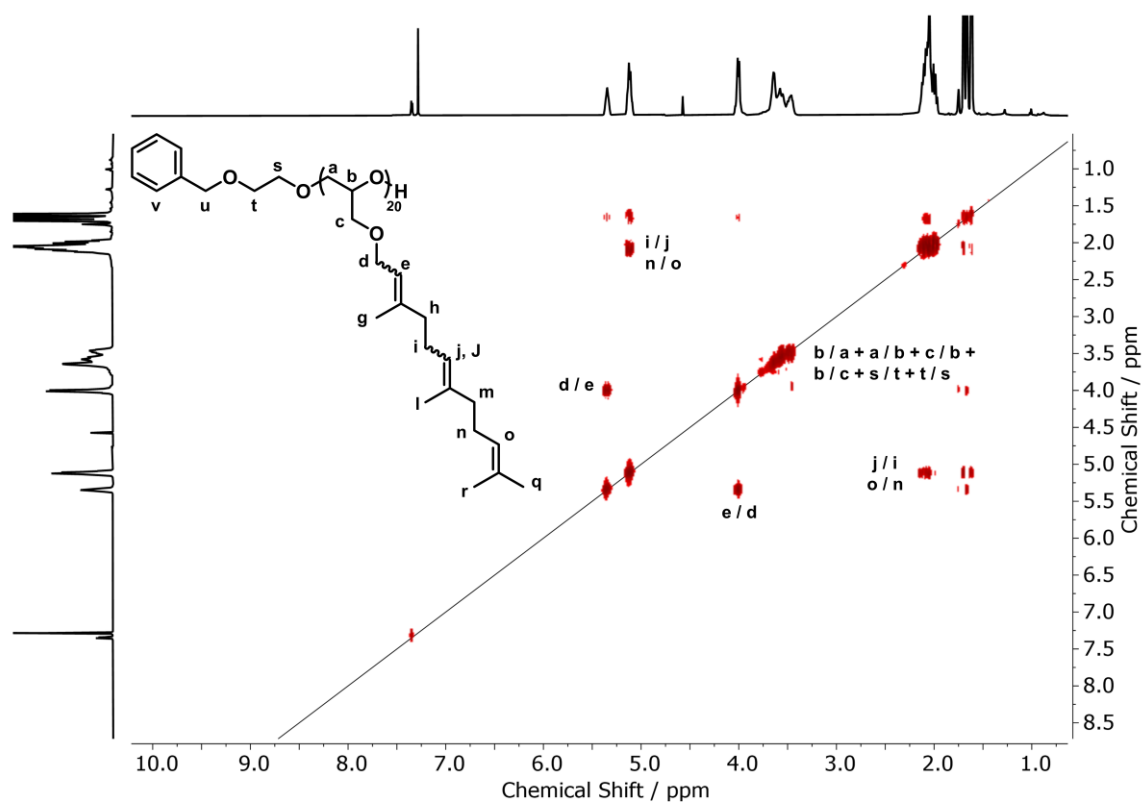
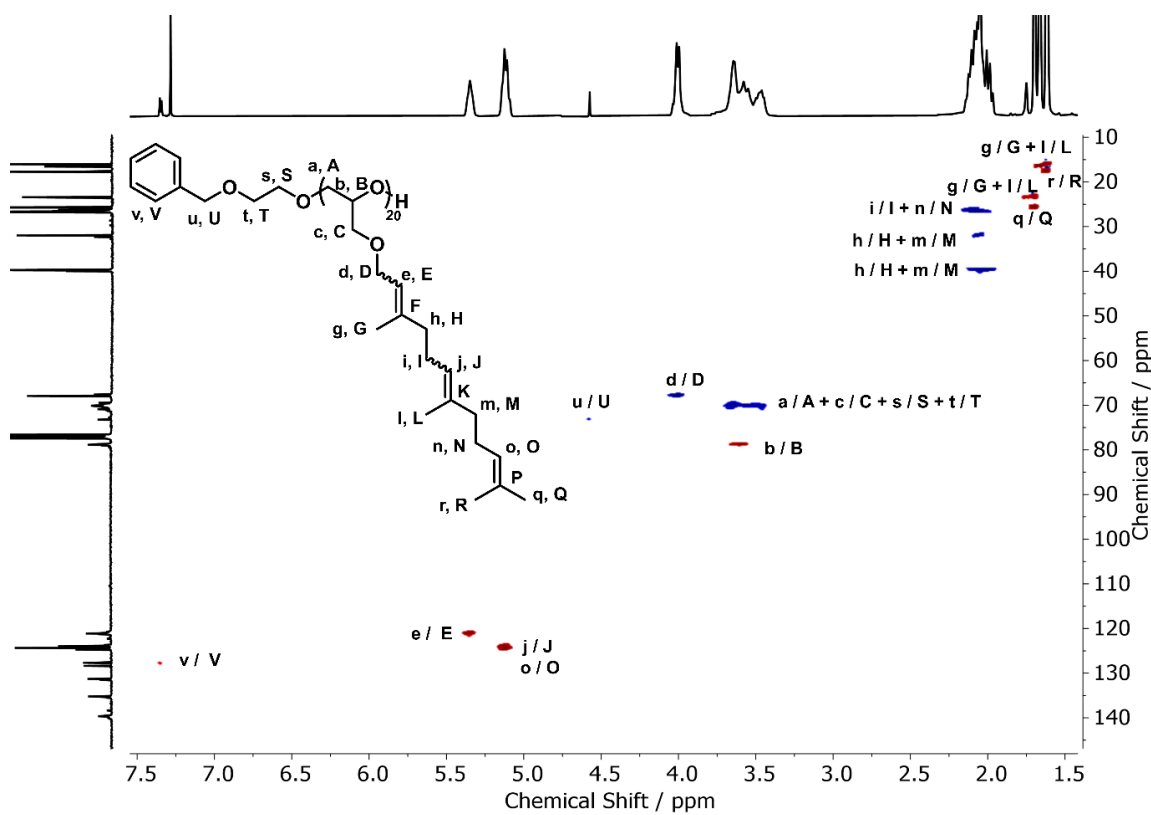


Figure S 22: SEC elution traces (RI detector, eluent: DMF, standard: PEG) for the synthesis of mPEG₁₁₄-b-PFarGE_n diblock copolymers, targeting a $P_{n,\text{targeted}} = 9$. The SEC analysis illustrates that the pretreatment of FarGE with MeI allows for masking of protic impurities (Scheme 2) and hence the resulting diblock copolymer features the targeted $P_n = 9$ (dark blue line). An impact of the polymerization temperature on the P_n is not observable.

Characterization of PFarGE Homopolymers

Figure S 23: ^1H NMR spectrum (400 MHz, CDCl_3) of PFarGE₂₀ homopolymer.Figure S 24: ^{13}C NMR spectrum (400 MHz, CDCl_3) of PFarGE₂₀ homopolymer.

Figure S 25: ^1H - ^1H COSY NMR spectrum (400 MHz, CDCl_3) of PFarGE₂₀ homopolymer.Figure S 26: ^1H - ^{13}C HSQC NMR spectrum (400 MHz, CDCl_3) of PFarGE₂₀ homopolymer.

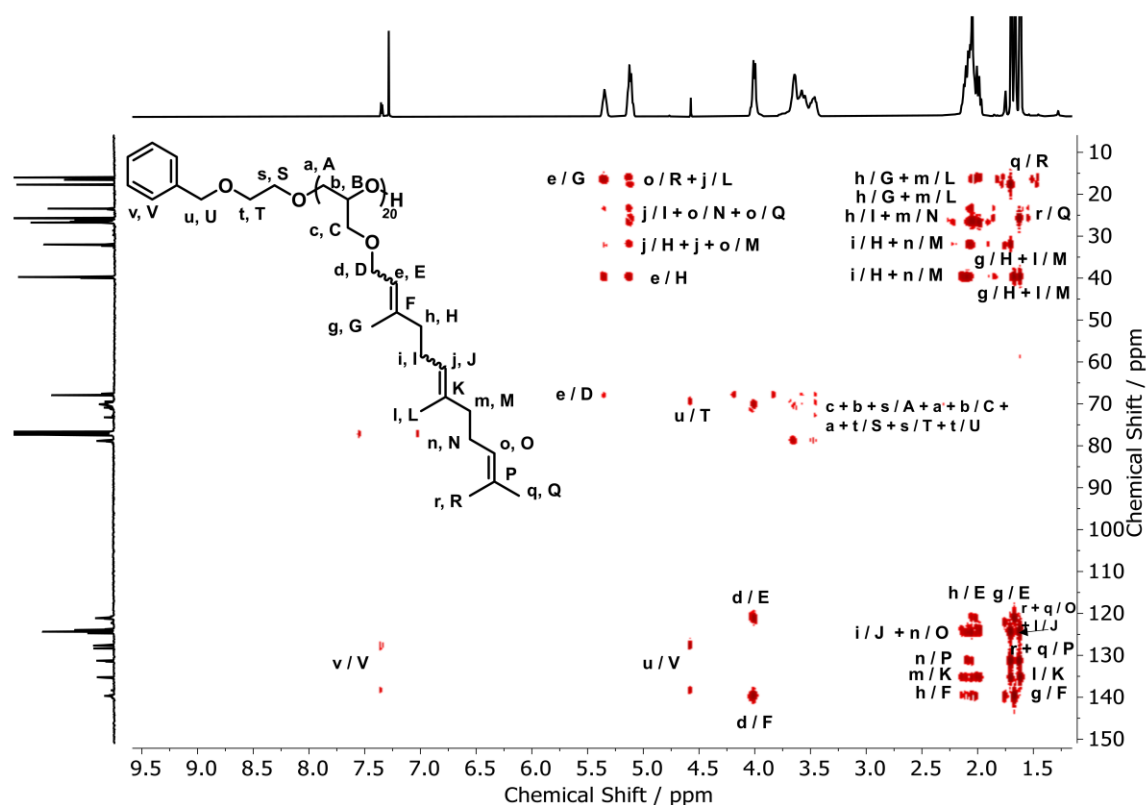


Figure S 27: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/75 MHz, CDCl_3) of PFarGE₂₀ homopolymer

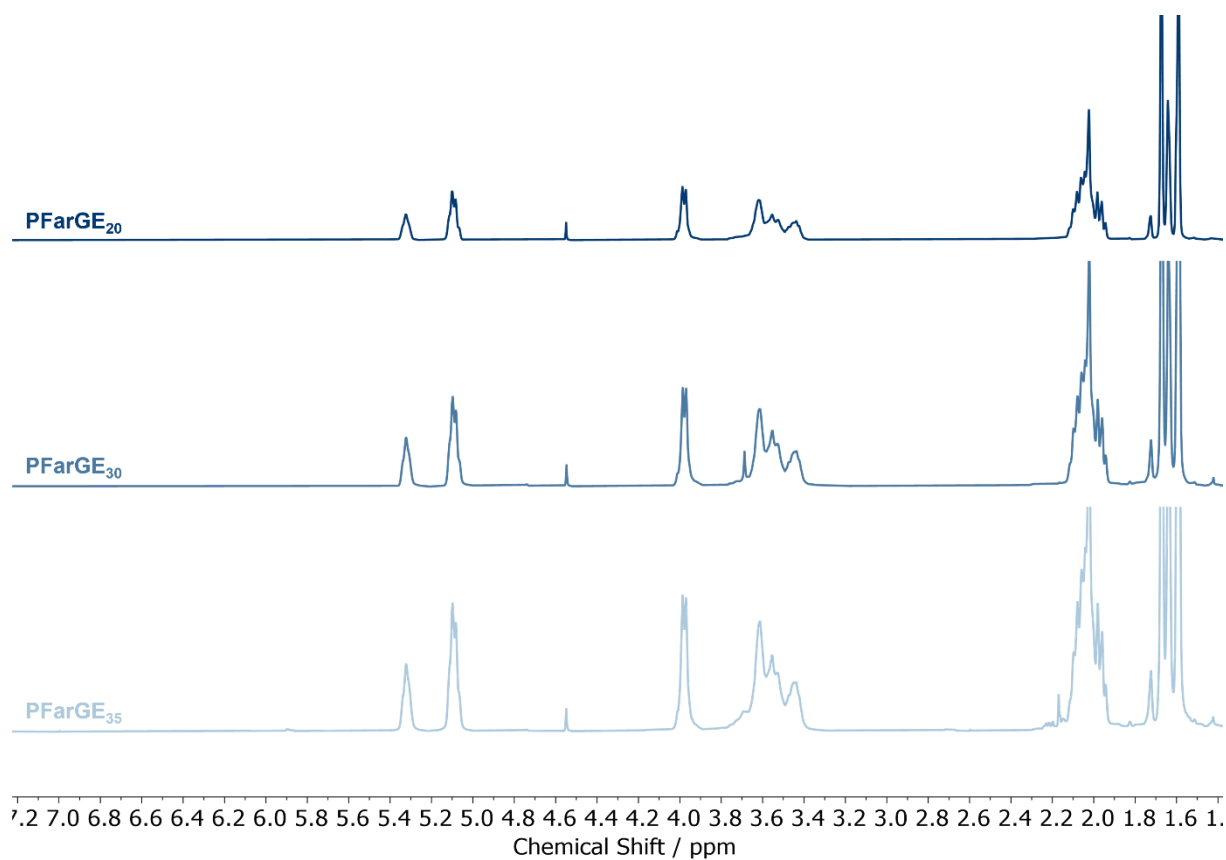


Figure S 28: Stacked NMR spectra (400 MHz, CDCl_3) of all PFarGE_m homopolymers, normalized to the initiator peak intensity at 4.53 - 4.57 ppm.

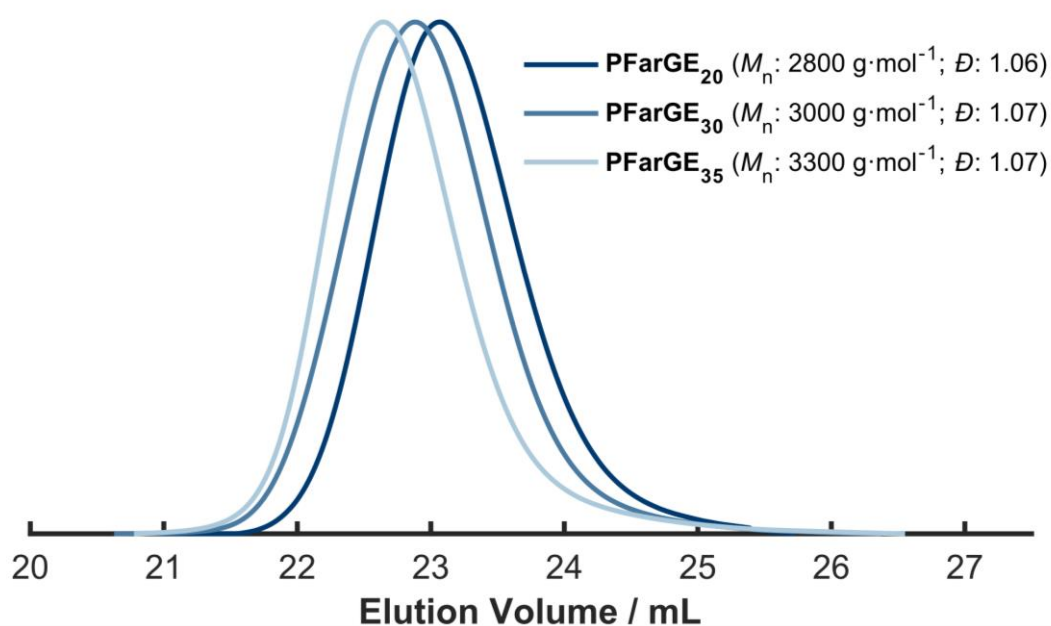


Figure S 29: SEC elution traces of PFarGE_m homopolymers (RI detector, eluent: DMF, standard: PEG).

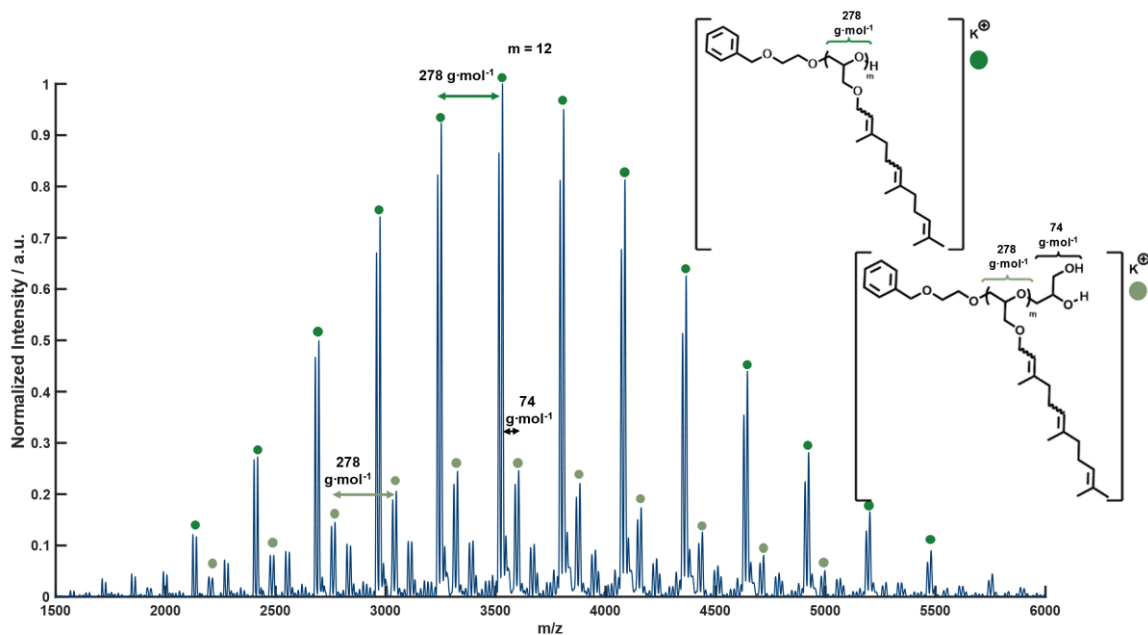


Figure S 30: MALDI-ToF mass spectrum (DCTB, KTFA, linear mode) of PFarGE₂₀. The right peaks of the two major distributions were ionized with a potassium cation (marked with green circles) and confirm the initiation by 2-(benzyloxy)ethanol. The lower intensity distribution (light green circles) indicates a cleavage of one farnesol group caused by the ionization process or the utilization of an acidic matrix, resulting in exactly one glycidol unit per polymer chain. The spacing between neighboring peaks per distribution corresponds to the molar mass of the FarGE repeat unit (278 gmol⁻¹), whereas the shift of the two distributions matches the molar mass of glycidol (74 gmol⁻¹).

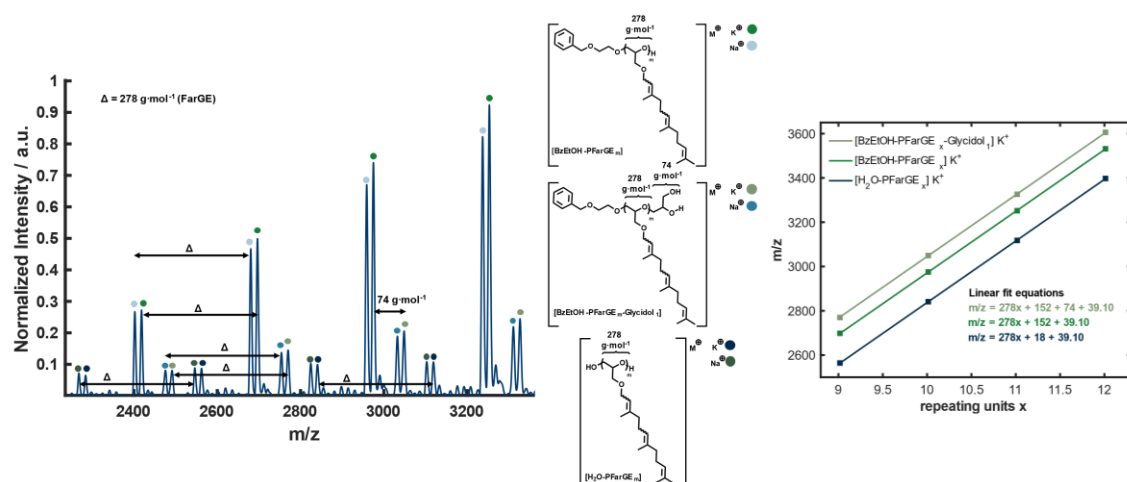
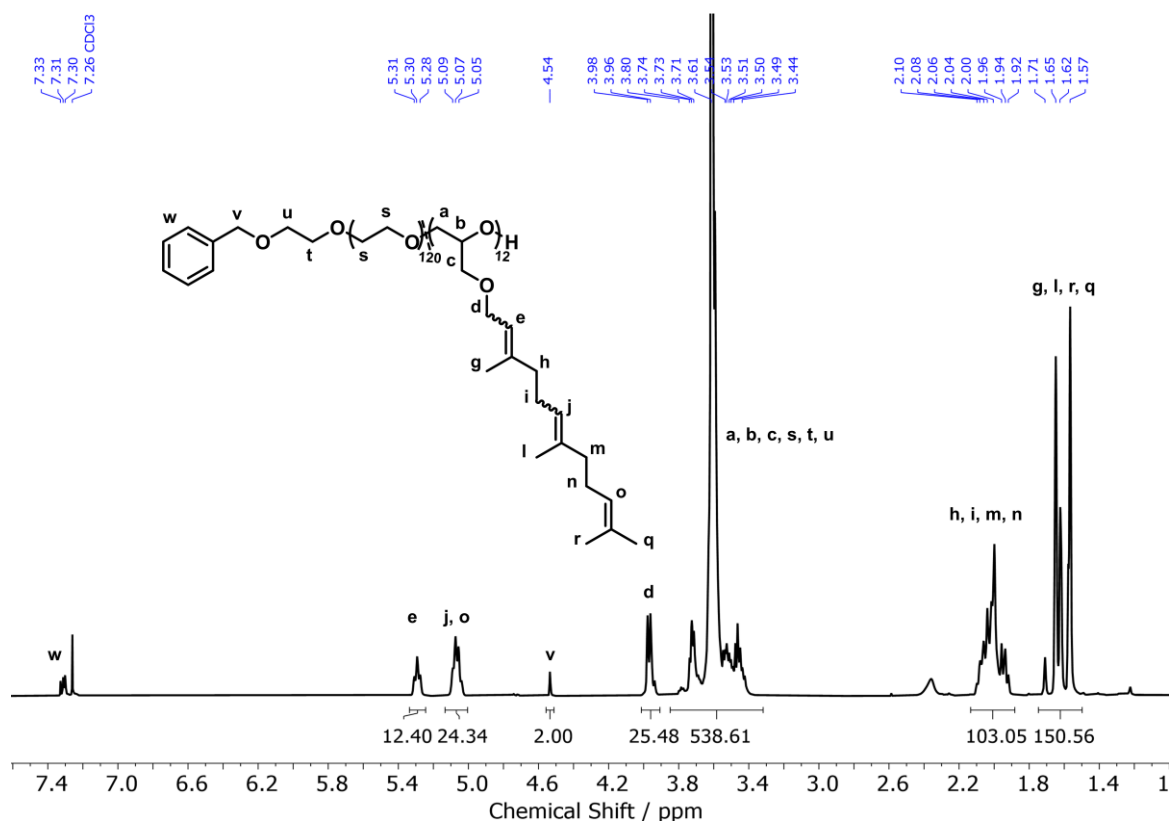
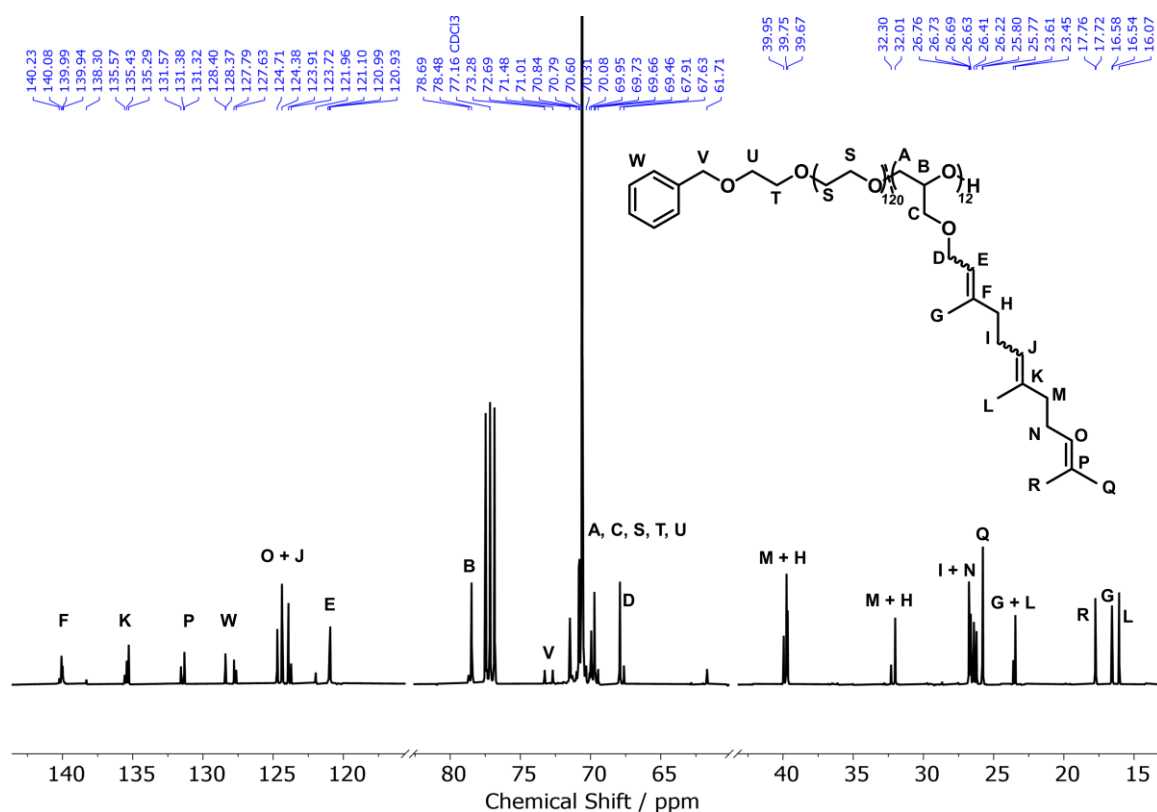


Figure S 31: Zoom-in of the MALDI-ToF mass spectrum of PFarGE₂₀ (left) with an assignment of all distributions (including counterions). The intercept M_{end} of the linear plot of m/z values (calculations based on K^+ ionization: $M_{\text{K}} = 39.10 \text{ g mol}^{-1}$) versus the number of FarGE repeat units x (278 g mol^{-1}) allows for the determination of the initiating species (right).

Characterization of Statistical Copolymers of FarGE and EO

Figure S 32: ¹H NMR spectrum (400 MHz, CDCl₃) of P(EG₁₂₀-co-FarGE₁₂).Figure S 33: ¹³C NMR spectrum (100 MHz, CDCl₃) of P(EG₁₂₀-co-FarGE₁₂).

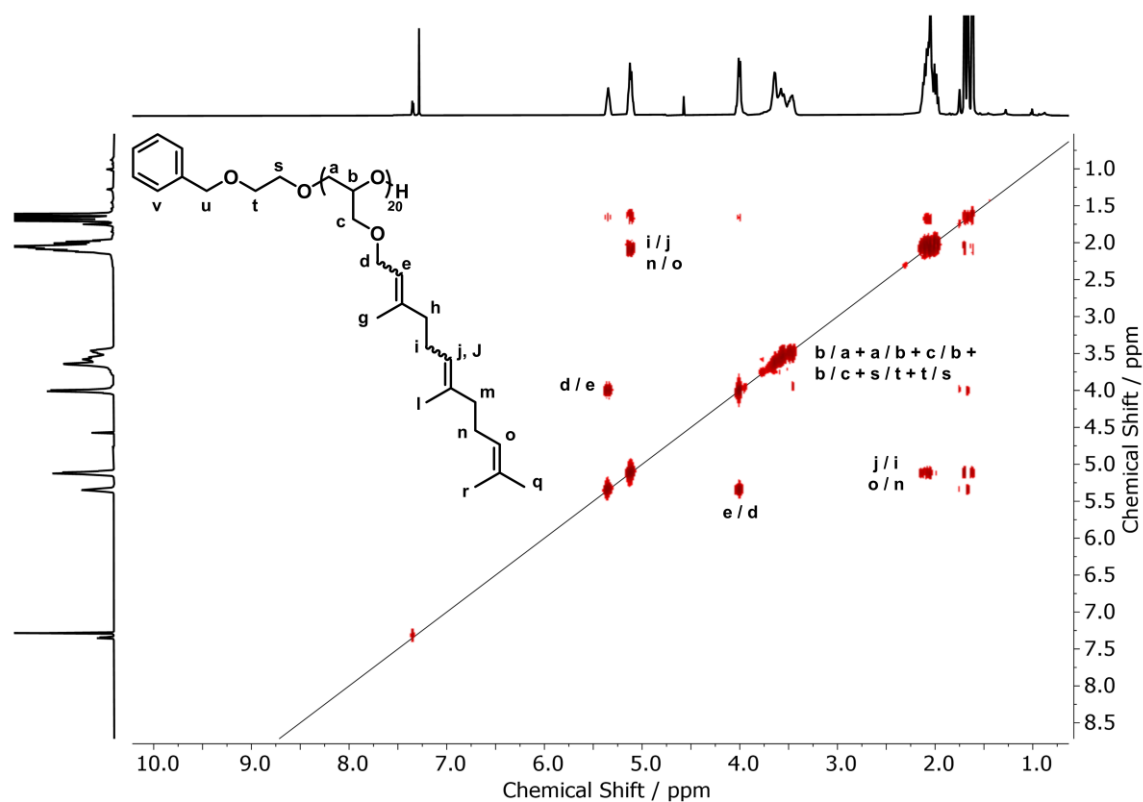


Figure S 34: ^1H - ^1H COSY NMR spectrum (400 MHz, CDCl_3) of $\text{P}(\text{EG}_{120}\text{-co-FarGE}_{12})$.

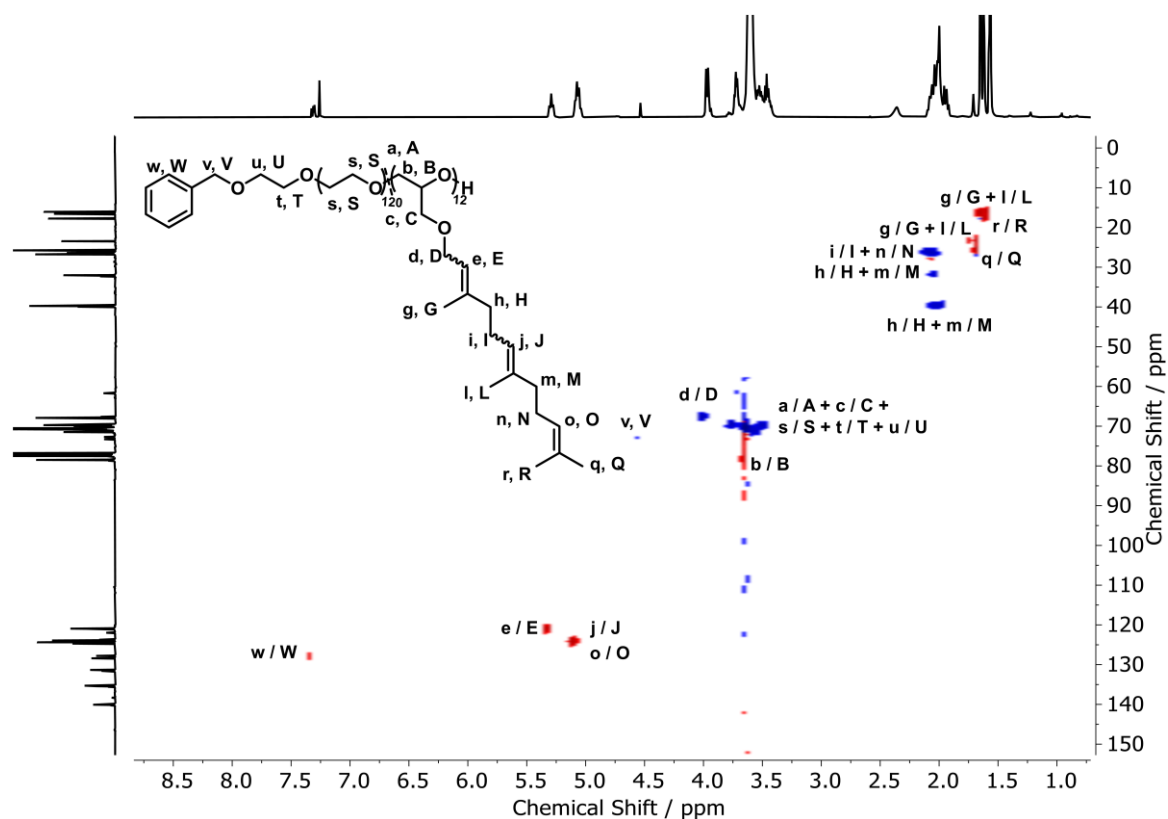


Figure S 35: ^1H - ^{13}C HSQC NMR spectrum (400 MHz/100 MHz, CDCl_3) of $\text{P}(\text{EG}_{120}\text{-co-FarGE}_{12})$.

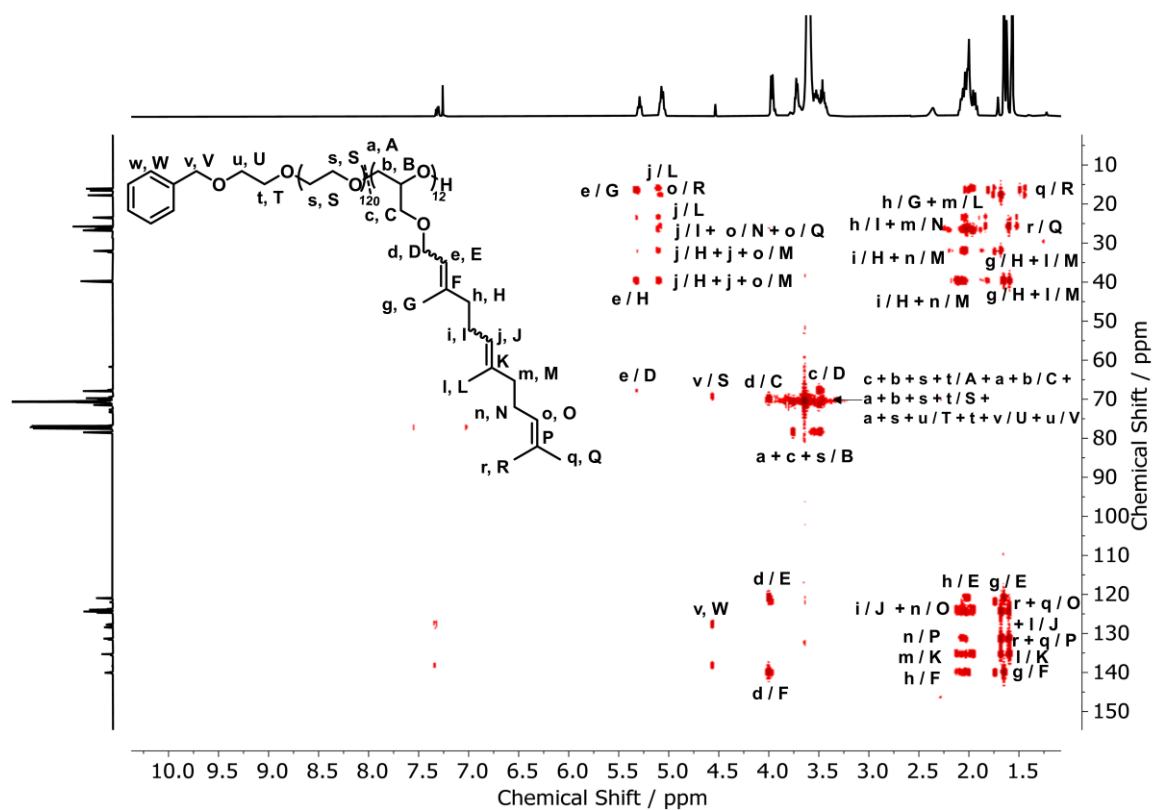


Figure S 36: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/100 MHz, CDCl_3) of $\text{P}(\text{EG}_{120}\text{-co-FarGE}_{12})$.

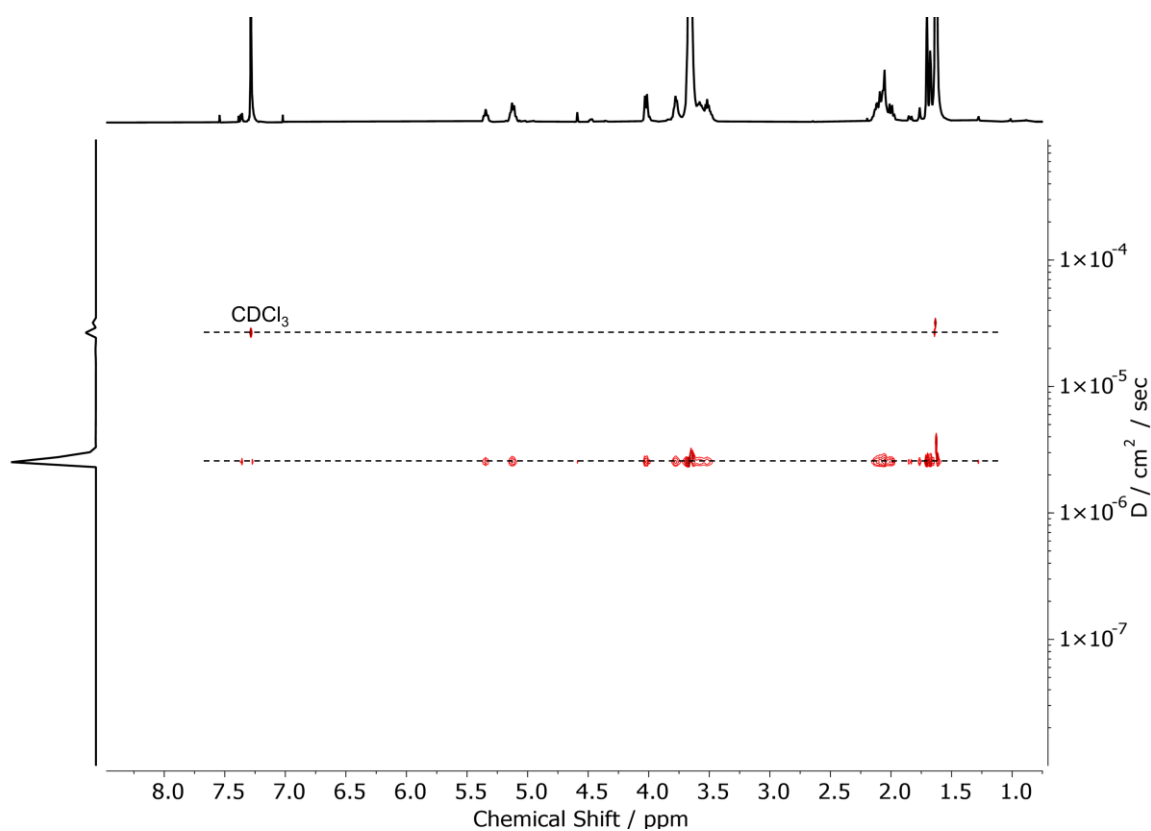


Figure S 37: DOSY NMR spectrum (400 MHz MHz, CDCl_3) of $\text{P}(\text{EG}_{120}\text{-co-FarGE}_{12})$, exhibiting one diffusion coefficient for the copolymer. The higher value diffusion coefficients are ascribed to CDCl_3 at 7.26 ppm and water at 1.60 ppm.

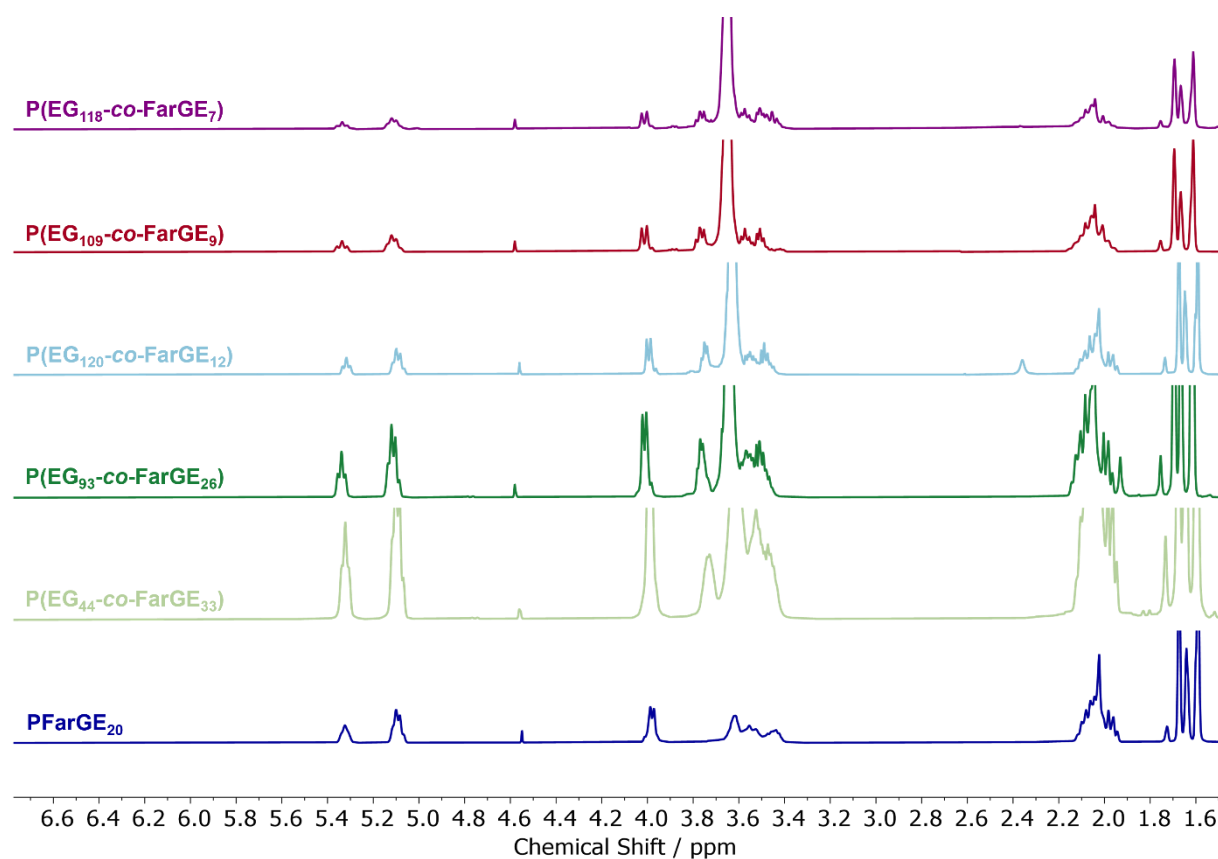


Figure S 38: Stacked NMR spectra (400 MHz, CDCl₃) of all statistical P(EG_n-co-FarGE_m) copolymers, normalized to the initiator peak intensity at 4.53 - 4.57 ppm.

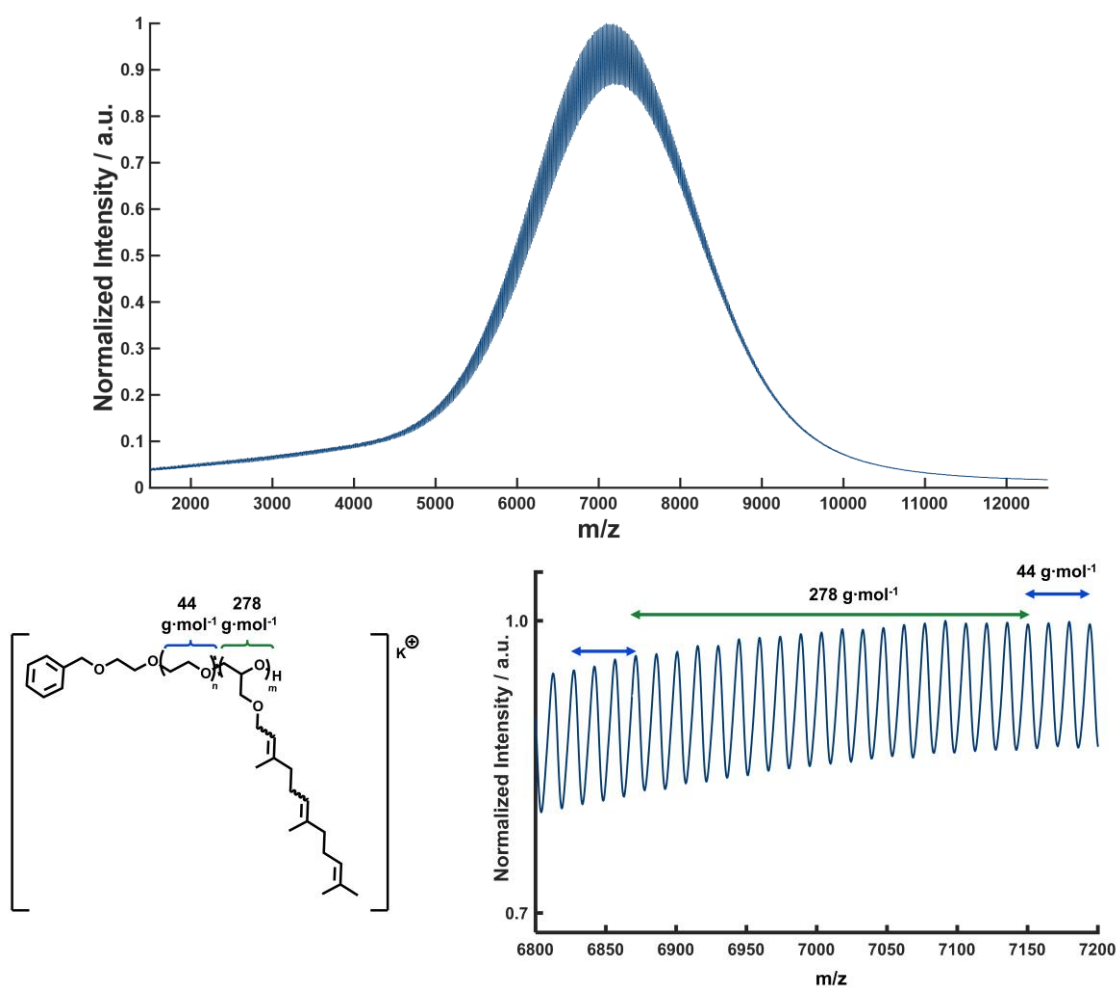


Figure S 39: MALDI-ToF mass spectrum (DCTB, KTFA, linear mode) of P(EG₁₀₉-co-FarGE₉) with a $M_{\text{peak,MALDI}} = 7100 \text{ g}\cdot\text{mol}^{-1}$ (top), showing the expected repeat unit of EO (44 g·mol⁻¹) and FarGE (278 g·mol⁻¹) in the enlarged section (bottom).

***In situ* ^1H NMR Copolymerization Kinetics of FarGE and EO**

Non-terminal, ideal copolymerization model and Jaacks fit

The non-terminal or ideal copolymerization model postulates that the selectivity towards comonomers is independent of the nature of the polymer chain end. It was first introduced by Wall in 1941 as a time-independent differential equation (6) and uses relative rates to describe copolymerizations²⁷:

$$\frac{d[\text{M}_1]}{d[\text{M}_2]} = r_1 \frac{[\text{M}_1]}{[\text{M}_2]} \quad (7)$$

$$\frac{d[\text{M}_1]}{[\text{M}_1]} = r_1 \frac{d[\text{M}_2]}{[\text{M}_2]} \quad (8)$$

The reactivity ratios are described by the rate constants:

$$r_1 = \frac{[k_1]}{[k_2]} \quad (9)$$

$$r_2 = \frac{[k_2]}{[k_1]} \quad (10)$$

The integration of the rearranged Wall's equation (7) leads to the Jaacks equation (8)²⁸:

$$\log \frac{[\text{M}_1, t=x]}{[\text{M}_1, t=0]} = r_1 \log \frac{[\text{M}_2, t=x]}{[\text{M}_2, t=0]} \quad (11)$$

The Jaacks equation allows for the determination of the reactivity ratios at any comonomer ratio when ideal copolymerization conditions are applicable ($r_1 \cdot r_2 = 1$).²⁸

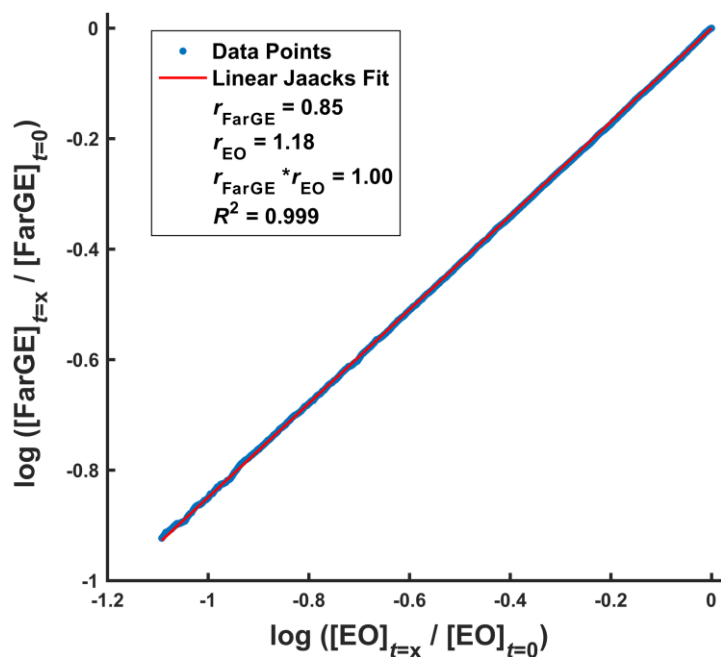


Figure S 40: Jaacks fit (non-terminal, ideal copolymerization model) of the *in situ* ^1H NMR copolymerization kinetics of FarGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C. Reactivity ratios: $r_{\text{FarGE}} = 0.85 \pm 0.0003$, $r_{\text{EO}} = 1.18 \pm 0.0004$, $r_{\text{FarGE}} * r_{\text{EO}} = 1$, $R^2 = 0.999$. The linear fit was conducted with a FarGE conversion of 90%.

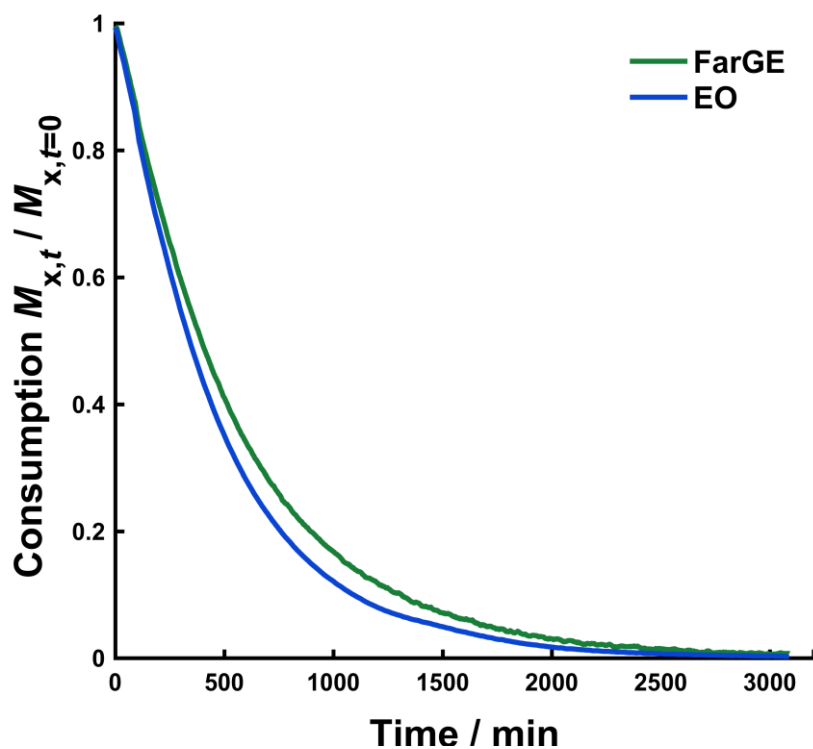


Figure S 41: Monomer consumption $M_{x,t}/M_{x,t=0}$ plotted versus time for the *in situ* ^1H NMR kinetics of FarGE (green) with EO (blue) in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

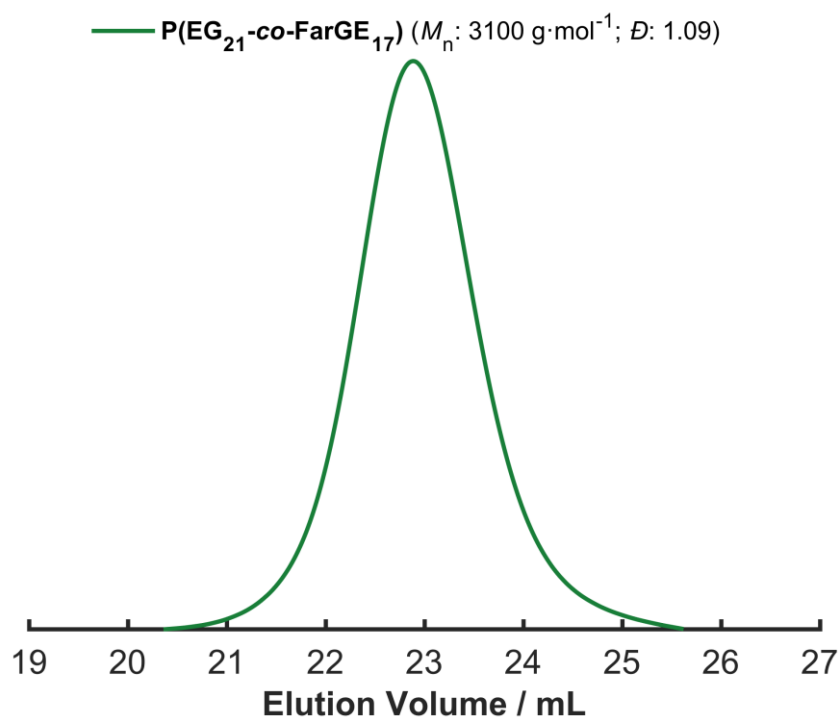


Figure S 42: SEC elugram (RI detector, eluent: DMF, standard: PEG) of the $P(EG_{21}\text{-co-FarGE}_{17})$ copolymer synthesized from the *in situ* ^1H NMR copolymerization kinetics in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C. The polymerization was conducted in a sealable NMR tube to investigate the reactivity of the EO/FarGE monomer pair (mole fractions: $n_{\text{EO}} = 0.55$, $n_{\text{FarGE}} = 0.45$). SEC analysis: $M_n = 3100 \text{ g}\cdot\text{mol}^{-1}$, $\mathcal{D} = 1.09$.

Thermal Characterization of Homo- and Copolymers

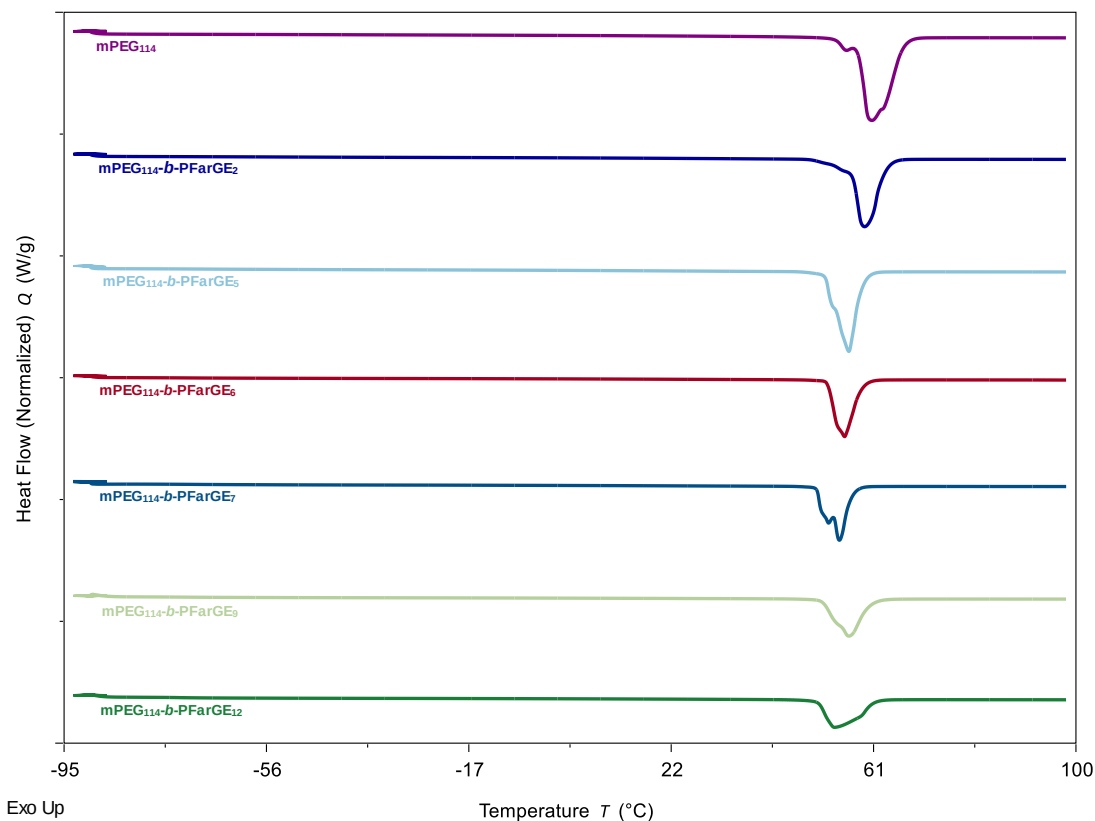


Figure S 43: DSC thermograms of mPEG₁₁₄-*b*-PFarGE_m diblock copolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

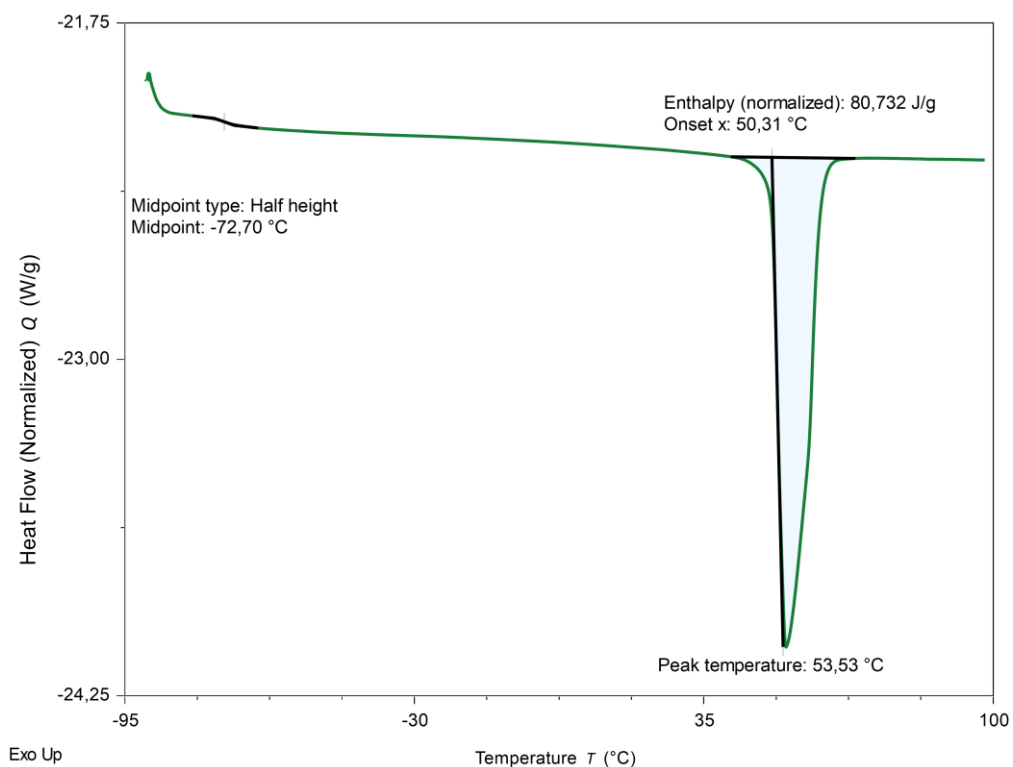


Figure S 44: Exemplary DSC thermogram of mPEG₁₁₄-*b*-PFarGE₁₂ diblock copolymer exhibiting the glass transition feature (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

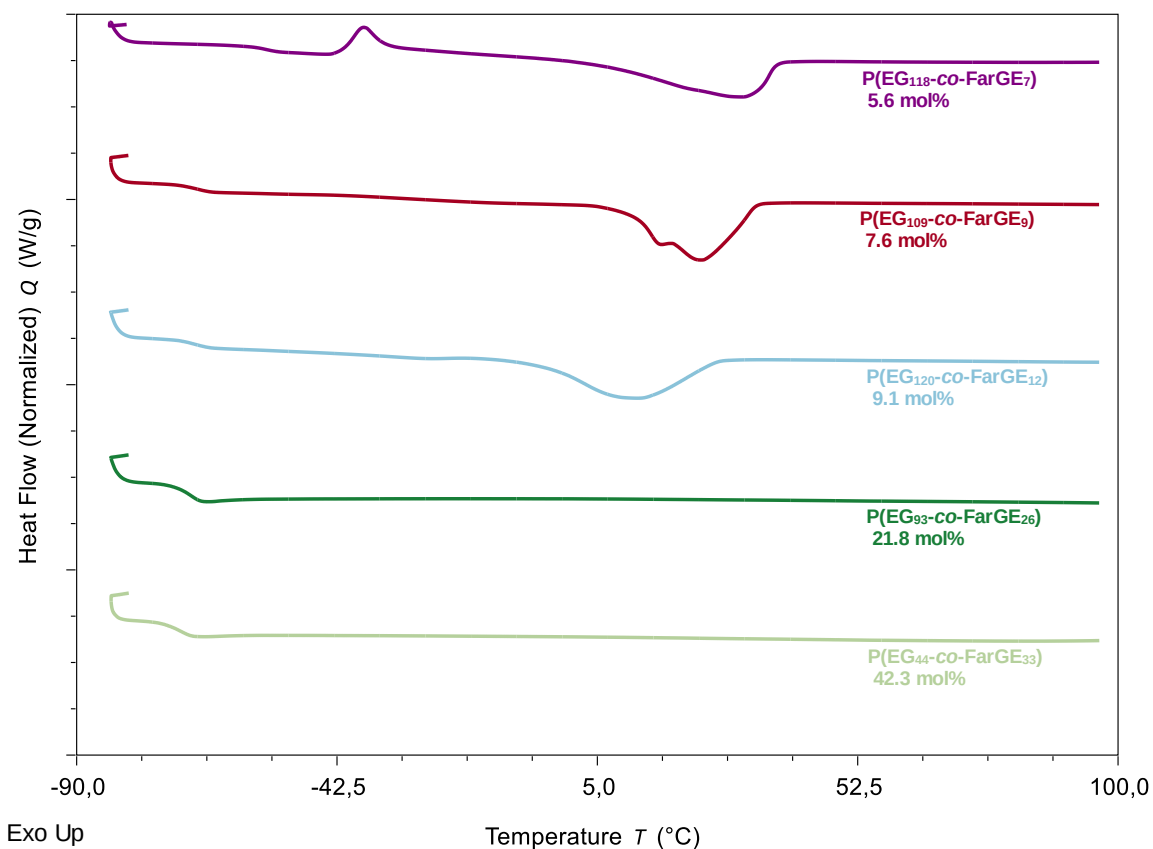


Figure S 45: DSC thermograms of $\text{P(EG}_n\text{-co-FarGE}_m\text{)}$ copolymers and PFarGE (second heating cycle, from -90 to 100 $^{\circ}\text{C}$, 10 $^{\circ}\text{C}\cdot\text{min}^{-1}$).

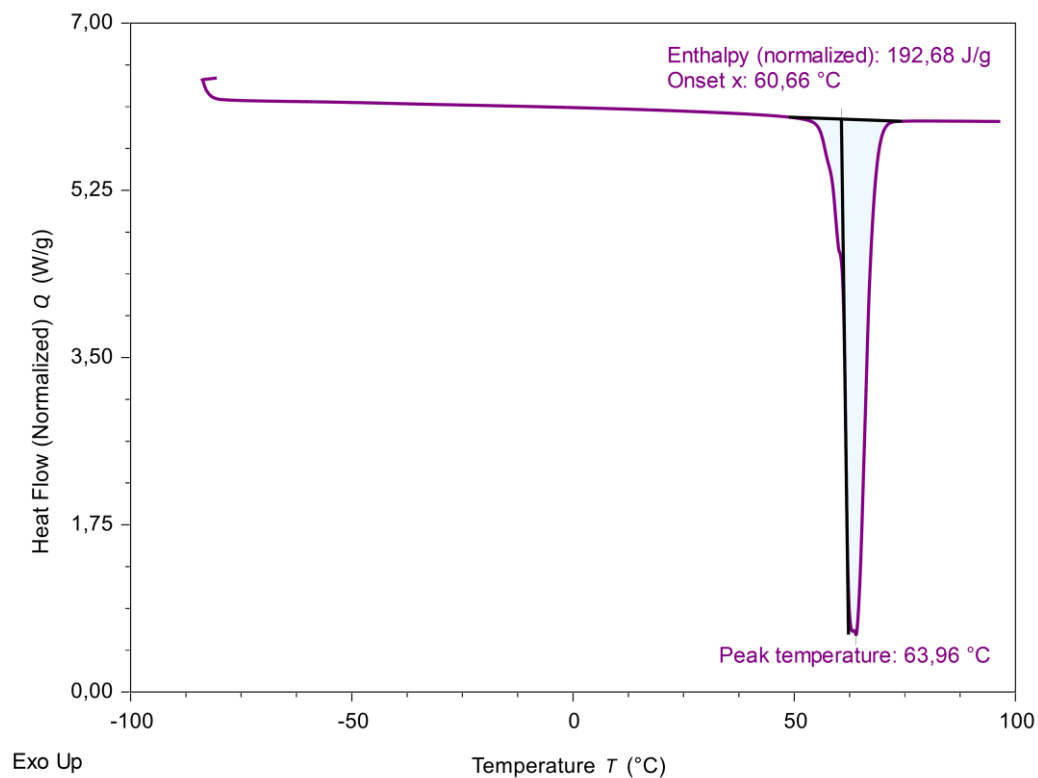


Figure S 46: DSC thermograms of PEG_{155} as reference (second heating cycle, from -90 to 100 $^{\circ}\text{C}$, 10 $^{\circ}\text{C}\cdot\text{min}^{-1}$).

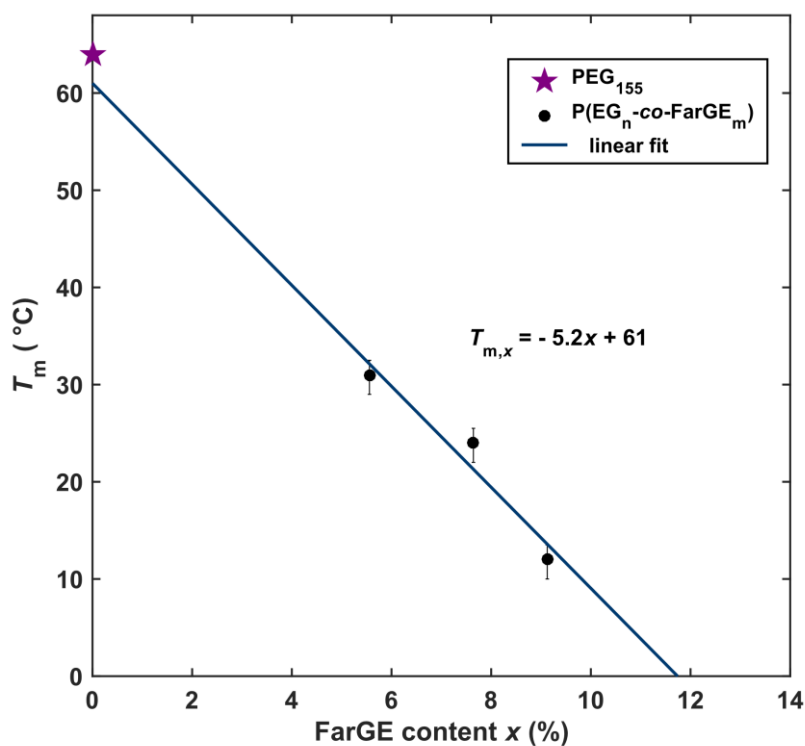


Figure S 47: Plot of the T_m of the statistical $P(EG_n\text{-}co\text{-}FarGE_m)$ copolymers as a function of FarGE content, including linear regression ($T_{m,x} = -5.2x + 61$, $R^2 = 0.95$). The T_m of PEG₁₅₅ ($M_n=6800$ gmol⁻¹) of 64 °C is graphically displayed as a reference and not included in the linear fit. Errors are estimated and error bars are set to a value of ± 1.5 °C.

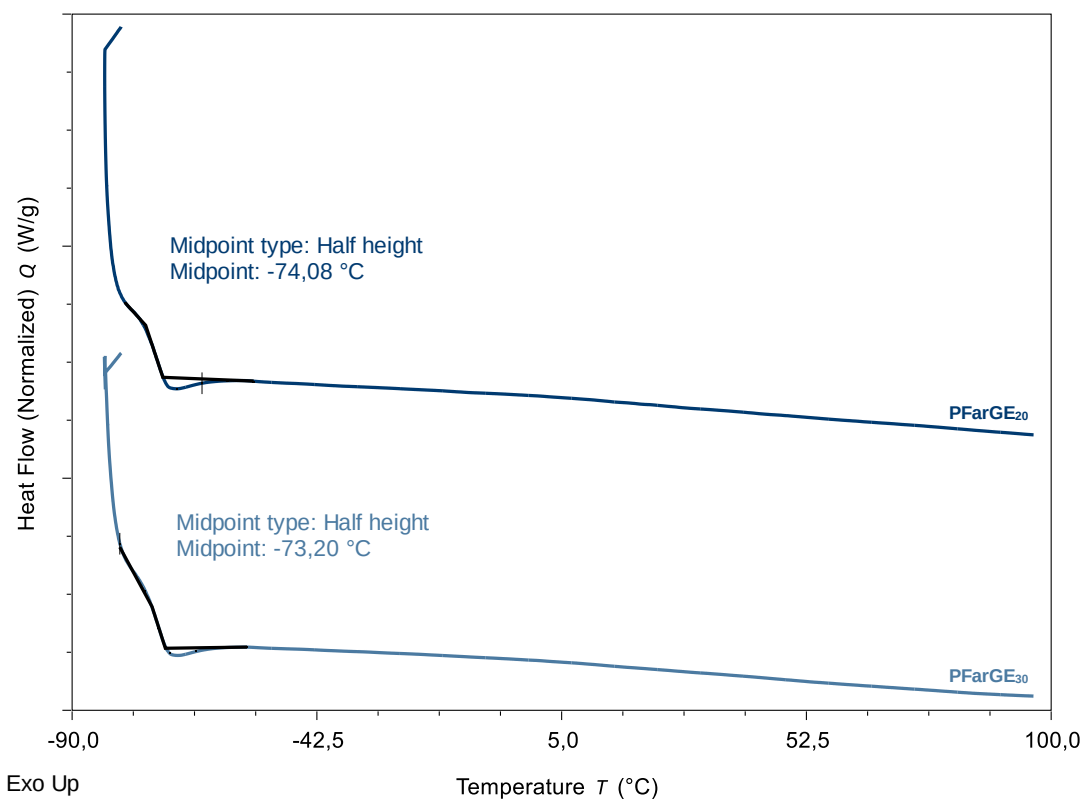


Figure S 48: DSC thermograms of PFarGE_m homopolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

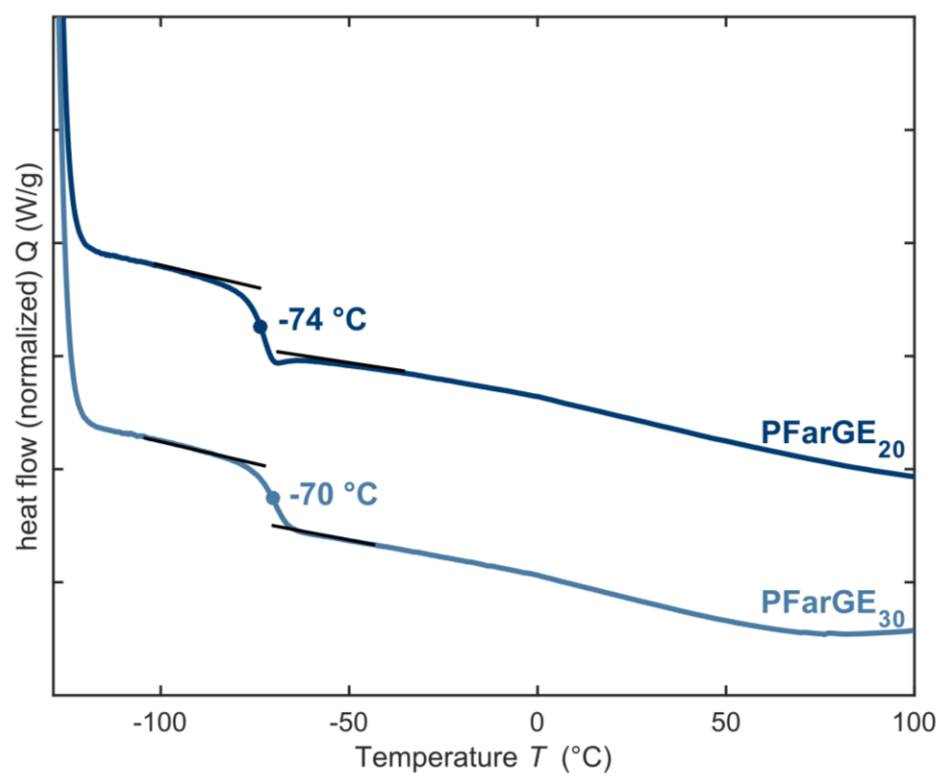


Figure S 49: Low temperature DSC thermograms of PFarGE_m homopolymers from the second heating cycle (10 °C·min⁻¹). The selected temperature range from -130 to 100 °C ensured a precise determination of the T_g due to the pronounced low temperature plateau for extrapolation.

Determination of CMCs

Surface Tensiometry

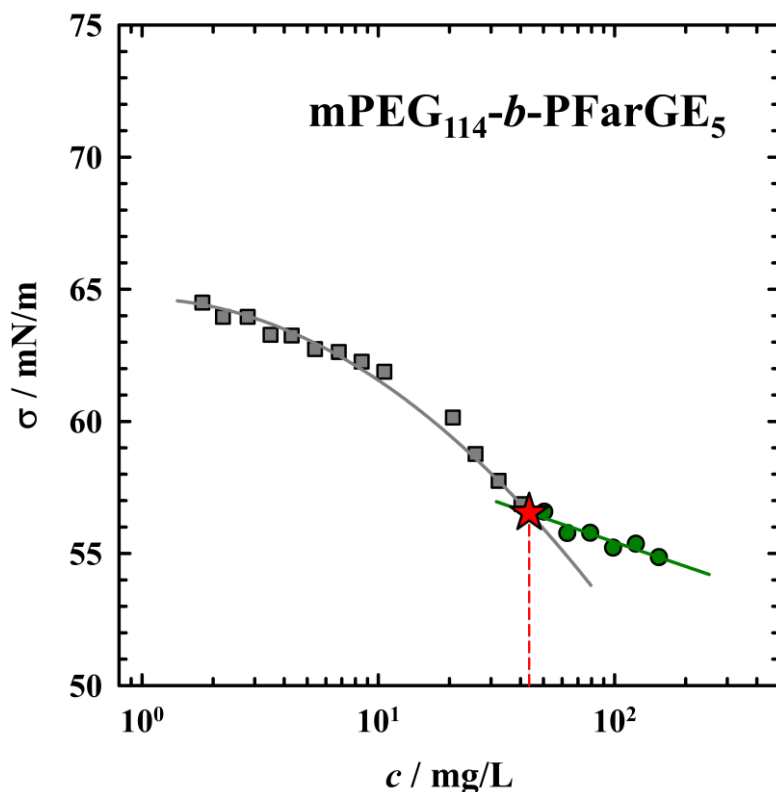


Figure S 50: Determination of the CMC (red star) via surface tensiometry of an aqueous solution of $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_5$ at $T = 23 \pm 1 \text{ }^\circ\text{C}$. The obtained CMC is $43 \pm 4 \text{ mg/L}$.

Static Light Scattering

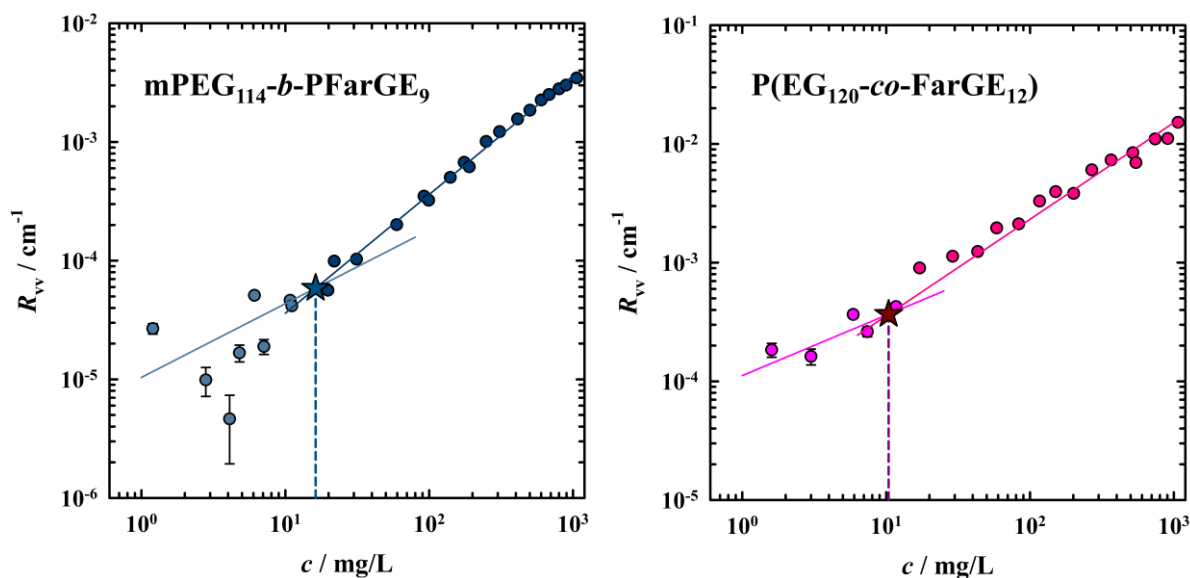


Figure S 51: Determination of the CMC of $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_9$ (left) and $\text{P(EG}_{120}\text{-co-FarGE}_{12})$ (right) via static light scattering at $T = 23 \text{ }^\circ\text{C}$. Scattering intensity R_{vv} is plotted versus concentration c of the diblock copolymer solution. From intersecting the fits for $c < \text{CMC}$ and $c > \text{CMC}$, we obtain $\text{CMC} = 16 \pm 4 \text{ mg/L}$ for $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_9$ and $\text{CMC} = 10 \pm 3 \text{ mg/L}$ for $\text{P(EG}_{120}\text{-co-FarGE}_{12})$.

Fluorescence Spectroscopy

Note that the fluorescence intensity ratio I_1/I_3 is sensitive to the hydrophobicity of the pyrene surroundings.⁷ However, since the hydrophobic part always consists of FarGE units, we do not observe large differences the investigated polymers and I_1/I_3 approaches a similar value ($I_1/I_3 \approx 1.2$) for both block and statistical copolymers.

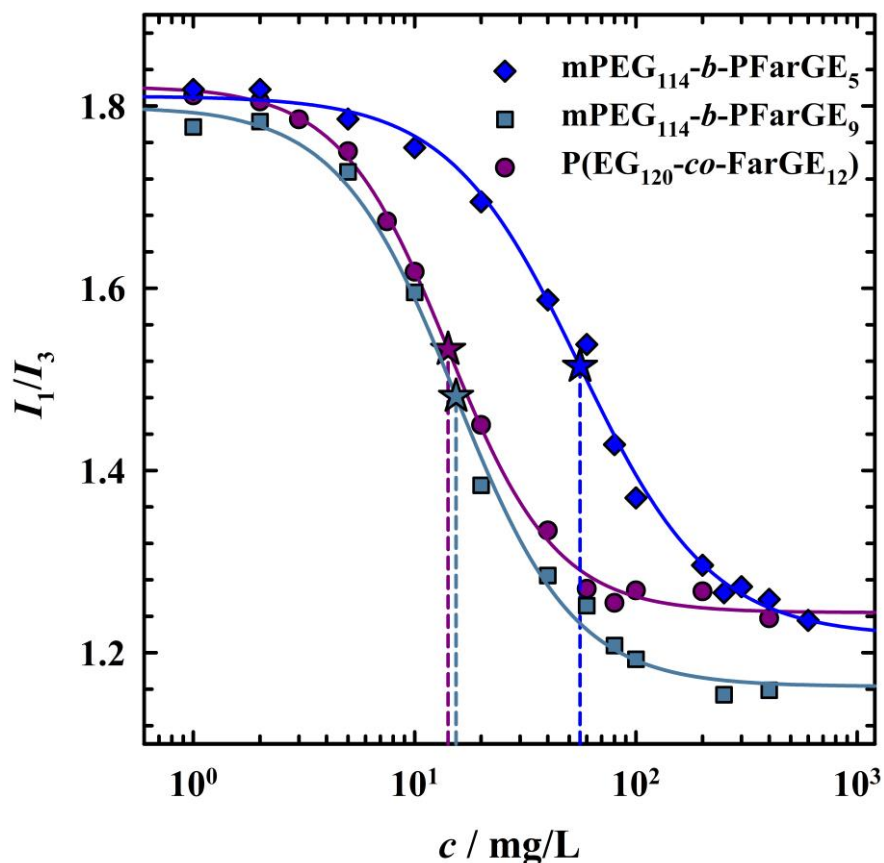
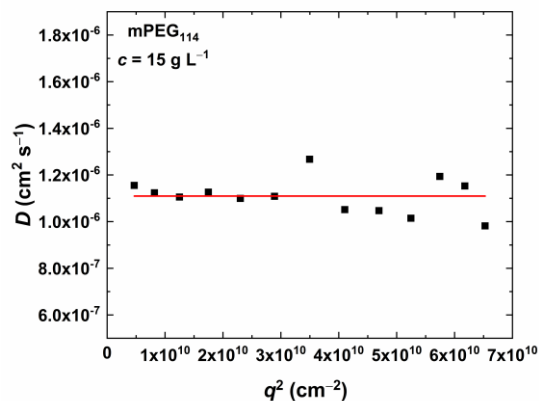
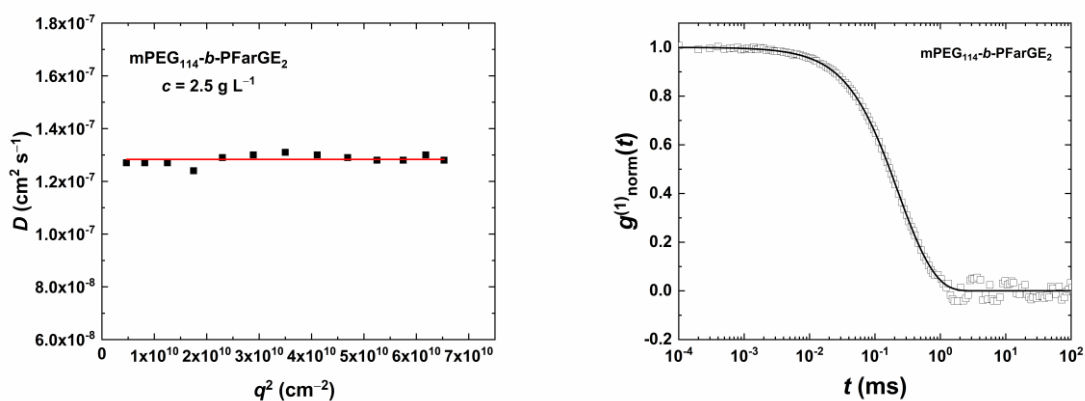
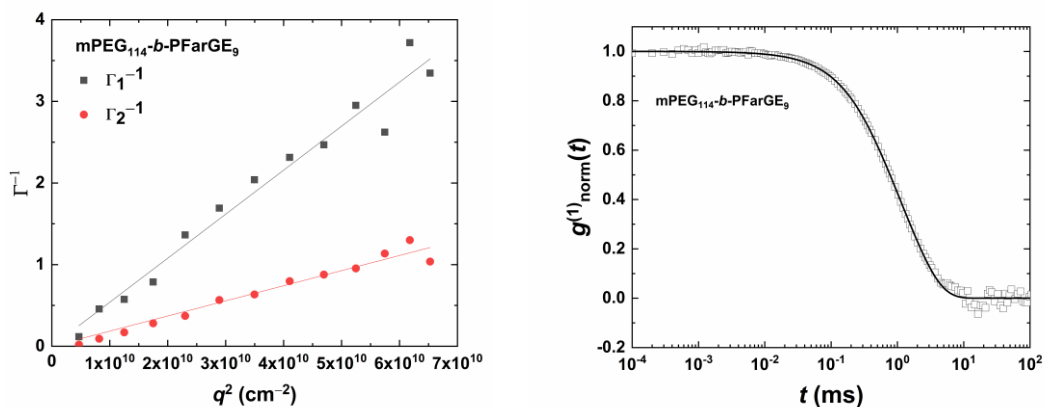


Figure S 52: Determination of the CMC via fluorescence spectroscopy. Comparison of plots of the pyrene intensity ratio I_1/I_3 ($c_{\text{pyrene}} = 7 \cdot 10^{-7}$ M) versus concentration, determined by fluorescence spectroscopy for the two block copolymers mPEG₁₁₄-*b*-PFarGE₅ (blue diamonds) and mPEG₁₁₄-*b*-PFarGE₉ (dark cyan squares) as well as the statistical P(EG₁₂₀-*co*-FarGE₁₂) (purple circles). CMCs are shown with stars, for which we obtain: CMC (mPEG₁₁₄-*b*-PFarGE₅) = 56 ± 4 mgL⁻¹; CMC (mPEG₁₁₄-*b*-PFarGE₉) = 15 ± 1 mgL⁻¹; CMC (P(EG₁₂₀-*co*-PFarGE₁₂)) = 14 ± 1 mgL⁻¹.

Dynamic Light Scattering

Figure S 53: Angle-independent apparent diffusion coefficients in H₂O for mPEG₁₁₄.Figure S 54: Angle-independent apparent diffusion coefficients in H₂O (left) and normalized autocorrelation function (right) for mPEG₁₁₄-b-PFarGE₂.Figure S 55: Inverse relaxation times vs. q^2 to evaluate the diffusion coefficients D for in H₂O (left) and normalized autocorrelation function (right) for mPEG₁₁₄-b-PFarGE₉.

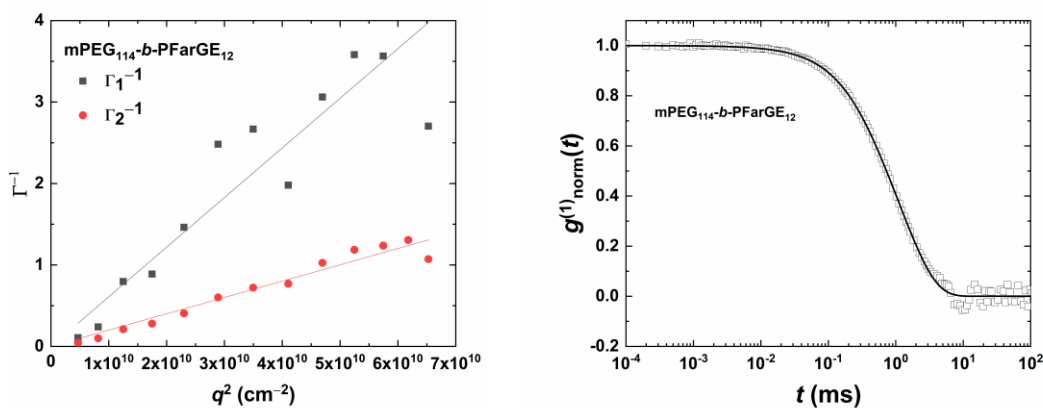


Figure S 56: Inverse relaxation times vs. q^2 to evaluate the diffusion coefficients D for in H₂O (left) and normalized autocorrelation function (right) for mPEG₁₁₄-b-PFarGE₁₂.

Transmission Electron Microscopy

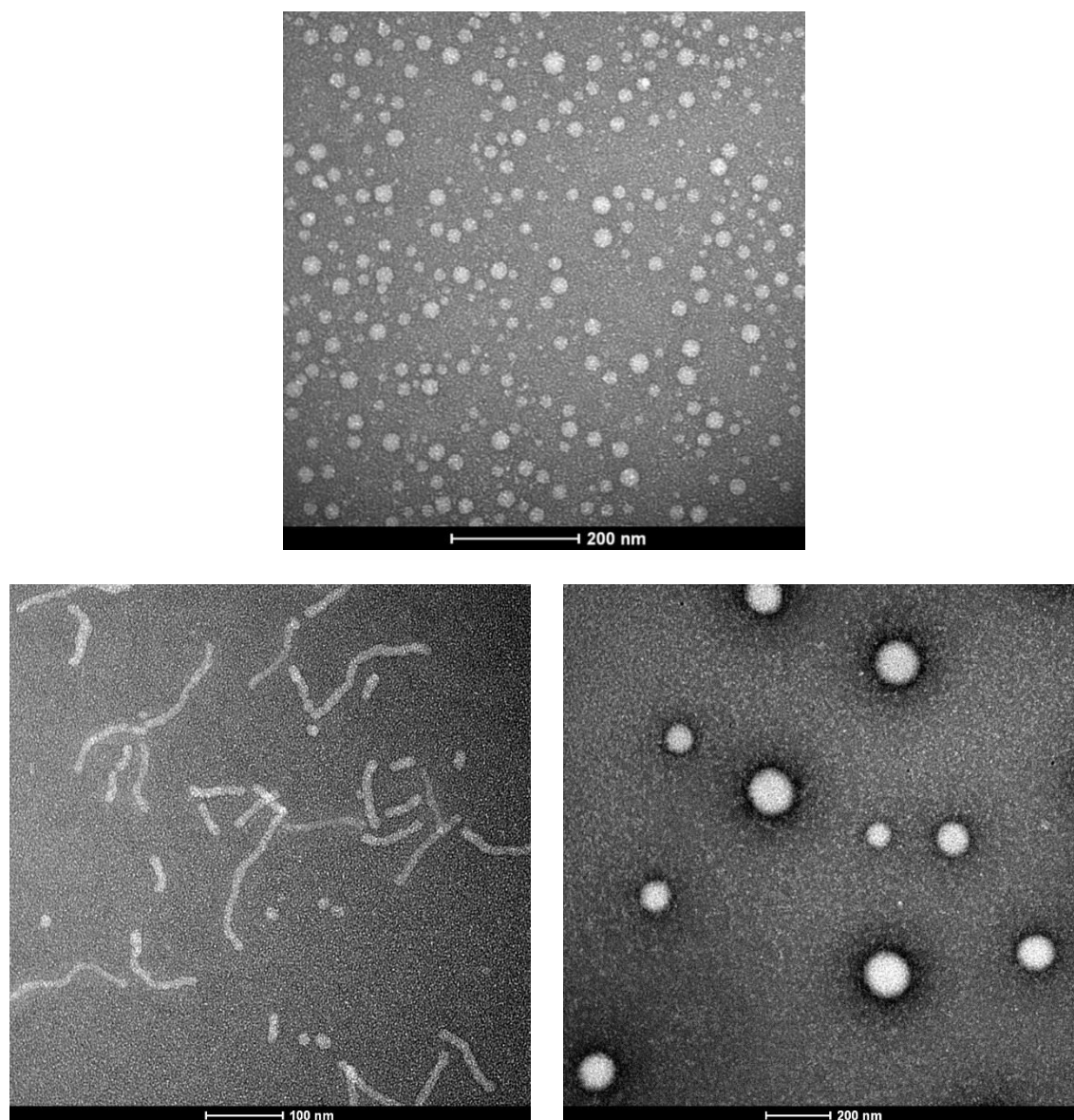


Figure S 57: TEM micrographs of mPEG₁₁₄-*b*-PFarGE_n diblock copolymers (top left: mPEG₁₁₄-*b*-PFarGE₂; bottom left: mPEG₁₁₄-*b*-PFarGE₉; bottom right: a statistical copolymer P(EG₁₂₀-*co*-FarGE₁₂) (bottom micrograph) in aqueous solution (0.1 g mL⁻¹). Negative staining was conducted with a 2 wt% uranyl acetate solution.

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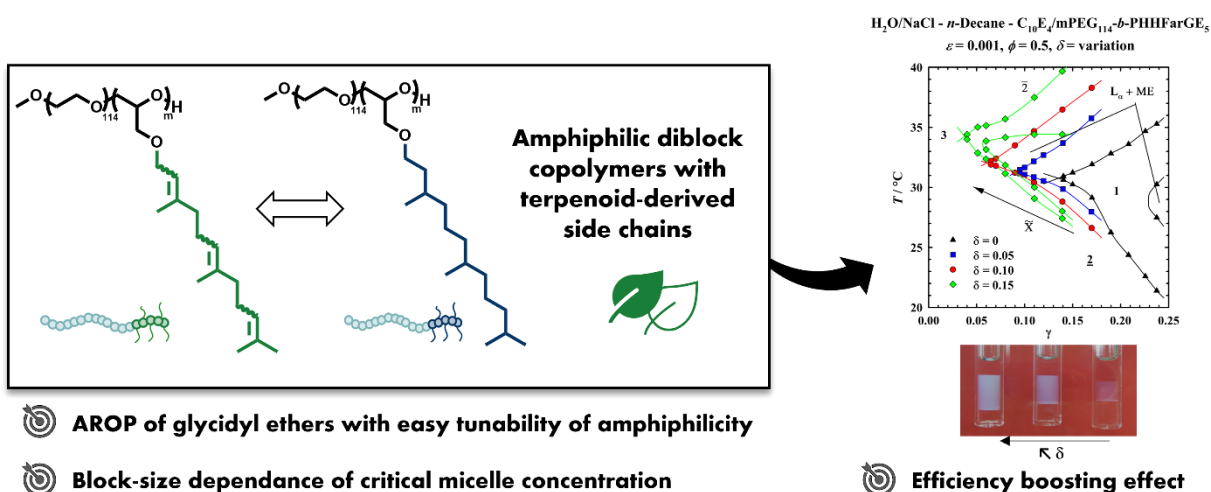
2.2 Amphiphilic, Bio-Based Farnesyl Glycidyl Ether Block Copolymers: Aqueous Self-Assembly and Solubilization Enhancement

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To be submitted.



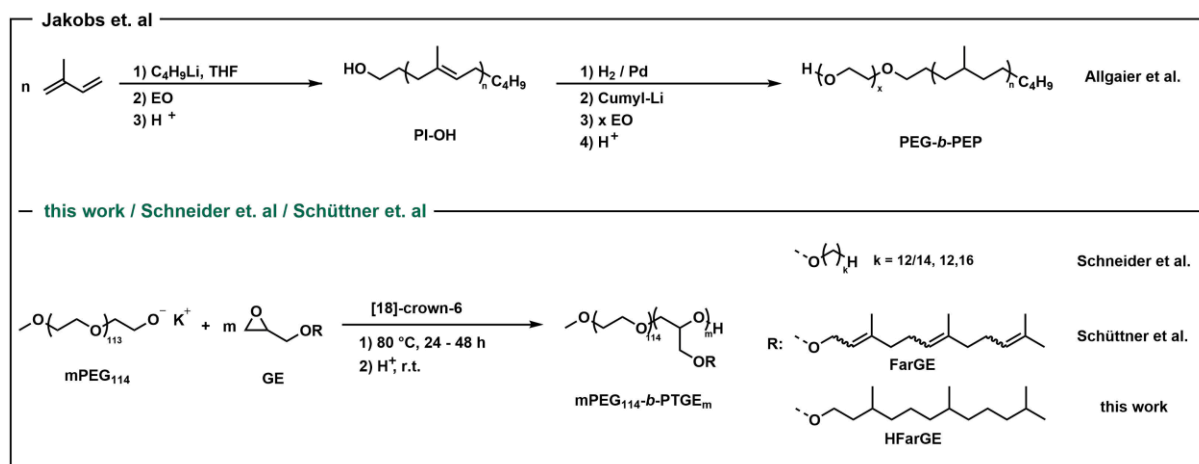
Abstract

Sustainability has become an essential driver for addressing the substitution of depleting fossil fuel resources with bio-renewable alternatives, including products that are active at surfaces and interfaces such as surfactants. Enhancing their solubilization performance has the additional potential to reduce the surfactant amount needed for a given application, thereby minimizing both ecological and economic impacts. Herein, we present the synthesis of amphiphilic polyether diblock copolymers of the type $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_m$ and $\text{mPEG}_{114}\text{-}b\text{-PHHFarGE}_m$. Anionic ring opening polymerization (AROP) of terpenyl glycidyl ethers (TGEs) starting from poly(ethylene glycol) monomethyl ether (mPEG_{114}) as a macroinitiator resulted in well-controlled molecular weights ($5590 - 8380 \text{ g}\cdot\text{mol}^{-1}$) with low dispersities $\bar{D}$ ($1.04 - 1.07$). The TGEs, namely farnesyl glycidyl ether (FarGE) and its novel, hydrogenated derivative hexahydrofarnesyl glycidyl ether (HHFarGE), are synthesized from farnesol, which is a terpenoid common in plants and essential oils. The adjustable hydrophobic block size allows for a fine-tuned amphiphilicity of the diblock copolymers, which was first studied with respect to their self-assembly in aqueous solution. The investigation of the critical micelle concentration (CMC) via fluorescence spectroscopy reveals low CMC values ($10 - 90 \text{ mg}\cdot\text{L}^{-1}$), highlighting the CMC decrease with larger TGE block size. Systematic studies on the influence of the diblock copolymers $\text{mPEG}_{114}\text{-}b\text{-P(HH)FarGE}_m$ as cosurfactants on the phase behavior of a model microemulsion reveal a significant efficiency boosting effect. The overall amount of amphiphile to fully solubilize equal amounts of water and *n*-decane into a thermodynamically stable microemulsion can be reduced by up to 73%, when replacing 15 wt% of C_{10}E_4 with polymer.

Introduction

Current predominant dependence on rapidly depleting fossil fuel resources and the awareness of our environmental footprint resets the focus towards a more sustainable design and application of polymeric materials.¹ Potential synthetic strategies involve the substitution of fossil-based monomers by those from bio-renewable feedstock.^{2,3} In this context, terpenes and their functional derivatives, so-called terpenoids, have emerged as highly versatile polymer building blocks.^{1,2,4,5} Their structural and functional variety enables the design and synthesis of polymers that are advanced materials, providing a vast field of polymer application ranging from pressure-sensitive adhesives to resins to thermoplastic elastomers.^{2,6-8} Not only are terpenes and terpenoids naturally occurring compounds in essential plant oils and fruits, but technological progress for microbial terpene production via biosynthesis is ongoing, thus increasing the availability and value of these building blocks.^{5,9,10}

Two acyclic terpenoids of interest, namely farnesol (3,7,11-Trimethyl-2,6,10-dodecatrien-1-ol) and its hydrogenated analogue hexahydrofarnesol (3,7,11-trimethyl-dodecan-1-ol, HHF), are characterized by their hydrophobic, branched C₁₅ chain.⁵ Industrially, farnesol can be sourced from the isomerization of the more abundant *trans*-nerolidol, whereas HHF is a byproduct of the microbial farnesane production, a sustainable aviation fuel.^{5,10,11} The hydrophobic nature renders the terpene-alcohols suitable for the synthesis of monomer building blocks for polymeric amphiphiles or a surfactant itself.¹² Aubry and coworkers reported on the coupling of HHF with sugars, valorizing an industrial byproduct into a fully bio-based sugar surfactant.¹³



Scheme 1: Comparison of synthetic strategies of various PEG-based diblock copolymers, which were investigated as cosurfactants in microemulsions.¹⁴⁻¹⁶

Since Hoar and Schulman's pioneering work in the 1940s¹⁷, microemulsions have gained significant research interest and have become indispensable for household,

biomedical and industrial applications.^{18,19} The concept that the solubilization efficiency of surfactants in microemulsion systems can be increased by adding small amounts of amphiphilic block copolymers (“efficiency boosting”), established a way to significantly reduce the amounts of surfactants needed to produce microemulsions.^{15,20,21} As reducing our environmental footprint includes surface and interfacially active components like surfactants, an enhanced solubilization performance enables the reduction of required surfactant amount, minimizing both ecological and economic impacts. While the poly(propylene)-*b*-poly(ethylene glycol) (PEP-*b*-PEG) polymers studied by Jakobs et al. in this context showed a strong efficiency increase, they are rather unsuitable for use on a larger scale due to a complex synthesis (Scheme 1).²⁰ Over the last two decades, several works have explored a variety of polymer structures to investigate the efficiency boosting effect.^{21–23} Examples include PEG-based di- and triblock copolymers with varying hydrophobic blocks as well as comb-like, Y-shaped and random copolymers.^{24–29} A follow-up work, Schneider et al. presented a simplified synthetic approach to a fully polyether-based surfactant, applying long-chain alkyl glycidyl ethers (AlkGE) for the hydrophobic block.¹⁵ Facile variation of the hydrophilic-to-hydrophobic ratio enabled a systematic study of the efficiency boosting, approximating a comparable boosting effect as for the PEP-*b*-PEG diblock copolymers.

Inspired by the growing interest in bio-based monomers and further expand the available “green” monomer toolkit, we investigated a new type of polyether-based copolymer surfactant comprising of the naturally occurring terpenoid farnesol.³⁰ The diblock copolymers of the type poly(ethylene oxide)-*b*-poly(farnesyl glycidyl ether) as well as their derivatives with a fully hydrogenated hydrophobic block, poly(ethylene glycol)-*b*-poly(hexahydrofarnesyl glycidyl ether)s, represent a novel group of amphiphilic block, whose bio-based nature and a simplified synthesis route (Scheme 1) could open new avenues of applications like in cosmetics.¹⁶ Fluorescence spectroscopy and light scattering measurements demonstrated the self-assembly of the polymers in water by determining the critical micelle formation concentrations. Subsequently, an increase in efficiency was observed for all diblock copolymers in the pseudo-ternary system water/NaCl – *n*-decane – C₁₀E₄. The greatest increase in efficiency was found for polymers of intermediate hydrophobic block size, suggesting that these polymers adsorb better at the water-oil interface in the surfactant film due to their size. The increase in hydrophobicity due to complete hydrogenation of the hydrophobic polymer block did not yield a significant difference in the efficiency boosting potential of the polymers. The measurements performed here provide a starting point for further investigation, in which these partially bio-based polymers will

be used to formulate sustainable and environmentally friendly microemulsion systems with sugar surfactants and glycerol-based oils.

Results and Discussion

Monomer Synthesis

The hydrophobic glycidyl ethers presented in this work, namely FarGE and its hydrogenated derivative HHFarGE, have been synthesized via literature-known aqueous phase transfer catalysis from epichlorohydrin (ECH) and the respective alcohols.^{16,31} It is important to note that ECH is available as a fully bio-sourced option via the Solvay's Epicerol™ process. In this context, glycerol, accrued as a byproduct in the biofuel production, is transformed into “green” ECH at a production scale of 100 kilotons per annum.^{32–34} While the synthesis as well as an in-depth characterization of FarGE have been previously published, HHFarGE represents a novel, fully saturated TGE with increased hydrophobicity and chain flexibility compared to FarGE.¹⁶ Considering the polarizable π bond in FarGE, a marginally higher hydrophobicity is anticipated for the hexahydrogenated derivative. The synthesis relies on a two-step sequence (Figure 1, top), starting from a commercially available stereoisomeric mixture of farnesol.

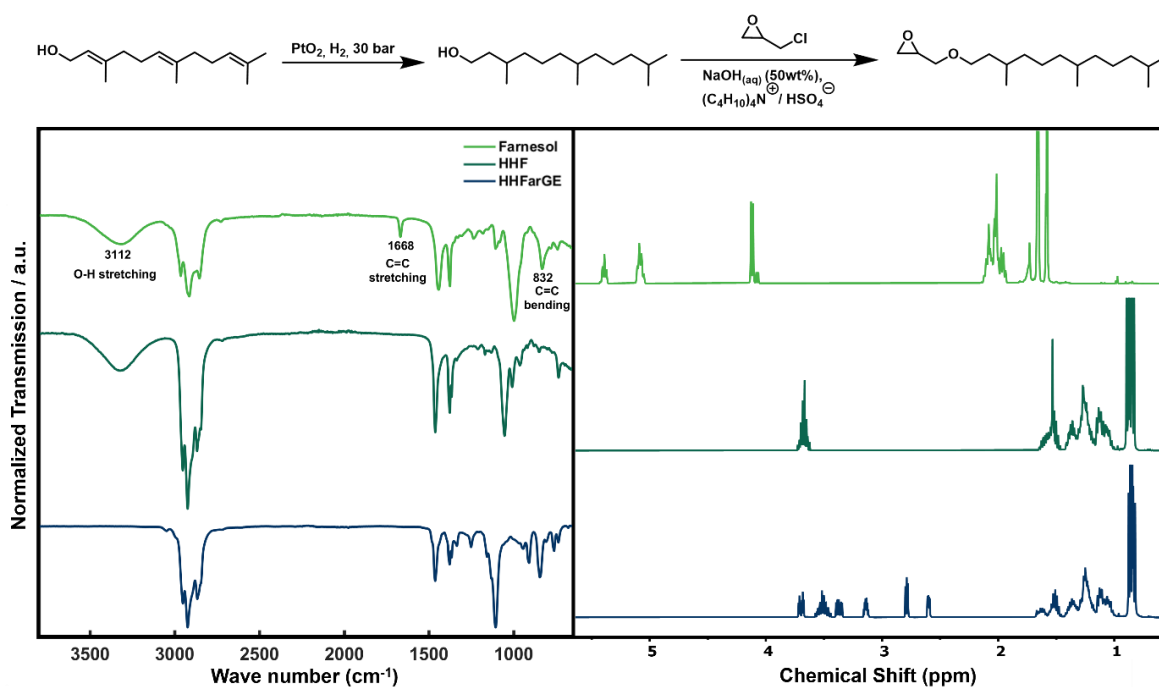


Figure 1: HHFarGE synthesis sequence starting from farnesol (top). FT-IR spectra (left) and ^1H NMR spectra (400 MHz, CDCl_3 , right) confirm the successful synthesis.

In the first step, a catalytic hydrogenation deploying platinum (IV)-oxide (PtO_2) transforms farnesol into HHF in quantitative yields ($> 90\%$) without elaborate purification. The hydrogen addition to the different farnesol stereoisomers produces a stereoisomeric HHF mixture as characterized by the doublets of carbon resonances in

^{13}C NMR analysis (Figure S 2).^{16,35,36} Secondly, the straightforward phase transfer catalysis requires two consecutive distillation steps to afford HHFarGE in high purity. The successful synthesis sequence is further attested by FT-IR and ^1H NMR spectra (Figure 1). Hydrogenation leads to the disappearance of the alkene signals of farnesol (5.41 - 5.05 ppm, right) as well as the associated C=C stretching and bending bands at 1668 and 832 cm^{-1} (left), respectively. The etherification with ECH during the second sequence step is demonstrated as the O-H stretching band (3112 cm^{-1}) disappears (left, bottom) and the epoxide functionality becomes visible between 3.20 and 2.52 ppm (right, bottom). Detailed NMR analyses of HHF and HHFarGE are displayed in Figures S 1 - S 10. An additional pretreatment of the TGEs with methyl iodide and NaH aims at the deactivation of potential protic impurities and serves as an additional drying process (Scheme S 2).

Synthesis and Characterization of mPEG₁₁₄-*b*-PHHFarGE_m and mPEG₁₁₄-*b*-PFarGE_m Diblock Copolymers

A key objective of this work is to investigate and compare the two types of polymeric amphiphiles regarding their self-assembly in aqueous solution with respect to their hydrophilic-lipophilic balance (HLB) as well as their efficiency boosting effect in microemulsion systems. According to literature, the amphiphilicity has a significant impact on the strength of the boosting effect.³⁷ Hence, relying on the crown ether-assisted AROP in bulk, we synthesized two series of diblock copolymers starting from commercial poly(ethylene glycol) monomethyl ether (mPEG₁₁₄) with varying TGE feed ratio.^{15,38} Maintaining the size of the hydrophilic block, the degree of polymerization (P_n) of the hydro-phobic block represents a switch to tailor the amphiphilicity and the respective diblock copolymer properties. Table 1 gives an extensive overview of the well-controlled polymerization results as well as the thermal characterization. The number-averaged molecular weights of the synthesized amphiphilic diblock copolymer range from 5800 to 6900 gmol^{-1} , as determined via ^1H NMR spectroscopy. Characterization is in line with the targeted value. However, the P_n is slightly lower (approximately one TGE unit (m)) than targeted for monomer batches not treated with methyl iodide (MeI) and sodium hydride (NaH) prior to polymerization. We have previously reported on the deactivation of residual protic impurities in the epoxide, which otherwise leads to homopolymer formation and a lower P_n .¹⁶ For the mPEG₁₁₄-*b*-PHHFarGE_m block copolymers, a viscosity increase with incremental P_n has been observed. To ensure sufficient stirring, the temperature was raised to 120 °C.

Surprisingly, this did not promote the occurrence of the well-known chain transfer reaction.³⁹ We tentatively ascribe this to the highly hydrophobic and sterically demanding character of the monomer, hindering or slowing down the nucleophilic attack in α -position to the epoxide ring.³⁸ Accordingly, DOSY analysis shows a single diffusion coefficient for the pure diblock copolymer, verifying the absence of PTGE homopolymer (Figure S 16).

Table 1: Characterization data for the series of amphiphilic mPEG₁₁₄-*b*-PTGE_m diblock copolymers with respect to molecular weights, dispersity and thermal properties.¹⁶

Entry	Sample	$M_n^a /$ g·mol ⁻¹	$M_n^b /$ g·mol ⁻¹	$\bar{D}^b$	$T_g^c /$ °C	$T_m^c /$ °C	$\Delta H_m^c /$ J·g ⁻¹
1	mPEG ₁₁₄	5040	5000	1.04	n.d.	61	217
2 ^d	mPEG ₁₁₄ - <i>b</i> -PFarGE ₂	5590	5800	1.07	-	59	147
3 ^d	mPEG ₁₁₄ - <i>b</i> -PFarGE ₅	6430	6300	1.04	-71	56	139
4	mPEG ₁₁₄ - <i>b</i> -PFarGE ₆	6710	6700	1.05	-70	55	99
5 ^d	mPEG ₁₁₄ - <i>b</i> -PFarGE ₇	6990	7000	1.05	-72	54	93
6	mPEG ₁₁₄ - <i>b</i> -PFarGE ₉	7540	7100	1.05	-71	56	88
7 ^d	mPEG ₁₁₄ - <i>b</i> -PFarGE ₁₂	8380	7800	1.04	-73	54	81
8	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₃	5890	5900	1.04	-	57	169
9	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₅	6460	6200	1.05	-67	57	115
10 ^d	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₆	6740	6400	1.05	-65	57	113
11	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₇	7030	6500	1.05	-70	56	104
12	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₈	7310	6600	1.06	-71	56	102
13 ^d	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₁₀	7880	6900	1.05	-71	55	98

^aNumber-averaged molecular weight determined via ¹H NMR spectroscopy. ^bDetermined via SEC measurements using DMF as eluent and PEG as standard. ^cGlass transition temperature, melting temperature and melting enthalpy determined by DSC at a heating rate of 10 °C/min. Errors are estimated as ± 2 °C. ^dMonomer batch without treatment with MeI was applied.

The well-controlled nature of the AROP is demonstrated by the monomodal molecular weight distributions with low dispersities $\bar{D}$ (1.04 – 1.07) (Figure 2 and Figure S 24).⁴⁰ Furthermore, the variation in TGE block size is illustrated by a continuous shift of the SEC elugrams toward lower elution volumes (higher molecular weights) compared to the mPEG₁₁₄ macroinitiator when the PTGE block size increases. The M_n s determined via NMR and SEC show a systematical discrepancy with increasing incorporation of TGE units, commonly known for multifunctional PEG.⁴¹ This is attributed to a decrease in

hydrodynamic radii of the block copolymers DMF due to the presence of the hydrophobic side chain and polarity difference in comparison to the PEG calibration. Moreover, as the chain collapse is more pronounced for the more hydrophobic mPEG₁₁₄-*b*-PHHFarGE_m, the corresponding homopolymers PHHFarGE_m are not soluble in DMF, and thus SEC characterization in THF as an eluent was carried out (Figure S 22). Two homopolymers of each block type, PHHFarGE_m and PFarGE_m, were prepared in analogy to a medium and large size block (Table S 1, Figures S 22 and S 23). Representative in-depth NMR analyses for mPEG₁₁₄-*b*-PHHFarGE_m and PHHFarGE_m are provided in the Supporting Information, Figures S 11 – S 15 and Figure S 17 – S21, respectively.

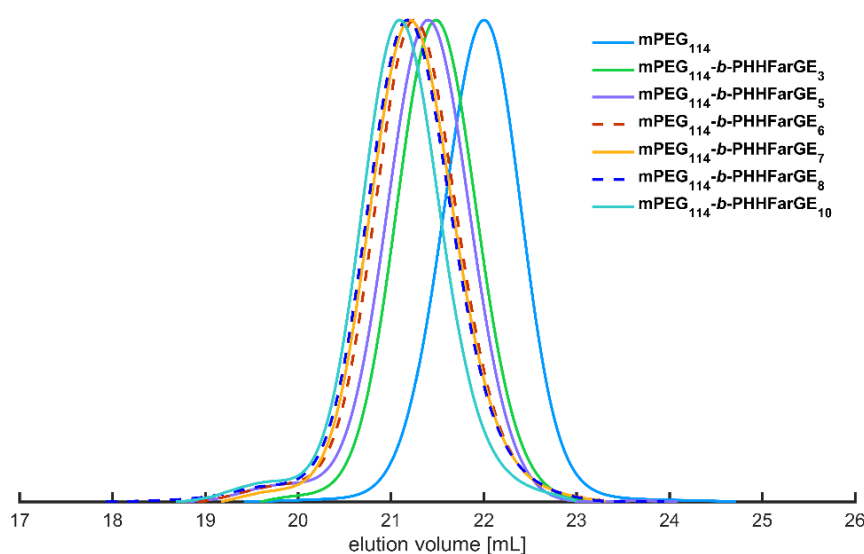


Figure 2: SEC elution traces of selected mPEG₁₁₄-*b*-PHHFarGE_m diblock copolymers compared to the mPEG₁₁₄ macroinitiator (RI detector, eluent: DMF, calibration: PEG standard).

Differential scanning calorimetry (DSC) measurements of both the diblock copolymers and homopolymers were carried out to evaluate the thermal properties. All diblock copolymers feature a distinct single melting endotherm with a melting temperature (T_m) ranging between 54 and 59 °C (Figures S 25 – S 27). Compellingly, the absence of a second melting endotherm indicates that the branching within the side chain structure impedes its crystallization.^{16,38} The marginal decrease of the T_m compared to the crystalline mPEG₁₁₄ macroinitiator (Table 1, entry 1) reflects the block copolymer architecture, indicating nano-segregated domains due to block incompatibility and mPEG crystallization. For mPEG₁₁₄-*b*-PFarGE_m and mPEG₁₁₄-*b*-P(HH)FarGE_m the glass transition temperature (T_g) values vary between -70 and -73 °C and -65 to -71 °C, respectively.¹⁶ The results are in line with the determined T_g s of the amorphous, low- P_n homopolymers (Table S 1, Figure S 28). Equally, the detection of a single T_g for the PTGE

block further suggests nano-segregated blocks driven by the strong PEG crystallization, resulting in the absence of the T_g of the PEG block.¹⁶

Investigation of Micellization – Determination of CMCs

To eventually enable the use of the novel poly(ethylene glycol)-*b*-poly(terpenyl glycidyl ether) copolymers as efficiency boosters in microemulsions or as additives in other fields, their amphiphilic properties were first studied in aqueous solution. Similar to conventional surfactants, amphiphilic diblock copolymers are characterized by their self-assembly in water.^{42,43} A variety of ordered morphologies can be formed when exceeding a certain amphiphile concentration.^{43,44} Due to the block incompatibility of the PTGE and PEG blocks, a core-shell structure is expected for the PEG₁₁₄-*b*-P(HH)FarGE_m diblock copolymers, which in turn, can transform into rod-like micelles for longer block sizes and higher polymer concentrations in solution.^{14,16} While surfactants are typically discussed via their critical micelle concentrations (CMC), it should be noted that a spherical structure (which is what is commonly understood when micelles are in scope) might be debatable in the case of larger polymeric aggregates, which are more sterically demanding and could potentially lead to non-spherical structures. We have recently shown that dynamic light scattering experiments of mPEG₁₁₄-*b*-PFarGE_m copolymers performed well above the CMC reveal monomodal micelles for lower degrees of polymerization (i.e., few FarGE units), while heterogeneous aggregate sizes were found for the more hydrophobic counterparts.¹⁶ However, given that more in-depth investigations into shape and structure were not available and to further stay in line with the well-established notation widely used in literature for other conventional and polymeric amphiphiles, we will refrain from introducing a more general description such as “critical aggregation concentration” and instead stay with the commonly used CMC concept.

As polymeric CMCs are expected to be considerably lower than those of conventional surfactants, we used fluorescence spectroscopy as a highly sensitive method to study the micellization behavior of the mPEG₁₁₄-*b*-P(HH)FarGE_m amphiphiles.^{45,46} The hydrophobic nature of TGE side chains renders the diblock copolymers suitable to solubilize pyrene as a fluorescent in the hydrophobic micellar core, taking advantage of the sensitivity of the pyrene emission spectrum to the polarity of its microenvironment.^{47,48} In addition, selected samples were compared with data obtained from previous light scattering results, allowing for the verification of the results from both methods.¹⁶ Table 2 contains the determined CMCs of the diblock copolymers in relation to the molecular weight and the HLB, which is defined by ratio of the molecular

weight of the P(HH)FarGE_m and PEG segments.⁴⁴ Both series of diblock copolymers show a decrease in CMC with an increasing hydrophobic block size, ranging from 90 to 14 mgL⁻¹ (FS). Figure 3 exemplifies both approaches of CMC determination for mPEG₁₁₄-*b*-PHHFarGE₅. On one hand, plotting the concentration-dependent excess Rayleigh ratio (R_{v}) obtained from SLS against the polymer concentration in aqueous solution reveals a change in the scattering signal upon exceeding the CMC (left). DLS measurements for concentrations above the CMC show high-quality autocorrelation functions (middle top), allowing for a reliable determination of R_h , whereas concentrations below the CMC are marked by a noisy signal (middle, bottom). On the other hand, the fluorescence spectroscopy relies on the concentration-dependent solubilization of pyrene within the micellar core, which ultimately leads to a change of the intensity ratio I_1/I_3 of the maximum of the first and third pyrene vibronic bands.^{47,49}

Table 2: Critical micelle concentrations (CMCs) of amphiphilic, terpenoid-derived mPEG₁₁₄-*b*-PHHFarGE_m and mPEG₁₁₄-*b*-PFarGE_m diblock copolymers in water at $T = 23 \pm 1$ °C, obtained via static light scattering and fluorescence spectroscopy.

Entry	Sample	$M_n^a / \text{g} \cdot \text{mol}^{-1}$	$M_{n, \text{TGE block}}^a / \text{g} \cdot \text{mol}^{-1}$	HLB ^b	CMC _{FS} ^c / mgL ⁻¹	CMC _{LS} ^d / mgL ⁻¹
1	mPEG ₁₁₄ - <i>b</i> -PFarGE ₂	5590	560	18.0	90 ± 5	-
2	mPEG ₁₁₄ - <i>b</i> -PFarGE ₅	6430	1250	16.1	53 ± 4	44 ± 7
3	mPEG ₁₁₄ - <i>b</i> -PFarGE ₆	6710	1670	15.0	25 ± 2	-
4	mPEG ₁₁₄ - <i>b</i> -PFarGE ₇	6990	1950	14.4	21 ± 1	-
5	mPEG ₁₁₄ - <i>b</i> -PFarGE ₉	7540	2500	13.4	15 ± 1	16 ± 4
6	mPEG ₁₁₄ - <i>b</i> -PFarGE ₁₂	8380	3340	12.0	14 ± 1	-
7	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₃	5890	860	17.1	56 ± 3	-
8	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₅	6460	1420	15.6	28 ± 2	24 ± 5
9	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₆	6740	1710	14.9	24 ± 1	-
10	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₇	7030	1990	14.3	22 ± 1	-
11	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₈	7310	2280	13.7	18 ± 1	-
12	mPEG ₁₁₄ - <i>b</i> -PHHFarGE ₁₀	7880	2850	12.7	14 ± 1	-

^aNumber-averaged molecular weight of diblock copolymers and FarGE block determined via ¹H NMR spectroscopy. ^bHydrophilic-lipophilic balance calculated according to Griffin: $\text{HLB} = 20 (1 - M_{\text{lipophilic}} / M_{\text{lipophilic+hydrophilic}}) = 20 (1 - M_{n, \text{TGE block}} / M_n)$.⁴⁴

^cCMC determined via fluorescence spectroscopy. ^dCMC determined via static light scattering.¹⁶

The inflection point of the sigmoidal trend marks the CMC with a red star (Figure 3, right, Figures S 30 and S 31). Overall, both determination methods are consistent within

the associated errors of the chosen approaches (FS: 28 ± 2 mgL⁻¹ vs. LS: 24 ± 5 mgL⁻¹). Figure 4 and Figure S 29 show an overlay of the intensity I_1/I_3 plots for the mPEG₁₁₄-*b*-PHHFarGE_m polymer series and visualize the shift of the CMC fitting curves towards lower CMCs with increasing block size. Additionally, the approximation of all curves towards a maximum (≈ 1.8) and a minimal (≈ 1.2) threshold is documented, validating the systematic applicability of the method (see SI for more details).

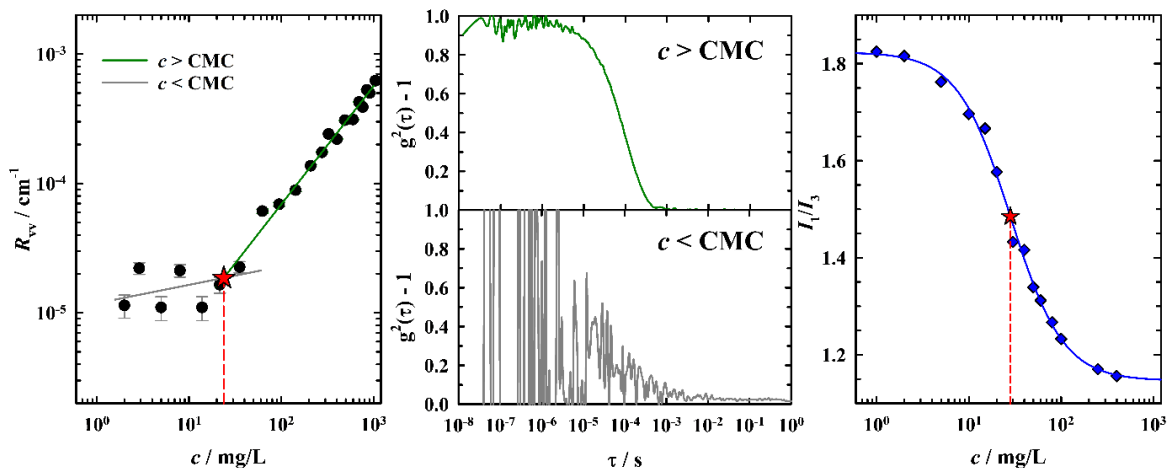


Figure 3: Concentration-dependent micellization of the terpenoid-based polyether mPEG₁₁₄-*b*-PHHFarGE₅ in water, studied by light scattering and fluorescence spectroscopy measurements at $T = 23 \pm 1$ °C. The CMC is denoted with a red star. Left: Excess Rayleigh ratio R_{vv} determined via SLS vs. PEG₁₁₄-*b*-PHHFarGE₅ concentration c , recorded at $\theta = 90^\circ$. Right: Pyrene I_1/I_3 ratio determined via fluorescence spectroscopy vs. polymer concentration c . Middle: Selected DLS correlation functions $g^2(\tau) - 1$ vs. lag time τ for concentrations above (top, green) and below (bottom, gray) the CMC.⁵⁰

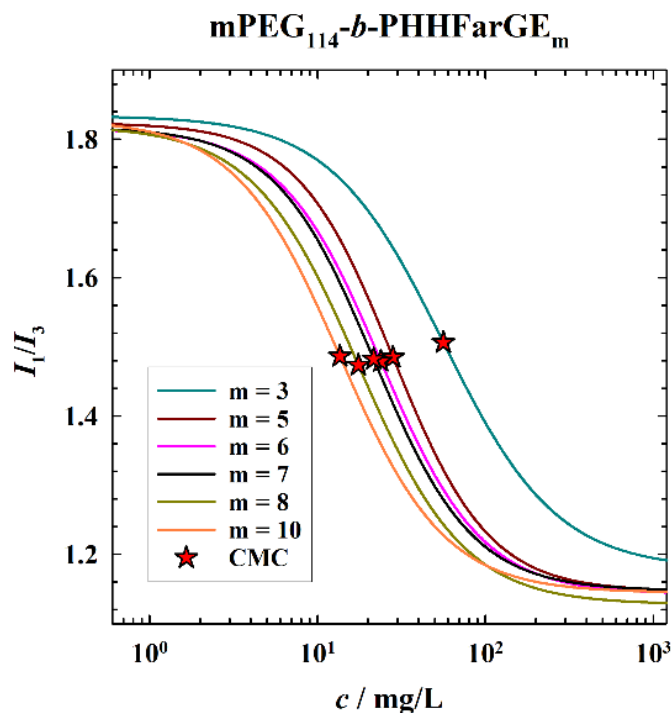


Figure 4: Overlay of intensity ratio I_1/I_3 plots versus diblock copolymer concentration for the mPEG₁₁₄-*b*-PHHFarGE_m diblock copolymer series, visualizing the anticipated shift to lower CMC values with increasing HHFarGE block size.⁵⁰ CMCs are depicted with stars. To maintain clarity, only the fitting curves are depicted without the respective data points, detailed fits are given in the Supporting Information.

The dependence of the CMC on the number of TGE units m , translating to the P_n of the hydrophobic block, is further explored for the two TGE types in Figure 5. Plotting the CMC against m of the FarGE and HHFarGE block, respectively, emphasizes that an increasing hydrophobicity results in a strong reduction of the CMC. Available data for polymeric systems in the literature suggests there is a strong dependence of the CMC on P_n of the hydrophobic block, therefore the number of hydrophobic TGE representing the primary influence in the micellization process.^{51,52} A net increase in hydrophobicity favors micellization and lowers the CMC. The observed decrease follows a power-law decay.^{40,53} Literature commonly reports an exponential decrease with the length of hydrophobic group (for low m), but in this case a power-law fit is more suitable to the experimental data (Figure 5). Yet, the deviating fit could be caused due to experimental errors of the measurement for low m .^{42,51} Similar observations have been made with conventional surfactants, where an increase in the alkyl chain length leads to a lower CMC.^{54–57}

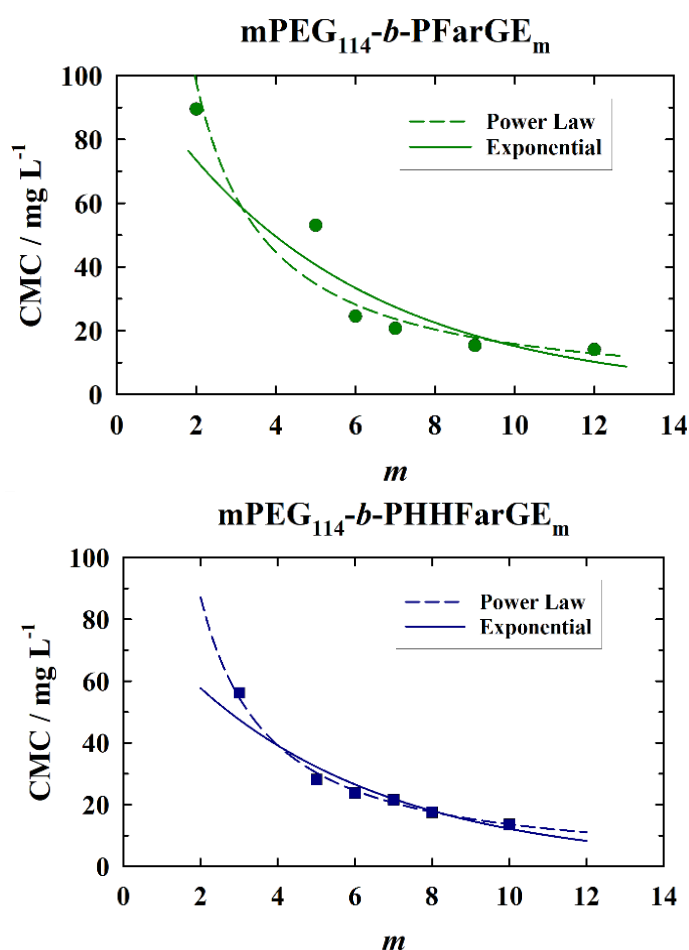


Figure 5: CMC, determined via fluorescence spectroscopy, as a function of hydrophobic block length m for mPEG₁₁₄-b-PFarGE_m (left) and mPEG₁₁₄-b-PHHFarGE_m (right). The hydrophilic block remained at a constant block length. Dashed lines serve primarily as guide to the eye, but also mirrors a power law fit.⁵⁰

Irrespective of the amphiphile, this can be explained on the basis of the hydrophobic effect, since the increasing size of the hydrophobic part of the molecule leads to a lower miscibility with water, which is why self-assembly into micelles occurs at lower concentrations.^{53,58} The differences between the two polymer types are small, indicating that hydrogenation of the farnesyl chain does not yield significantly different behavior of the polymers in aqueous solution. Furthermore, CMC values are in line with previously reported results of PEG-based diblock copolymers, for which the CMC generally resides in a lower range when a more hydrophobic block is applied.^{41,46,59,60} Overall, the data corroborates the highly amphiphilic character of the diblock copolymers while the potential ability to incorporate a hydrophobic compound for drug-delivery systems is demonstrated.⁵²

Efficiency Boosting in Microemulsion

Having observed the micellization of PEG-P(HH)FarGE polymers in aqueous solutions, self-aggregation of the polymers in ternary water – oil – non-ionic surfactant microemulsion systems was investigated. One-phase bicontinuous microemulsions can be formed if there is a sufficiently high amount of surfactant to completely solubilize water and oil. As demonstrated by Jakobs et al.,²⁰ the solubilization capacity of surfactants can be enhanced by adding suitable amphiphilic polymers as co-surfactants. Known as the “efficiency boosting effect”, this can be attributed to the adsorption of amphiphilic copolymers into the surfactant membrane, from where they extend in a mushroom-like conformation into the oil and water sub-phase, respectively.²¹ This effect is shown in Figure 6 for a system consisting of brine, *n*-decane and tetraethylene glycol monodecyl ether (C₁₀E₄), to which different amounts of mPEG₁₁₄-*b*-PFarGE₅ were added while maintaining a constant amphiphile concentration in the sample. Impressively, the microemulsion phase grows from left to right by increasing the proportion of amphiphilic block copolymers, indicating a strong efficiency increase. This effect was subsequently further investigated quantitatively with various polymers and different amphiphile concentrations.

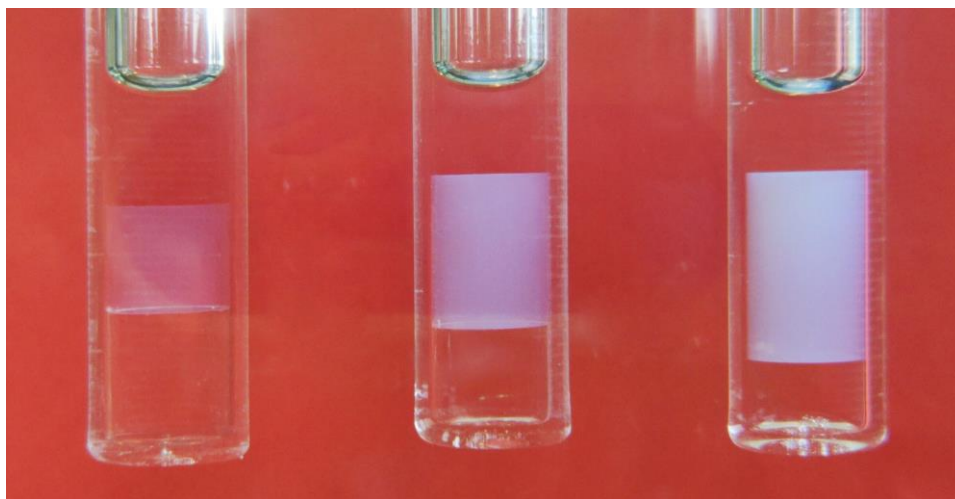


Figure 6: Efficiency boosting effect by the addition of mPEG₁₁₄-*b*-PFarGE₅ to the system H₂O/NaCl – *n*-decane – C₁₀E₄, shown at different polymer concentrations δ . Oil-water-ratio ($\phi = 0.5$) and amphiphile mass fraction ($\gamma = 0.05$) are constant. Temperature $T = 32$ °C, close to the phase inversion temperature of the polymer-free system. Left: $\delta = 0.00$. Middle: $\delta = 0.03$. Right: $\delta = 0.06$. With increasing δ , the microemulsion phase grows while oil and water excess phases shrink. Samples appear more turbid because of larger water/oil domain sizes, which result in an increased scattering.⁵⁰

To determine the viability of mPEG-*b*-P(HH)FarGE block copolymers as co-surfactants and efficiency boosters, various fish cuts were measured. Samples were initially prepared at high amphiphile concentrations γ and subsequently diluted until close to the optimum point $\tilde{X}$ (also called “X point” or “fish tail point”), characterized by $\tilde{T}$ and $\tilde{\gamma}$, which denotes the minimum amphiphile concentration required to form a one-phase microemulsion. A low $\tilde{\gamma}$ therefore indicates a high efficiency. The polymer-free system H₂O/NaCl – *n*-decane – C₁₀E₄ was measured as reference. Results for the mPEG-*b*-P(HH)FarGE_m copolymers are shown in Figure 7, with the black triangles being the reference system, which was found to be in very good agreement with literature data.²⁰ The observed phase behavior is typical for non-ionic surfactant systems.⁶¹ At low temperatures, an oil-in-water microemulsion co-exists with an oil excess phase, denoted as $\underline{2}$. When temperature is raised and $\gamma > \tilde{\gamma}$, a one-phase microemulsion (1) can be obtained. If the surfactant concentration is not high enough to fully solubilize water and oil ($\gamma < \tilde{\gamma}$), a three-phase region (3) is instead observed. Increasing the temperature decreases the mutual solubility of surfactant and water, eventually resulting in a water excess phase that co-exists with a water-in-oil microemulsion, denoted as $\overline{2}$. At very high surfactant concentrations, a two-phasic co-existence of lamellar and microemulsion phase is embedded in the one-phase region.

$\text{H}_2\text{O}/\text{NaCl} - n\text{-Decane} - \text{C}_{10}\text{E}_4/\text{mPEG}_{114}\text{-}b\text{-PFarGE}_m$ $\text{H}_2\text{O}/\text{NaCl} - n\text{-Decane} - \text{C}_{10}\text{E}_4/\text{mPEG}_{114}\text{-}b\text{-PHHFarGE}_m$
 $\varepsilon = 0.001, \phi = 0.5, \delta = 0.05$

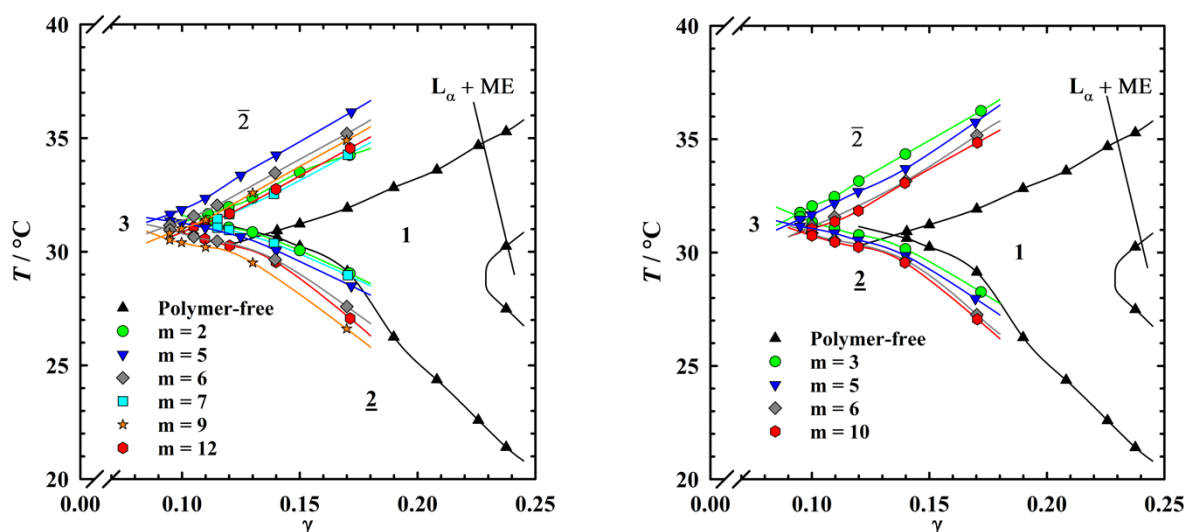


Figure 7: $T(\gamma)$ diagrams of the system $\text{H}_2\text{O}/\text{NaCl} - n\text{-decane} - \text{C}_{10}\text{E}_4 / \text{mPEG}_{114}\text{-}b\text{-P(HH)FarGE}_m$, recorded with 5 wt.% of polymer in the amphiphile mixture ($\delta = 0.05$). Both FarGE and HHFarGE polymers result in a marked efficiency boosting effect.⁵⁰

It is visible from Figure 7 that the addition of $\text{mPEG-}b\text{-P(HH)FarGE}$ results in a significant efficiency increase, corresponding to a decreasing value of $\tilde{\gamma}$. The above-mentioned temperature-dependent phase sequence $\underline{2} \rightarrow 1/3 \rightarrow \bar{2}$ was observed irrespective of the polymer. Similar boosting strengths are found for the FarGE and HHFarGE polymers; upon replacement of 5 wt% C_{10}E_4 with $\text{mPEG-}b\text{-P(HH)FarGE}$, $\tilde{\gamma}$ shifts from 0.135 in the polymer-free system to approximately $\tilde{\gamma} \approx 0.085\text{-}0.100$ for the polymer-containing systems. This is comparable to the boosting effect of $\text{PEG-}b\text{-PAlkGE}$ block copolymers¹⁵ but somewhat less pronounced than for the $\text{PEG-}b\text{-PEP}$ polymers²⁰. The optimum temperature ($\tilde{T}$) is only marginally affected by the addition of polymer, showing deviations of less than 1 K. From studies of conventional non-ionic surfactants, it is well-known that an increase in hydrophobicity results in an efficiency gain and a strong shift towards lower temperatures.⁶² In accordance, a closer look at the temperature effect of the $\text{mPEG-}b\text{-P(HH)FarGE}$ s shows that polymers with shorter hydrophobic blocks produce a somewhat stronger shift towards higher temperatures. Regarding their influence on efficiency however, the copolymers with a medium size of the hydrophobic block result in the largest gain in solubilization performance. This might be attributed to unfavorable sterics of the (HH)FarGE blocks, which may at a certain block size become too large to be ideally incorporated into the existing interfacial polymer/surfactant layer between water and oil. Comparison of Figure 7 left and right shows that the complete hydrogenation of the farnesyl chain does not have any noticeable impact on the solubilization capacity of the surfactants, since the

obtained efficiency gain upon the addition of HHFarGE is similar to that of the FarGE copolymers.

$\text{H}_2\text{O}/\text{NaCl} - n\text{-Decane} - \text{C}_{10}\text{E}_4/\text{mPEG}_{114}\text{-}b\text{-PFarGE}_5$ $\text{H}_2\text{O}/\text{NaCl} - n\text{-Decane} - \text{C}_{10}\text{E}_4/\text{mPEG}_{114}\text{-}b\text{-PHHFarGE}_5$
 $\varepsilon = 0.001, \phi = 0.5, \delta = \text{variation}$

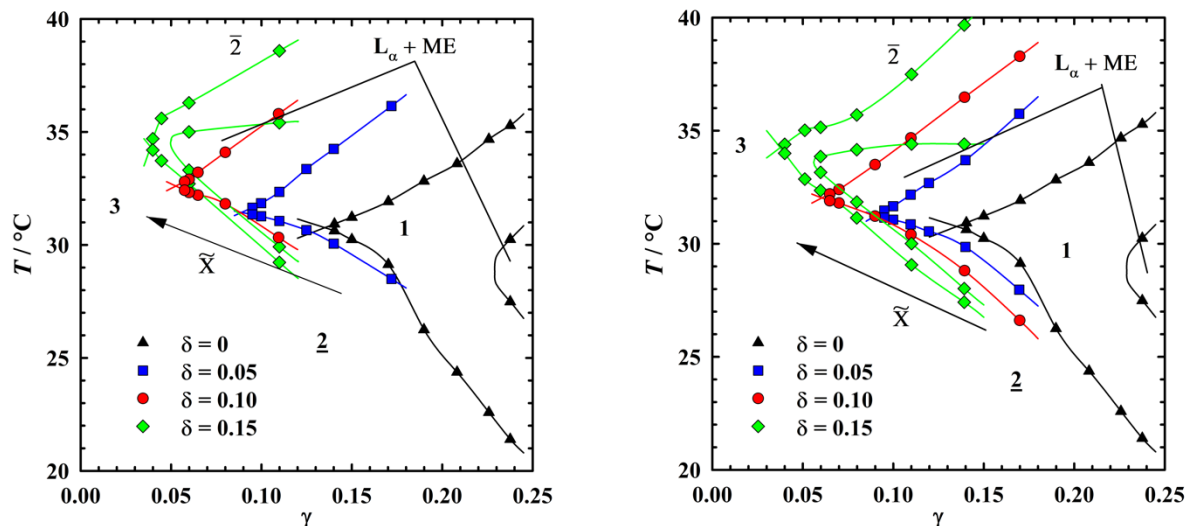


Figure 8: $T(\gamma)$ diagrams of the system $\text{H}_2\text{O}/\text{NaCl} - n\text{-decane} - \text{C}_{10}\text{E}_4 / \text{mPEG}_{114}\text{-}b\text{-P(HH)FarGE}_m$, recorded with varying amounts of polymer in the amphiphile mixture (δ). The boosting effect continues for both FarGE and HHFarGE polymers.⁵⁰

After proving the boosting potential of the amphiphilic $\text{mPEG}_{114}\text{-}b\text{-P(HH)FarGE}_m$ block copolymers, two of the most efficient polymers, $\text{mPEG}_{114}\text{-}b\text{-PFarGE}_5$ and $\text{mPEG}_{114}\text{-}b\text{-PHHFarGE}_5$, were selected to investigate the efficiency change at higher polymer concentrations δ . Fish cuts for the respective systems are shown in Figure 8. As observed for $\delta = 0.05$, the two polymer types only show marginal differences regarding their phase behavior. By gradually increasing the polymer content, the amphiphile amount needed for complete solubilization could be reduced to $\tilde{\gamma} \approx 0.037$ at $\delta = 0.15$. This also results in an increase of the water/oil domain sizes in the bicontinuous microemulsion, which would be possible to quantify via small-angle (neutron) scattering. Such large domain sizes result in pronounced scattering, which explains why the samples shown in Figure 6 appear increasingly milky when moving to higher polymer concentrations. While initial polymer addition suppresses the formation of liquid-crystalline phases, the highest polymer concentration shows a pronounced coexistence of lamellar phase and microemulsion up to low γ , which has also been observed in other studies.^{15,20} The appearance of such mesophases has been found to correlate with the molecular weight of the polymers.⁶³ With regard to temperature, the phase inversion temperature $\tilde{T}$ is about 2 K higher than for the polymer-free sample. A strong efficiency and moderate temperature increase was also observed by Jakobs for a

mPEG₅-*b*-PEP₅ polymer²⁰ (note that the index in that case does not refer to the number of repeat units, but the molecular block weight in kg/mol).

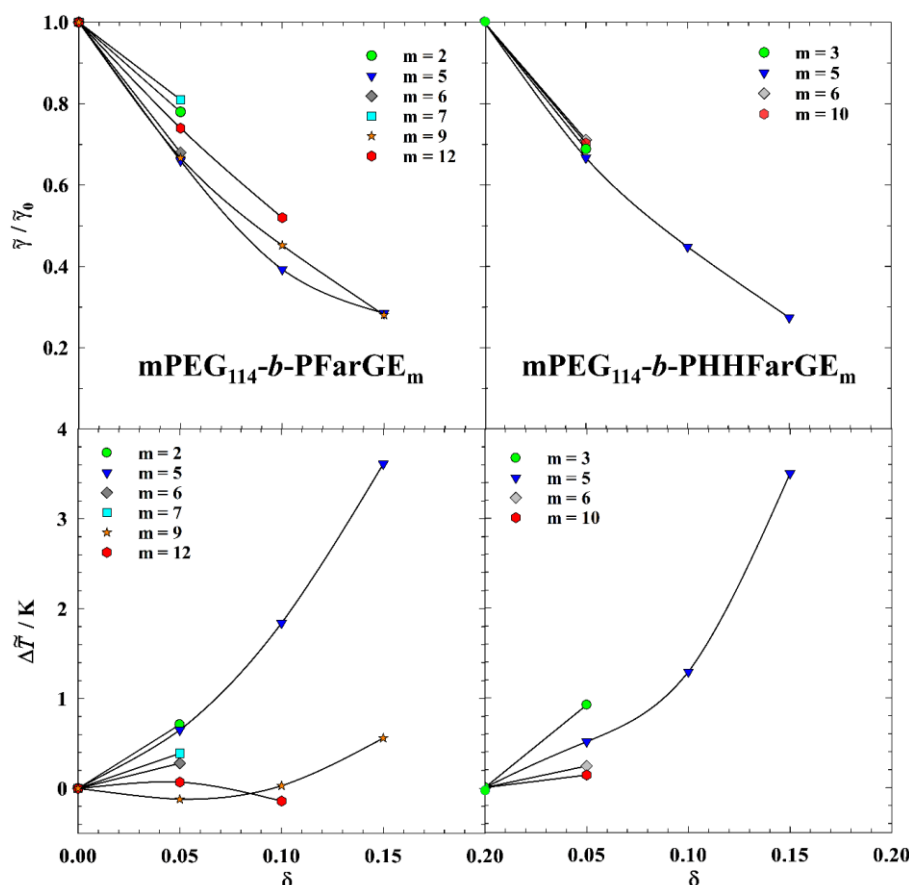


Figure 9: Scaling of efficiency (top) and corresponding changes of the phase inversion temperature (bottom) at the $\tilde{X}$ point for the system H₂O/NaCl – *n*-decane – C₁₀E₄ /mPEG₁₁₄-*b*-P(HH)FarGE_m. Left: mPEG₁₁₄-*b*-PFarGE_m polymers. Right: mPEG₁₁₄-*b*-PHHFarGE_m polymers.⁵⁰

Further phase behavior studies were conducted with some of the other polymers. To illustrate the boosting effect of various mPEG-*b*-P(HH)FarGE copolymers at different mass fractions δ , the phase inversion temperatures and surfactant mass fractions $\tilde{X}$ points of the polymer-containing systems were normalized to the polymer-free system. The diagrams are shown in Figure 9. Diagrams on the left side refer to mPEG₁₁₄-*b*-PFarGE_m, while those on the right refer to mPEG₁₁₄-*b*-PHHFarGE_m. In dependence on polymer mass fractions, the upper diagrams show the relative efficiency change ($\tilde{\gamma}/\tilde{\gamma}_0$, where 0 refers to the polymer-free system), while the lower diagrams show the corresponding changes in phase inversion temperature ($\tilde{T} - \tilde{T}_0$). With the most efficient polymers mPEG₁₁₄-*b*-PFarGE₅ and mPEG₁₁₄-*b*-PHHFarGE₅, about one third of amphiphilic component can be saved if 5 wt.% surfactant is replaced by polymer. Even with the weakest efficiency-boosting polymer, mPEG₁₁₄-*b*-PFarGE₇, which may be related to impurities, the required amphiphile mass for full solubilization can be reduced by almost 20%. For both polymer types, the influence on $\tilde{T}$ is small, but within

measurement uncertainties clearly follows the anticipated trend of an increasing $\tilde{T}$ with decreasing hydrophobicity, i.e., a smaller size of the (HH)FarGE block, therefore confirming measurements with conventional non-ionic surfactants.^{54,55} The greatest efficiency enhancement comes from the polymers of medium block size, for which $\tilde{\gamma}/\tilde{\gamma}_0 \approx 0.3$ is obtained at the highest polymer concentration, emphasizing that replacing 15 wt.% of C₁₀E₄ with polymer reduces the amount of amphiphile required for complete solubilization of water and oil by over 70%.

These results prove the suitability of mPEG-*b*-P(HH)FarGE block copolymers as efficiency boosters for ternary microemulsion systems. Moving towards an application of microemulsion systems containing these polymers, further experiments are required, since due to its high cost in pure form, C₁₀E₄ is not an economically viable option for large-scale use. Furthermore, as for other alcohol ethoxylates, it is typically not synthesized from renewable sources and therefore potentially ecotoxic.^{64,65} As a next step towards more sustainable formulations, C₁₀E₄ is being replaced by a sugar surfactant, *n*-octyl β -D-glucopyranoside (C₈G₁), which is readily accessible from renewable feedstocks. In order to also replace *n*-decane, the oil will be changed to isopropyl myristate (IPM). Investigations of microemulsion systems of the type H₂O – IPM – sugar surfactant (plus alcohol as co-surfactant) can be found in literature for a range of pure and commercially available technical-grade sugar surfactants.^{66,67} Adding mPEG-*b*-P(HH)FarGEs to an exemplary C₈G₁ system will clarify whether these copolymers can be equally beneficial co-surfactants in bio-based microemulsions. If successful, further investigations could take place with farnesene-based sugar surfactants, which were synthesized recently.¹³

Conclusion

Aiming at more economic and ecological strategies of the synthesis and application of surfactants, we have presented the crown ether-assisted one-step AROP of bio-renewable TGEs, namely FarGE and its novel, saturated derivative HHFarGE. The series of conveniently prepared amphiphilic diblock copolymers $m\text{PEG}_{114}\text{-}b\text{-P(HH)FarGE}_m$ feature molecular weights in the range of 5590 – 8380 $\text{g}\cdot\text{mol}^{-1}$ and molecular weight distributions with low $\mathcal{D}$ (1.04 – 1.07). Like conventional surfactants, the diblock copolymers self-assemble in aqueous solution when exceeding the CMC. Due to the high side chain hydrophobicity, the P_n of the TGEs represents a simple handle to adjust the amphiphilicity and CMC. Thus, the CMC was studied via fluorescence spectroscopy and light scattering, revealing low CMC values (14 – 90 $\text{mg}\cdot\text{L}^{-1}$) that systematically decrease in dependence on the TGE block length.

To evaluate the applicability as cosurfactants in microemulsions, we investigated the effect of a series of diblock copolymers $m\text{PEG}_{114}\text{-}b\text{-P(HH)FarGE}_m$ on the phase behavior of a conventional pseudo-ternary, non-ionic microemulsion system ($\text{H}_2\text{O}/\text{NaCl}$ – n -decane – C_{10}E_4) by varying the type and number m of TGE repeating units.

The observed reduction in the amphiphile amount required for complete water/oil solubilization into a one-phase microemulsion indicates a strong efficiency boosting effect. It was most prominent for the intermediate length hydrophobic block size in $m\text{PEG}_{114}\text{-}b\text{-P(HH)FarGE}_5$, underlining an improved absorption at the oil-water interface due to a favorable compromise between hydrophobicity and steric demand.

Surprisingly, no significant effect by virtue of the hydrogenation is observable, despite the slight increase of side chain flexibility due to the removal of double bonds in FarGE, signaling that the boosting effect is rather related to the number of TGE units and their impact on amphiphilicity and steric demand.

Not only do the advantages of the previously reported diblock copolymers, such as facile synthesis with upscaling options and availability of commercial reactants, account for the novel system, but the amphiphiles are additionally characterized by their bio-renewable nature.^{15,20} Prospective endeavors of combining $m\text{PEG}_{114}\text{-}b\text{-P(HH)FarGE}_m$ diblock copolymers as efficiency boosters in formulations with bio-based sugar surfactants can further provide avenues to enhance performance and sustainability of microemulsions, valorizing their potential in various industrial and biomedical applications.^{13,66–68}

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Supporting Information

Experimental Section

Reagents

Solvents and chemicals were generally acquired from commercial suppliers (Sigma-Aldrich, Fluka, Alfa Aesar, Acros, TCI) and were used without prior purification, unless stated otherwise. Deuterated solvents were purchased from Deutero GmbH. Farnesol was obtained as an isomeric mixture from Aldrich (95% purity) and ethylene oxide (EO) from Air Liquide. All terpenyl glycidyl ethers (TGEs), namely hexahydrofarnesyl glycidyl ether (HHFarGE) and farnesyl glycidyl ethers (FarGE), were dried azeotropically with benzene under reduced pressure overnight prior to polymerization. For homopolymer synthesis, the TGEs were dried over calcium hydride (CaH_2) and vacuum transferred before polymerization. Poly (ethylene glycol) monomethyl ether (mPEG_{114}), received from Fluka, was applied as a macroinitiator for the diblock copolymer synthesis and the following data was revealed by ^1H NMR and SEC analysis: $M_{n, \text{NMR}}$: $5050 \text{ g}\cdot\text{mol}^{-1}$, degree of polymerization (P_n) = 114, D = 1.05. Dialysis membranes (regenerated cellulose, $\text{MWCO} = 1,000 \text{ g}\cdot\text{mol}^{-1}$) were purchased from Orange Scientific.

Instrumentation

Nuclear Magnetic Resonance (NMR) Spectroscopy.

^1H (400 MHz), ^{13}C (100 MHz), ^1H - ^1H -COSY, ^1H - ^{13}C HSQC and ^1H - ^{13}C HMBC NMR spectra were recorded on a Bruker Avance II HD 400 spectrometer (equipped with a 5 mm BBFO-Smartprobe (Z-gradient), an automated tuning and matching device (ATM) as well as a SampleXpress 60 auto sampler) at 23 °C. All spectra were referenced internally to residual proton signals of the deuterated solvent (^1H NMR spectra) and the deuterated solvent itself (^{13}C NMR spectra). NMR spectroscopy data is reported as follows: chemical shift, multiplicity and integration. Spectra annotation uses lowercase letters for proton signals and capital letters for carbon signals.

Size Exclusion Chromatography (SEC).

SEC was performed in dimethylformamide (DMF) with $1 \text{ g}\cdot\text{mL}^{-1}$ lithium bromide as an eluent (flow rate of $1 \text{ mL}\cdot\text{min}^{-1}$, at 50 °C) on an Agilent 1100 series SEC system with a HEMA 300/100/40 Å column cascade, equipped with UV (254 nm) and RI detectors. The DMF SEC calibration was carried out with poly(ethylene glycol) standards provided

by Polymer Standard Service (PSS). Additional SEC measurements of the homopolymers were conducted in THF (flow rate of $1\text{ mL}\cdot\text{min}^{-1}$) using an instrument consisting of a Waters 717 plus autosampler, a set of three MZ-Gel SDPlus columns based on SDV with particle sizes of $5\text{ }\mu\text{m}$ (porosities of 100, 10^3 and $10^5\text{ }\text{\AA}$) and a TSP Spectra P 100 pump. An Agilent Technologies 1260 Infinity RI-detector as well as a SpectraSYSTEM UV2000 UV-detector (254 nm) were used. Polystyrene standards provided by PSS were used for calibration and toluene was applied as an internal standard. All data recording and analysis was carried out using PSS WinGPC Unity.

Fourier-Transformations-Infrared (FT-IR) Spectroscopy.

FT-IR spectroscopy was conducted using a *Nicolet iS10* FT-IR spectrometer (Thermo Scientific, Waltham, MA, USA) equipped with a diamond ATR unit in a frequency range of $650\text{--}3500\text{ cm}^{-1}$.

Differential Scanning Calorimetry (DSC).

DSC for thermal analyses of the synthesized polymers was performed on a DSC 250, TA Instrument, utilizing indium and *n*-octane as calibration standard. All samples were dried azeotropically, hermetically sealed in an aluminium pan and measured against an empty pan as reference under a nitrogen atmosphere. The DSC analysis temperature protocol ranges from $-90\text{ }^{\circ}\text{C}$ to $100\text{ }^{\circ}\text{C}$ and consists of two cooling and heating cycles at a rate of $10\text{ }^{\circ}\text{C}\cdot\text{min}^{-1}$ to remove the thermal history. For the diblock copolymer analysis, a 5 min hold after each cycle was added. The temperature for the homopolymer analysis was set to $-90\text{ }^{\circ}\text{C}$ to $50\text{ }^{\circ}\text{C}$. All analysis data was obtained from the second heating cycle using the TRIOS software.

Fluorescence Spectroscopy (FS) for CMC determination.

The determination of the CMC was realized fluorometrically using pyrene as a hydrophobic fluorescence dye and has been widely established.^{1–4} Two polymer stock solutions (concentration range of $0.10\text{--}1\text{ g}\cdot\text{L}^{-1}$) per diblock copolymer were prepared using Milli-Q water and equilibrated overnight. For each measurement, a defined aliquot of an ethanolic pyrene solution (0.7 mM) was added to a volumetric flask, followed by solvent evaporation. Then, a calculated amount of the polymeric stock solution was added to the volumetric flask and diluted with distilled water (Milli-Q) to obtain a final pyrene concentration (c_{pyrene}) of $7\cdot 10^{-7}\text{ M}$. For each polymer, a concentration series of pyrene-containing polymer solutions (0.0005 to $0.60\text{ g}\cdot\text{L}^{-1}$) were measured. The samples were gently shaken at room temperature (r.t.) overnight to

enable micelle equilibration and solubilization of pyrene by the micelles. Pyrene emission spectra were recorded on a Jasco FP-8200 spectrofluorometer through a quartz cell at $T = (23 \pm 1)^\circ\text{C}$ in a wavelength range of 350-450 nm. Quartz cells were washed once with the corresponding polymer solution prior to the measurement. Selected instrument parameters were as follows: excitation wavelength $\lambda_{\text{ex}} = 334$ nm, slit_{em} = 2.5 nm, slit_{ex} = 2.5 nm, scan speed: 20 nm·min⁻¹, data interval = 0.5 nm, response = 0.5 sec. The intensity ratio I_1/I_3 , referring to the first ($\lambda_{\text{peak}} = 372\text{-}373$ nm) and third ($\lambda_{\text{peak}} = 383\text{-}384$ nm) vibronic bands in the pyrene fluorescence spectrum,^{4,5} is extremely sensitive to the polarity of the medium surrounding pyrene molecules. In an aqueous solution of amphiphilic polymers, a ratio change of I_1/I_3 hence reflects the pyrene location in the polar aqueous solution or a non-polar micellar core.^{1,6} Plotting I_1/I_3 against polymer concentration is a convenient approach to estimate the CMC of the respective polymer.

Static and Dynamic Light Scattering (SLS/DLS) for CMC determination.

Light scattering experiments were performed to determine the critical micelle concentration (CMC) with a 3D LS Spectrometer (LS Instruments, Switzerland) equipped with a diode-pumped laser with a wavelength of $\lambda = 561$ nm (Cobolt, Sweden). A combination of dynamic (DLS) and static light scattering (SLS) was conducted at a scattering angle of $\theta = 90^\circ$ and a maximum incident laser intensity of $I_0 \approx 82$ mW. A decalin bath connected to a thermostat (Julabo, Germany) was used to set the temperature to $T = (23.0 \pm 0.1)^\circ\text{C}$. The polymer concentrations ranged between 0.003 g·L⁻¹ and 1 g·L⁻¹ and solutions were prepared in 10 mL volumetric flasks. For each sample concentration, an aliquot of 1 mL of the polymer solution was filled into a borosilicate test tube (Fisher Scientific, USA), which were previously cleaned with acetone and filtered double-distilled water. As measurement setup, 60 repetitions of 5 s each was chosen for all polymer concentrations. The 2D Pseudo Cross Correlation mode was applied to avoid errors in the correlation function at short lag times, which is caused by after-pulsing of the detectors. The static light scattering intensity was evaluated using the mean count rate (*meanCR* in kHz). *meanCR* is derived from the geometric mean of the count rates recorded at the two detectors (CR_A and CR_B), following $\text{meanCR} = \sqrt{CR_A * CR_B} * \sin(\theta) \equiv C$. All values were further corrected by considering the scattering intensity of a polymer-free water sample (see below). The conversion of count rates to absolute units (1/cm) was possible by using the scattering intensity of a known scatterer, toluene. The reference Rayleigh ratio for our setup was obtained

according to a procedure by Wu et al.⁷ The Rayleigh ratio with unpolarized incident light and detection without a polarizer for toluene follows $R_{u,25}$, ($\theta = 90^\circ$, $T = 25^\circ\text{C}$)

$$R_{u,25} = 4.9 * 10^6 * \lambda^{-4.17} \left[\frac{1}{\text{cm}} \right] \quad (1)$$

Vertically polarized incident light was applied while a vertical polarizer detected the signal. Hence, we convert R_u to R_{vv} via the depolarization factor ρ_u ($\rho_u = 0.491$ at $T = 23^\circ\text{C}$)⁸ and the relation:

$$R_{vv} = R_u(2 - \rho_u)/(1 + \rho_u) \left[\frac{1}{\text{cm}} \right]. \quad (2)$$

As the temperature dependence of the Rayleigh ratio of toluene is similar to that of benzene, it is incorporated via

$$R_{vv,T} = R_{vv,25}(1 + 0.00368(T - 25^\circ\text{C})) \left[\frac{1}{\text{cm}} \right]. \quad (3)$$

The excess Rayleigh ratio is determined from

$$R_{vv,T,sample} = \left(\frac{C_{sample}}{I_{0,sample}} - \frac{C_{water}}{I_{0,water}} \right) * \left(\frac{I_{0,toluene}}{C_{toluene}} \right) R_{vv,T,toluene}, \quad (4)$$

with $I_{0,x}$ labelling the incident laser beam intensity used for measurements of water, toluene, and the sample. The setup conditions ($\lambda = 561 \text{ nm}$, $T = 23^\circ\text{C}$, $\theta = 90^\circ$) lead to $R_{vv,T,toluene} = 1.694 * 10^{-5} \frac{1}{\text{cm}}$.

Phase Behavior Studies.

Phase behavior of water/NaCl – *n*-decane – tetraethylene glycol monodecyl ether (C_{10}E_4) / PEG-P(HH)FarGE systems was studied in the form of $T(\gamma)$ cuts, also known as fish cuts. For all measurements, a constant salinity (0.1 wt% of NaCl in water to buffer electrostatic interactions with ionic surfactant impurities) and a constant water-to-oil ratio ϕ was set, using equal volumes of water and oil, corresponding to $\phi = \frac{V_o}{V_w + V_o} = 0.5$.

Temperature T , amphiphile mass fraction γ and polymer-to-surfactant ratio δ were varied, with

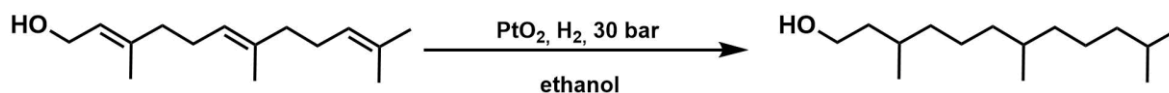
$$\gamma = \frac{m_{\text{Polymer} + \text{Surfactant}}}{m_{\text{sample}}} \text{ and } \delta = \frac{m_{\text{Polymer}}}{m_{\text{Polymer}} + m_{\text{Surfactant}}}.$$

Components were filled into 5 or 10 mL test tubes in the order polymer > surfactant > oil > brine. A stirring bar was inserted afterwards and the test tube was sealed. Temperature of the water bath was regulated via a thermostat (Thermo Scientific Haake

SC 100 and Thermo Scientific Haake A 25) and can be read off a thermometer with an accuracy of ± 0.01 K (Greisinger GTF 401 and Greisinger GMH 3750). A magnetic stirrer (Heidolph MR Hei-Mix L) with a speed range of 0 to 1400 rpm was used to ensure prospering mixing of the samples. Two-phase regions could be determined from sample turbidity and awaiting phase separation. The presence of anisotropic phases can be detected using vertically oriented polarizing filters. After successful determination of all phase boundaries, the sample was diluted by adding equal volumes of water and oil, therefore obtaining lower γ .

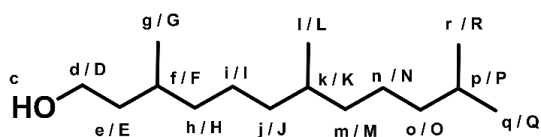
Monomer Synthesis

Hydrogenation of Farnesol.



Scheme S 1: Hydrogenation of farnesol utilizing PtO_2 under 30 bar H_2 , yielding hexahydrofarnesol.

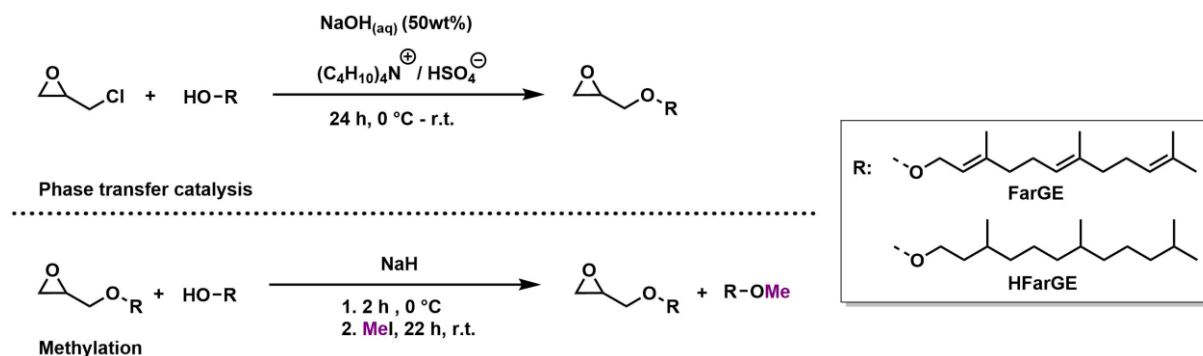
To synthesize hexahydrofarnesol (HHF, IUPAC: 3,7,11-trimethyldodecan-1-ol), we altered a literature-known hydrogenation procedure deploying platinum (IV)-oxide (PtO_2) as catalyst.⁹ Farnesol (IUPAC: 3,7,11-Trimethyl-2,6,10-dodecatrien-1-ol; 15.00 g, 16.85 mL, 0.068 mol, 1.00 equiv.), dissolved in 6.75 mL ethanol, and PtO_2 (0.055 g, 0.241 mmol, 0.0012 mol% per double bond, 0.004 equiv.) were introduced in a high pressure autoclave reactor, equipped with a stirring bar, and the hydrogenation was performed under 30 bar H_2 at room temperature (r.t.). The reaction conversion was tracked via ^1H NMR spectroscopy and quantitative conversion achieved after 30 h. The hydrogenation mixture was filtered and residual ethanol was removed via rotary evaporation to yield HHF as a colorless liquid in quantitative amounts (90%). NMR characterization reveals a stereoisomeric mixture after hydrogenation and is in agreement with previously reported literature (Figure S 1 - Figure S 4).¹⁰



^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 3.73 – 3.62 (m, 2H, H_d), 1.66 – 0.95 (m, 17H, H_e , H_f , H_h , H_i , H_j , H_k , H_m , H_n , H_o , H_p), 0.91 – 0.80 (m, 12H, H_g , H_l , H_r , H_q).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 61.39 (C_D), 40.16 + 40.08 (d, C_E), 39.50 (C_O), 37.63 + 37.59 (d, C_M), 37.50 (C_H), 37.46 + 37.40 (d, C_J), 32.92 (C_K), 29.66 + 29.64 (d, C_F), 28.12 (C_P), 24.95 + 24.93 (C_N), 24.51 (C_I), 22.86 + 22.76 (C_Q + C_R), 19.87 (d) + 19.82 + 19.75 (d) (C_G + C_L). d denotes a doublet signal of the carbon resonance due to the stereoisomeric mixture.

Phase transfer catalysis and methylation of protic impurities in the terpenyl glycidyl ether.



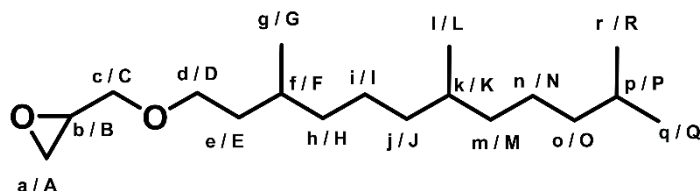
Scheme S 2: Phase transfer catalysis of terpenoids with subsequent methylation of potential protic impurities.

The terpenyl glycidyl ethers (TGEs) such as FarGE and its novel hydrogenated derivative HHFarGE were synthesized in a literature-modified phase transfer catalysis.^{11,12} In the following, the procedure is described exemplarily for HHFarGE. A 250 mL three-necked flask, equipped with a dropping funnel and mechanical stirrer, was charged with epichlorohydrin (ECH, 32.8 mL, 38.65 g, 0.418 mol, 5.30 equiv.), tetrabutylammonium hydrogen sulfate (TBAHS, 1.07 g, 0.003 mol, 0.04 equiv.) and an aqueous sodium hydroxide solution ($V_{\text{solution}} = 40.03$ mL, NaOH: 19.93 g, 0.50 mol, 12.7 equiv.). While keeping the reaction mixture to 0 °C with an ice bath, HHF (20.5 mL, 18.00 g, 0.079 mol, 1 equiv.) was added dropwise within 30 min under vigorous stirring. Subsequently, the reaction was stirred at room temperature (r.t.) until completion (t : 20 - 24 h) and quenched with ice-water mixture. The aqueous layer was extracted with diethyl ether (DEE) three times and washed with saturated sodium chloride until neutrality. After combining the organic phase and drying over magnesium sulfate, DEE was removed under reduced pressure. After an initial facile Kugelrohr distillation, 3-Chloroallyl glycidyl ether (3-Chloro-AGE), which is a known side product for the phase transfer catalysis, was removed via in vacuo distillation ($p = 5 \cdot 10^{-3}$ mbar, $T_{\text{b,3-Chloro-AGE}} = 30$ °C). A final purification was performed via Kugelrohr distillation and liquid HHFarGE ($p = 5 \cdot 10^{-3}$ mbar, $T_{\text{Kugelrohr, HHFarGE}} = 160$ °C) was isolated in yields of 78 to 80%.

Protic impurities in the monomer were deactivated by treatment with methyl iodide (MeI) and sodium hydride (NaH), resulting in *O*-methylation of any residual terpenoid (Scheme S 2).^{12,13} Thus, a flame-dried Schlenk flask, filled with NaH (0.272 g, 11.0 mmol, 0.22 equiv.), was cooled to 0 °C while the HHFarGE monomer (14.635 g, 51.5 mmol, 1.00 equiv.) was added. Hydrogen gas formation was complete after 2 h and MeI (0.73 g, 5.0 mmol, 0.10 equiv.) was syringed into the flask and the reaction mixture was allowed to warm up to r.t.. After stirring for 22 h, hexane was added to dilute the

reaction suspension before filtration, which removes accrued sodium iodide during methylation. After a Kugelrohr distillation HHFarGE was isolated as a colorless liquid in quantitative yields. The pretreatment reaction simultaneously serves as an extensive drying process.

Characterization of HHFarGE.

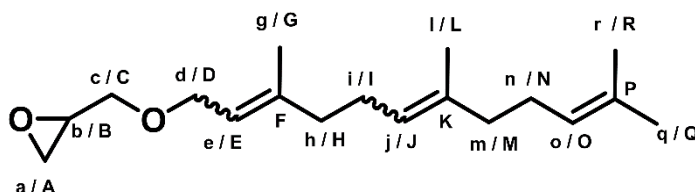


^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 3.72 – 3.67 (dt, J = 11.5, 3.5 Hz, 1H, H_c), 3.59 – 3.43 (m, 2H, H_d), 3.42 – 3.30 (m, 1H, H_e), 3.20 – 3.05 (m, 1H, H_b), 2.85 – 2.71 (m, 1H, H_a), 2.67 – 2.52 (m, 1H, H_a), 1.71 – 0.98 (m, 17H, H_e , H_f , H_h , H_i , H_j , H_k , H_m , H_n , H_o , H_p), 0.93 – 0.77 (m, 12H, H_g , H_l , H_r , H_q).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 71.61 (C_c), 70.14 + 70.11 (C_d), 51.04 (C_b), 44.48 + 44.46 (C_a), 39.48 (C_o), 37.61 + 37.57 (C_m), 37.49 (C_h), 37.45 + 37.38 (C_j), 36.86 + 36.77 (C_e), 32.90 (C_k), 29.96 + 29.94 (C_f), 28.10 (C_p), 24.94 + 24.92 (C_n), 24.47 (C_l), 22.85, 22.76 ($\text{C}_q + \text{C}_r$), 19.86 + 19.82 + 19.79 + 19.76 ($\text{C}_g + \text{C}_l$).

Characterization of FarGE.

A detailed NMR characterization and the respective NMR spectra have been previously published.¹² In accordance, the stereochemistry-induced carbon shifts are labelled according to the respective farnesol stereoisomer, using *E* (*trans*) and *Z* (*cis*) nomenclature for the C-2 and C-6 carbon in lower cases. Hence, carbon atoms are distinguished as follows: X_{EE} (2*E*,6*E*-farnesol), X_{EZ} (2*E*,6*Z*-farnesol) and X_{ZE} (2*Z*,6*E*-farnesol).



Purification by Kugelrohr distillation: $p = 5 \cdot 10^{-3}$ mbar, $T_{\text{Kugelrohr, FarGE}} = 170$ °C

^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 5.36–5.29 (m, 1H, H_e), 5.11–5.03 (m, 2H, H_j , H_o),

4.09–3.97 (m, 2H, H_d), 3.71–3.60 (m, 1H, H_c), 3.39–3.32 (m, 1H, H_c), 3.17–3.08 (m, 1H, H_b), 2.79–2.70 (m, 1H, H_a), 2.62–2.51 (m, 1H, H_a), 2.18–1.88 (m, 8H, H_h , H_i , H_m , H_n), 1.73+1.85+1.57 (s, 12H, H_g , H_l , H_r , H_q , $J = 5.0, 4.2$ Hz).

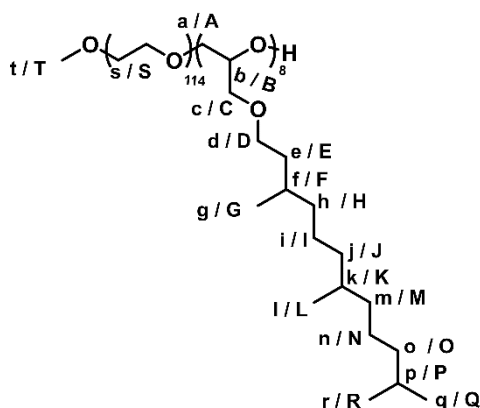
^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.93 + 140.68 ($C_{F(ZE)}$), ($C_{F(EE)}$), 140.64 ($C_{F(EZ)}$), 135.61 ($C_{K(ZE)}$), 135.46 ($C_{K(EZ)}$), 135.31 ($C_{K(EE)}$), 131.54 ($C_{P(EZ)}$), 131.34 ($C_{P(ZE)}$), 131.29 ($C_{P(EE)}$), 124.67 ($C_{J(EZ)}$), 124.37 + 124.34 ($C_{O(EE, EZ, ZE)}$), 123.86 ($C_{J(EE)}$), 123.66 ($C_{J(ZE)}$), 121.53 ($C_{E(ZE)}$), 120.55 ($C_{E(EE, EZ)}$), 70.73 ($C_{C(ZE)}$), 70.66 ($C_{C(EE, EZ)}$), 67.79 ($C_{D(EE, EZ)}$), 67.54 ($C_{D(ZE)}$), 50.90 (C_B), 44.44 (C_A), 39.92 ($C_{H(EZ)}$), 39.74 ($C_{M(EE, ZE)}$), 39.63 ($C_{H(EE)}$), 32.27 ($C_{H(ZE)}$), 32.01 ($C_{M(EZ)}$), 26.76 ($C_{N(EE)}$), 26.71 ($C_{N(ZE)}$), 26.63 ($C_{N(EZ)}$), ($C_{I(ZE)}$), 26.31 ($C_{I(EE)}$), 26.18 ($C_{I(EZ)}$), 25.76 ($C_{Q(EZ)}$), 25.73 ($C_{Q(EE, ZE)}$), 23.55 ($C_{G(ZE)}$), 23.41 ($C_{L(EZ)}$), 17.71 ($C_{R(EE, ZE)}$), 17.67 ($C_{R(EZ)}$), 16.52 ($C_{G(EE, EZ)}$), 16.03 ($C_{L(EE, ZE)}$).

Polymerization Procedures

Synthesis procedure for diblock copolymerization of and FarGE and HHFarGE with mPEG₁₁₄

Two series of diblock copolymers, mPEG₁₁₄-*b*-FarGE_m and mPEG₁₁₄-*b*-HHFarGE_m respectively, were synthesized using mPEG₁₁₄ as macroinitiator in a crown-ether-assisted anionic ring opening polymerization.¹² Protic impurities contained in the TGEs were methylated using MeI if not noted otherwise in Table 1. Note that a detailed mPEG₁₁₄-*b*-PFarGE_m and PFarGE characterization will not be discussed as it has been published previously.¹²

The following protocol illustrates the general procedure for the diblock copolymer synthesis, exemplarily for mPEG₁₁₄-*b*-HHFarGE₈ (Table 1, entry 12). mPEG₁₁₄ (1.500 g, 0.30 mmol, 1.0 equiv.), potassium *tert*-butoxide (KO^tBu, 0.027 g, 0.24 mmol, 0.8 equiv.) and 18-crown-6 (0.127 g, 0.48 mmol, 2.0 equiv.) were mixed in a dry Schlenk flask applying positive nitrogen flow, suspended in benzene and stirred for 1 h at 60 °C under vacuum to generate the initiator salt. Following, the initiator salt was dried azeotropically overnight at 60 °C. The dry monomer HHFarGE (0.83 mL, 0.770 g, 2.7 mmol, 9.0 equiv) was syringed into the flask and the reaction mixture was stirred for 24 h at 80 °C. Note that the polymerization temperature was increased up to 120 °C (with incremental *P_n*) as the viscosity increase impeded sufficient stirring at 80 °C. The polymerization was terminated after cooling to r.t. by adding 1 mL of methanol and the polymer was dissolved in dichloromethane (DCM). Three-fold precipitation in cold diethyl ether (-20 °C) allowed for the removal of homopolymer residues. After dialysis (MWCO = 1000 g·mol⁻¹) in Milli-Q®, enabling the removal of traces of 18-crown-6 and potassium salts, the polymer was obtained in yields of 70 – 95%.



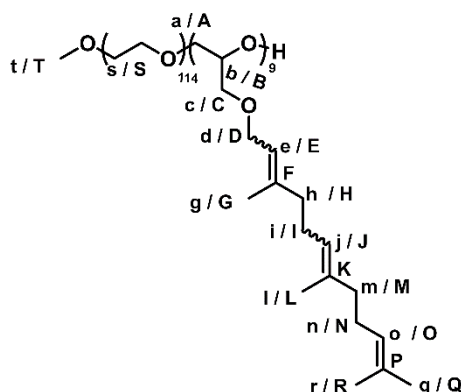
^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 3.87 – 3.34 (m, H_a , H_b , H_c , H_d , H_s), 3.34 (s, H_t), 1.67 – 0.94 (m, H_e , H_f , H_h , H_i , H_j , H_k , H_m , H_n , H_o), 0.94 – 0.68 (m, H_g , H_l , H_r , H_q).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 78.84, 78.63, 78.37 (C_B), 71.98, 71.84, 70.83, 70.78, 70.67, 70.61, 70.58, 70.07, 70.02, 69.99 (C_A , C_C , C_D , C_S), 59.09 (C_T), 39.41 (C_O), 37.60, 37.53, 37.48, 37.36, 37.33, 37.32 (C_M , C_H , C_I), 36.82, 36.74, 36.66 (C_E), 32.85 (C_K), 30.06 + 29.98 (C_F), 28.01 (C_P), 24.86, 24.48, 24.43 (C_N , C_L), 22.79 + 22.68 (C_Q , C_R), 19.78, 19.71 (C_G , C_{L_r}).

SEC analysis (RI detector, eluent: DMF, standard: PEG): $M_n = 6600 \text{ g}\cdot\text{mol}^{-1}$; $\bar{D} = 1.06$

$T_g = -71^\circ\text{C}$ $T_m = 56^\circ\text{C}$

The following characterization refers to mPEG₁₁₄-*b*-FarGE₉ (Table 1 and 2, entry 5). The polymer characterization and the respective NMR spectra have been previously published.¹²



^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 5.39–5.22 (m, H_e), 5.20–4.98 (m, H_i , H_o), 4.04–3.86 (m, H_d), 3.83–3.38 (m, H_a , H_b , H_c , H_s), 3.36 (s, H_t), 2.13–1.84 (m, H_h , H_i , H_m , H_n), 1.75–1.41 (m, H_g , H_l , H_r , H_q).

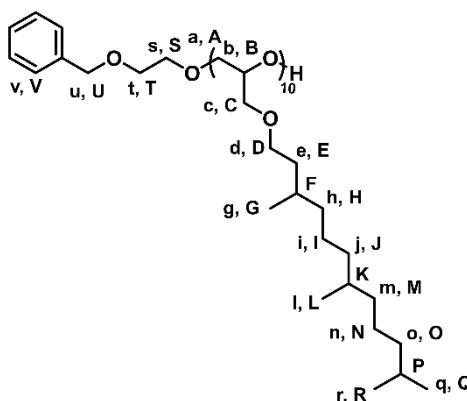
^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.01, 139.83, 139.71 (C_F), 135.51, 135.40, 135.25 (C_K), 131.54, 131.31 (C_P), 124.74, 124.40, 123.95, 123.73 (C_O , C_I), 121.24, 121.14, 121.07, 120.75 (C_E), 78.87, 78.68, 78.37 (C_B), 71.98, 71.20, 71.07, 70.82, 70.61, 70.14, 69.87, 69.70 (C_A , C_C , C_S), 67.93, 67.62 (C_D), 59.09 (C_T), 40.01, 39.76, 39.73, 32.34, 32.01 (C_H , C_M), 26.78, 26.64, 26.53, 26.46, 26.43, 26.27, 26.21 (C_N , C_L), 25.80, 25.76 (C_Q), 23.62, 23.59, 23.45 (C_G , C_{L_r}), 17.75, 17.71 (C_R), 16.59, 16.51 (C_G), 16.06 (C_{L_r}).

SEC analysis (RI detector, eluent: DMF, standard: PEG): $M_n = 7100 \text{ g}\cdot\text{mol}^{-1}$; $\bar{D} = 1.05$

$T_g = -71 \text{ }^\circ\text{C}$ $T_m = 56 \text{ }^\circ\text{C}$

Synthesis procedure for PHHFarGE and PFarGE homopolymer

The homopolymerization was performed with 2-(benzyloxy)ethanol (BzEtOH) as initiator while following the diblock copolymer synthesis protocol. Purification was achieved either via threefold precipitation in cold methanol ($-20 \text{ }^\circ\text{C}$) or dialysis, followed by drying under reduced pressure overnight. PHHFarGE₁₀ is characterized exemplary in the following (Table 1 and 2, entry 13).

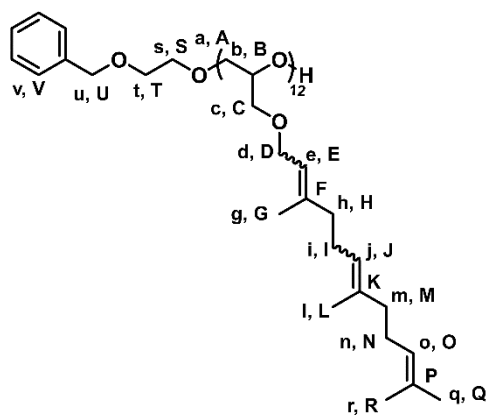


^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 7.38 – 7.31 (m, H_v), 4.56 (s, H_u), 3.97 – 3.26 (m, H_a , H_b , H_c , H_d , H_s , H_t), 1.69 – 0.94 (m, H_e , H_f , H_h , H_i , H_j , H_k , H_m , H_n , H_o), 0.94 – 0.70 (m, H_g , H_l , H_r , H_q).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 128.49, 127.80, 127.70 (C_v), 78.95, 78.77 (C_b), 73.36, 72.05, 71.96, 71.45, 71.06, 70.77, 70.26, 70.19, 69.89, 69.71, 69.58 (C_a , C_c , C_d , C_s , C_t), 39.52 (C_o), 37.81, 37.71, 37.65, 37.58, 37.56, 37.48, 37.45, 37.03 (C_m , C_h , C_l), 36.94, 36.89, 36.86, 36.78 (C_e), 32.96 (C_k), 30.18, 30.15, 30.10 (C_f), 28.09 (C_p), 24.98, 24.58, 24.55, 24.51 (C_n , C_i), 22.88, 22.79 (C_q , C_r), 19.88, 19.81 (C_g , C_l).

SEC analysis (RI detector, eluent: THF, standard: PEG): $M_n = 3300 \text{ g}\cdot\text{mol}^{-1}$; $\bar{D} = 1.12$

$T_g = -74 \text{ }^\circ\text{C}$



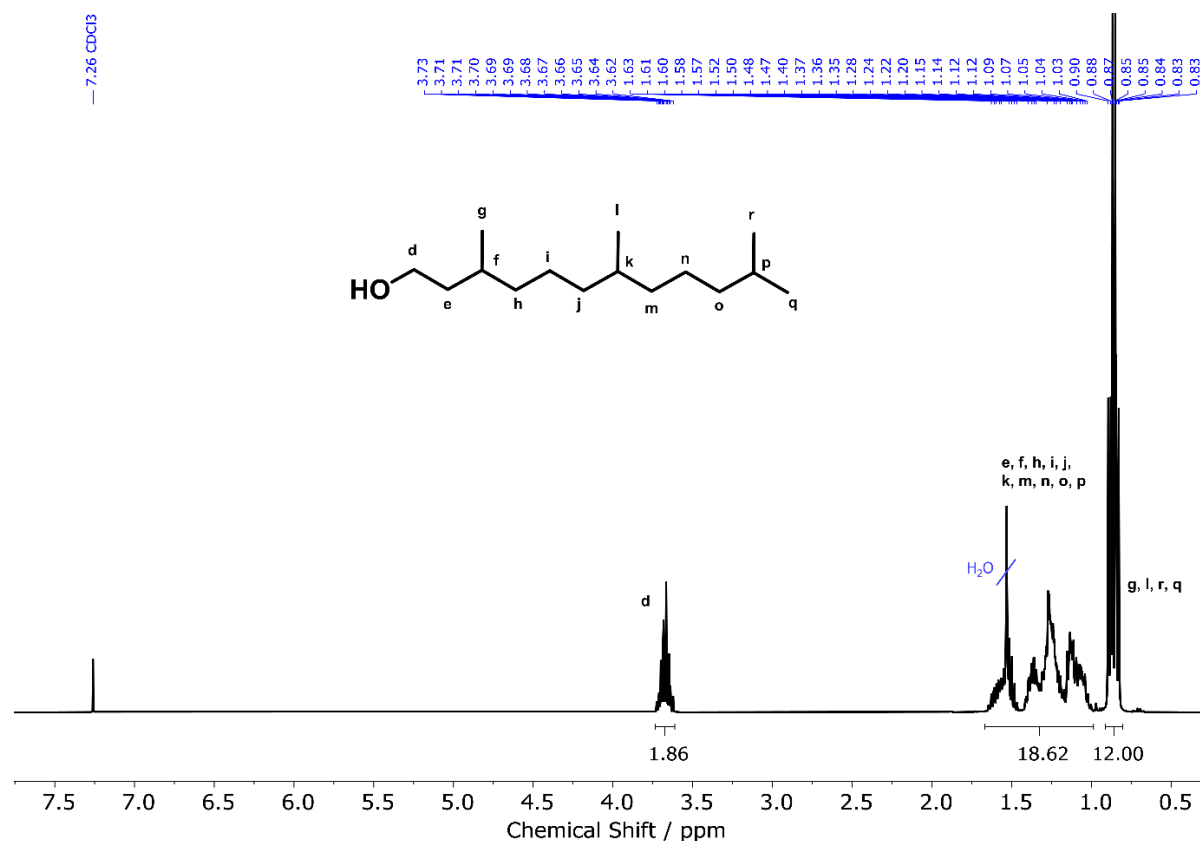
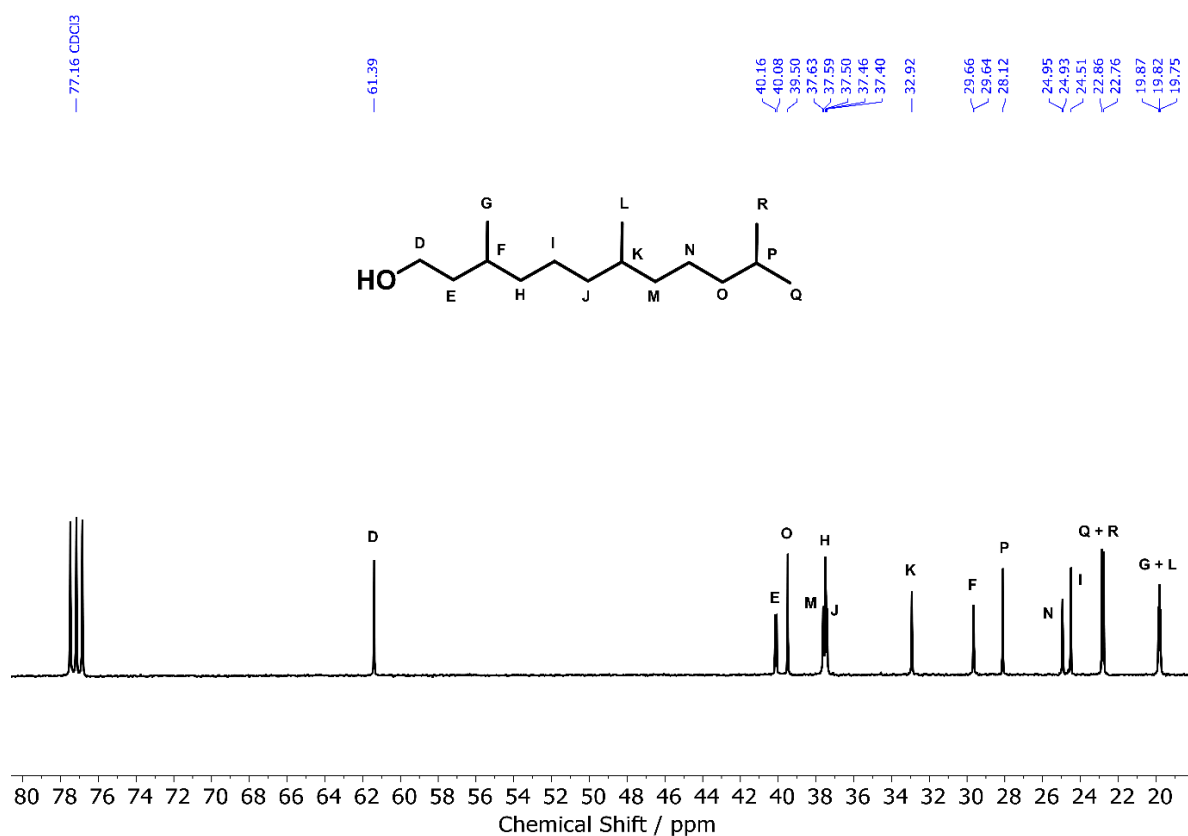
^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 7.36 – 7.29 (m, H_v), 5.38 – 5.25 (m, H_e), 5.17 – 5.02 (m, H_j , H_o), 4.55 (s, H_u), 4.09 – 3.88 (m, H_d), 3.88 – 3.32 (m, H_a , H_b , H_c , H_s , H_t), 2.19 – 1.85 (m, H_h , H_i , H_m , H_n), 1.83 – 1.43 (m, H_g , H_l , H_r , H_q).

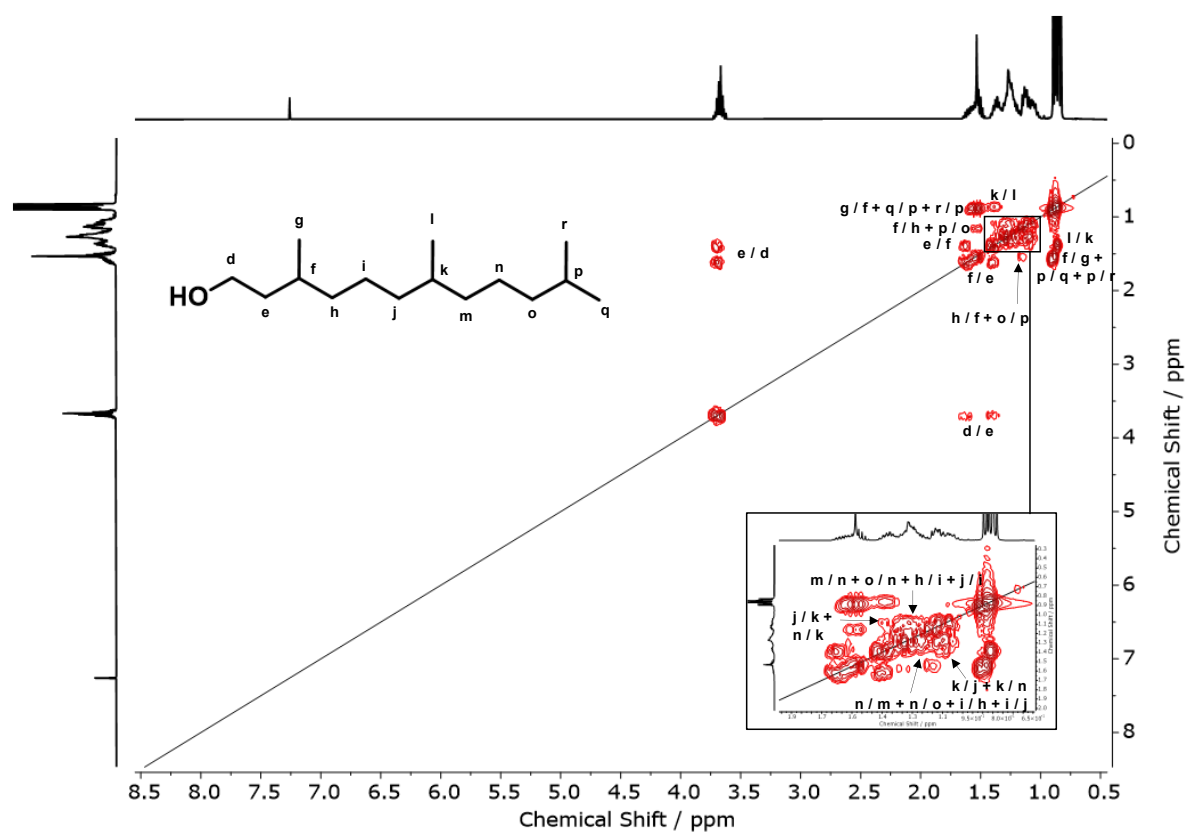
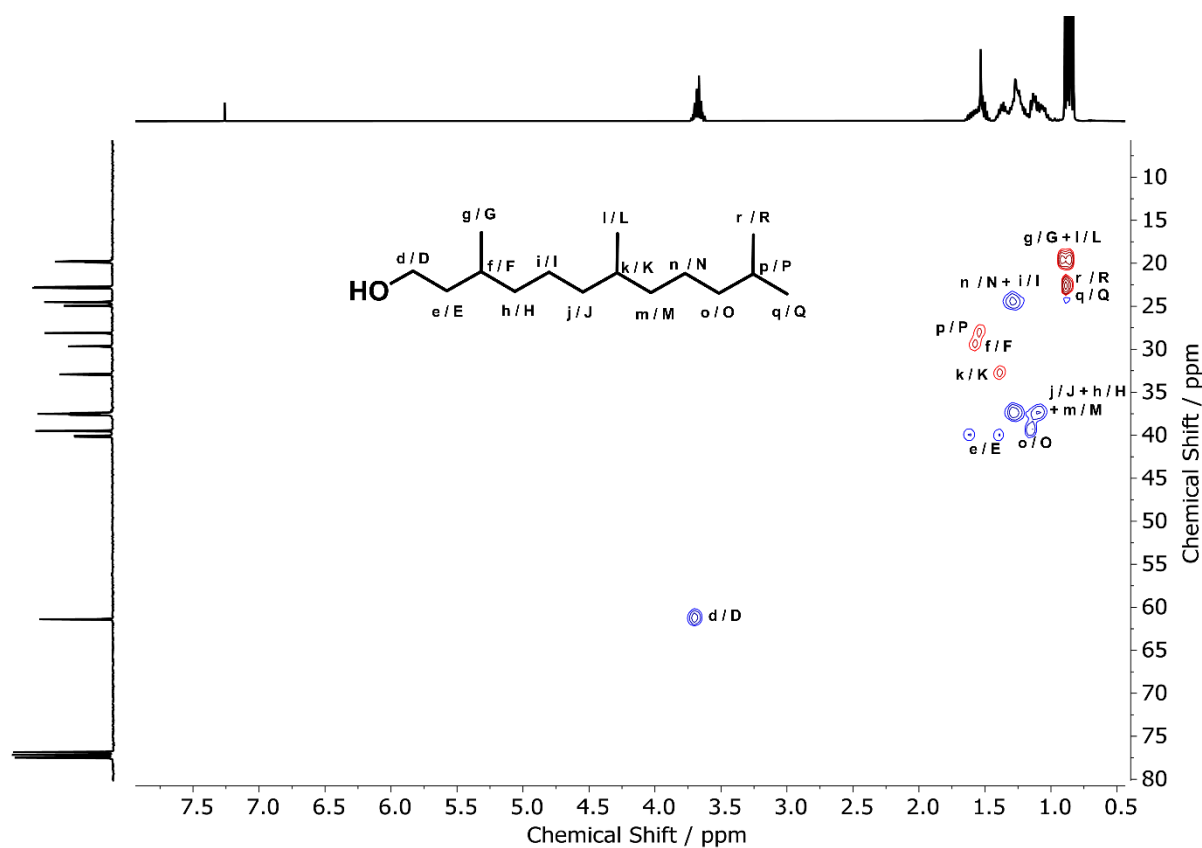
^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.14, 139.90, 139.82, 139.67 (C_f), 135.50, 135.44, 135.36 (C_k), 131.64, 131.41 (C_p), 128.48, 127.80, 127.68 (C_v), 124.84, 124.49, 124.47, 124.07, 124.05, 123.87 (C_o , C_j), 121.37, 121.25, 121.17, 121.09, 121.02, 120.93, 120.85, 120.82 (C_e), 79.10, 78.98, 78.81 (C_b), 73.34 (C_u), 71.45, 71.22, 71.03, 70.48, 70.40, 70.25, 70.03, 69.92, 69.82, 69.57 (C_a , C_c , C_s , C_t), 68.06, 68.03, 67.73 (C_d), 40.11, 40.06, 39.86, 39.83, 39.79, 32.44, 32.11 (C_h , C_m), 26.88, 26.86, 26.74, 26.64, 26.61, 26.56, 26.53, 26.37, 26.34 (C_n , C_i), 25.88, 25.85 (C_q), 23.70, 23.65, 23.54 (C_g , C_l), 17.83, 17.80 (C_r), 16.68, 16.66, 16.60 (C_g), 16.14 (C_l).

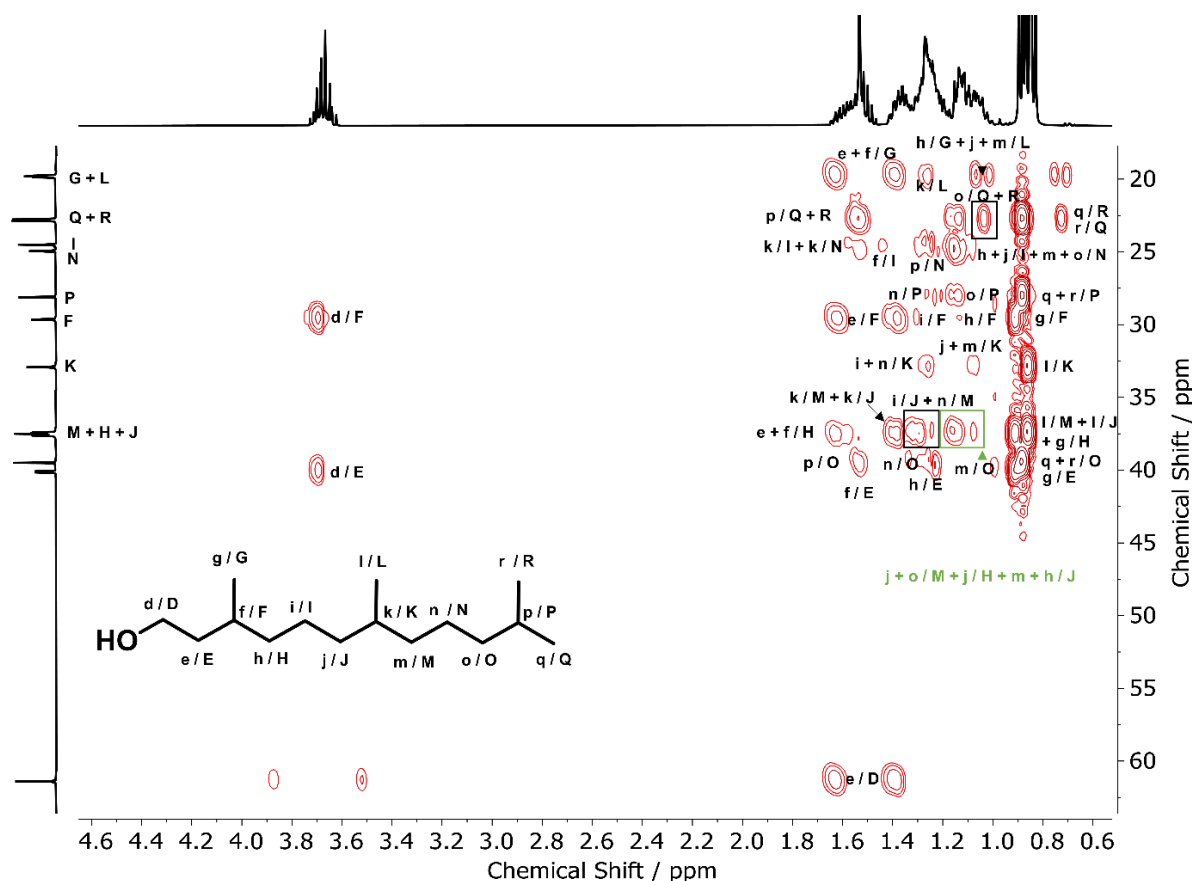
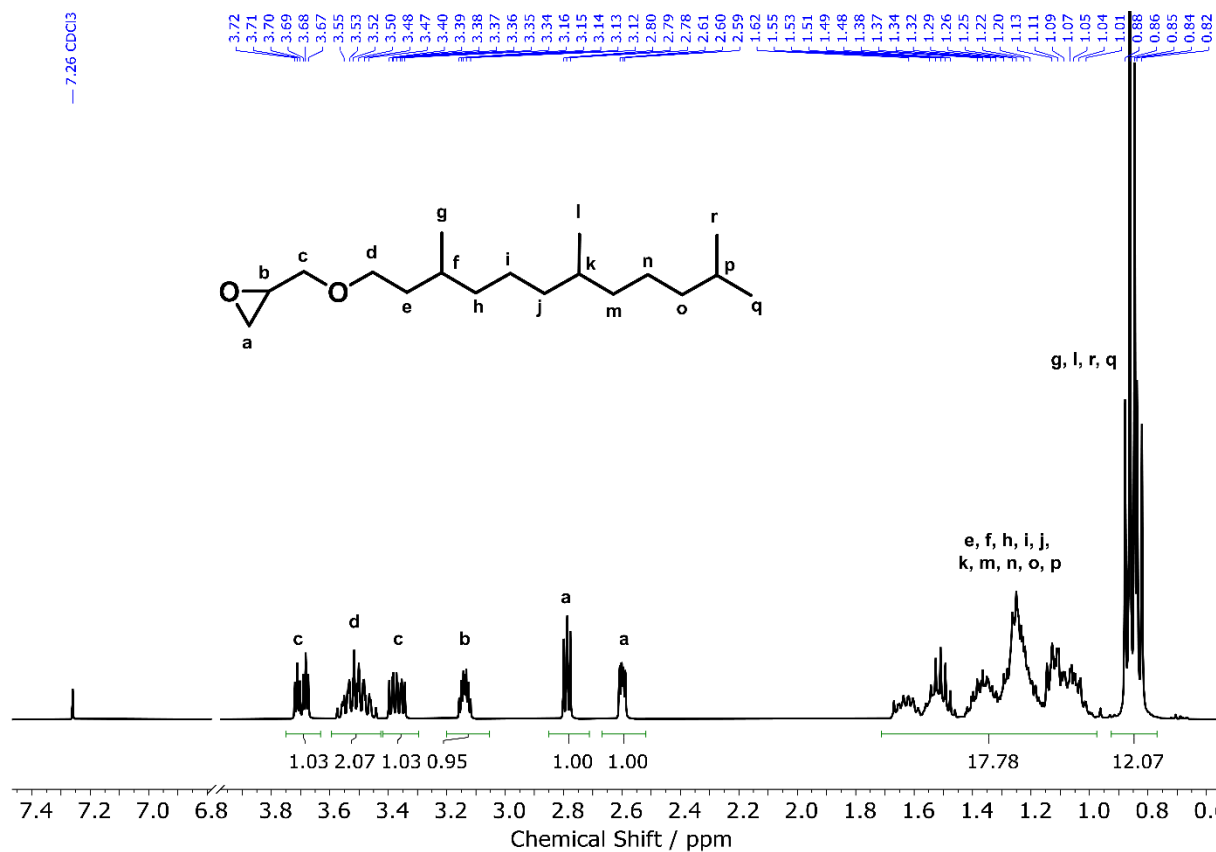
SEC analysis (RI detector, eluent: THF, standard: PEG): $M_n = 3500 \text{ g}\cdot\text{mol}^{-1}$; $\bar{D} = 1.20$

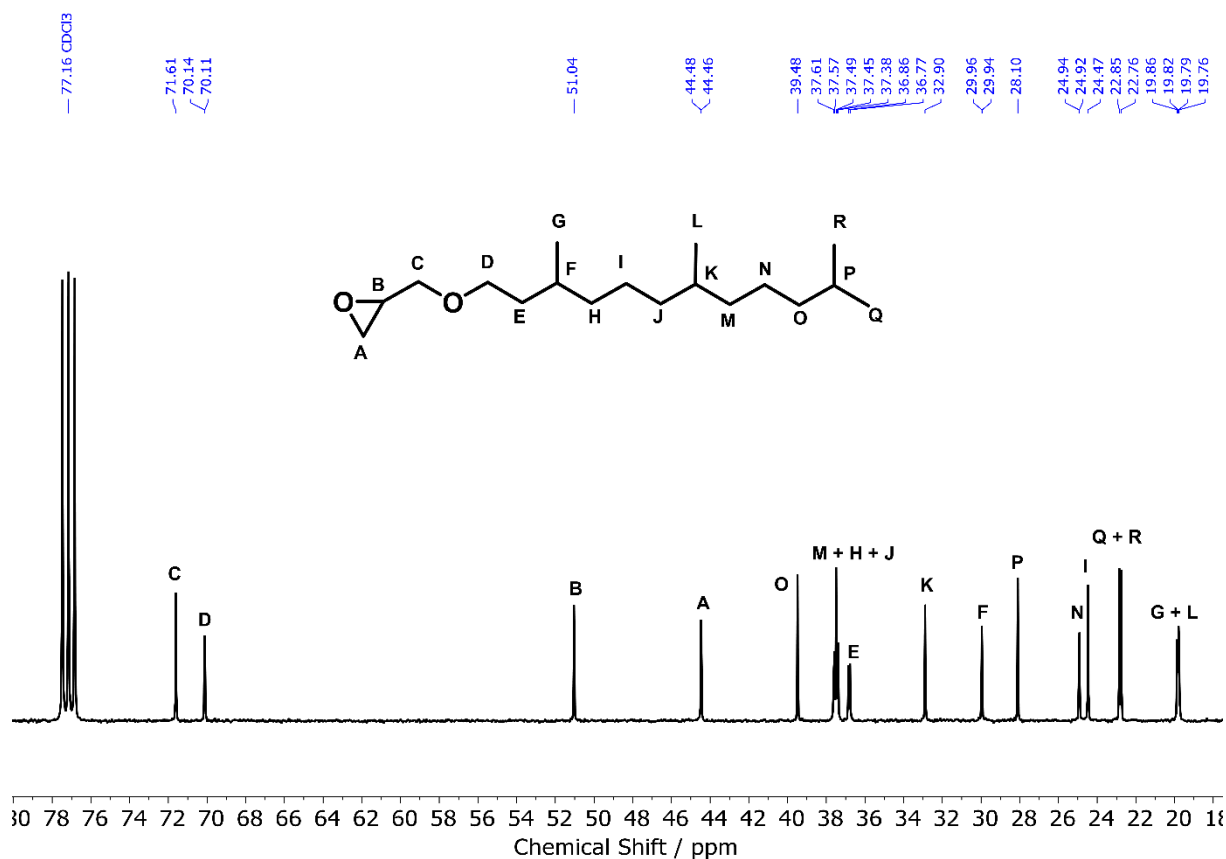
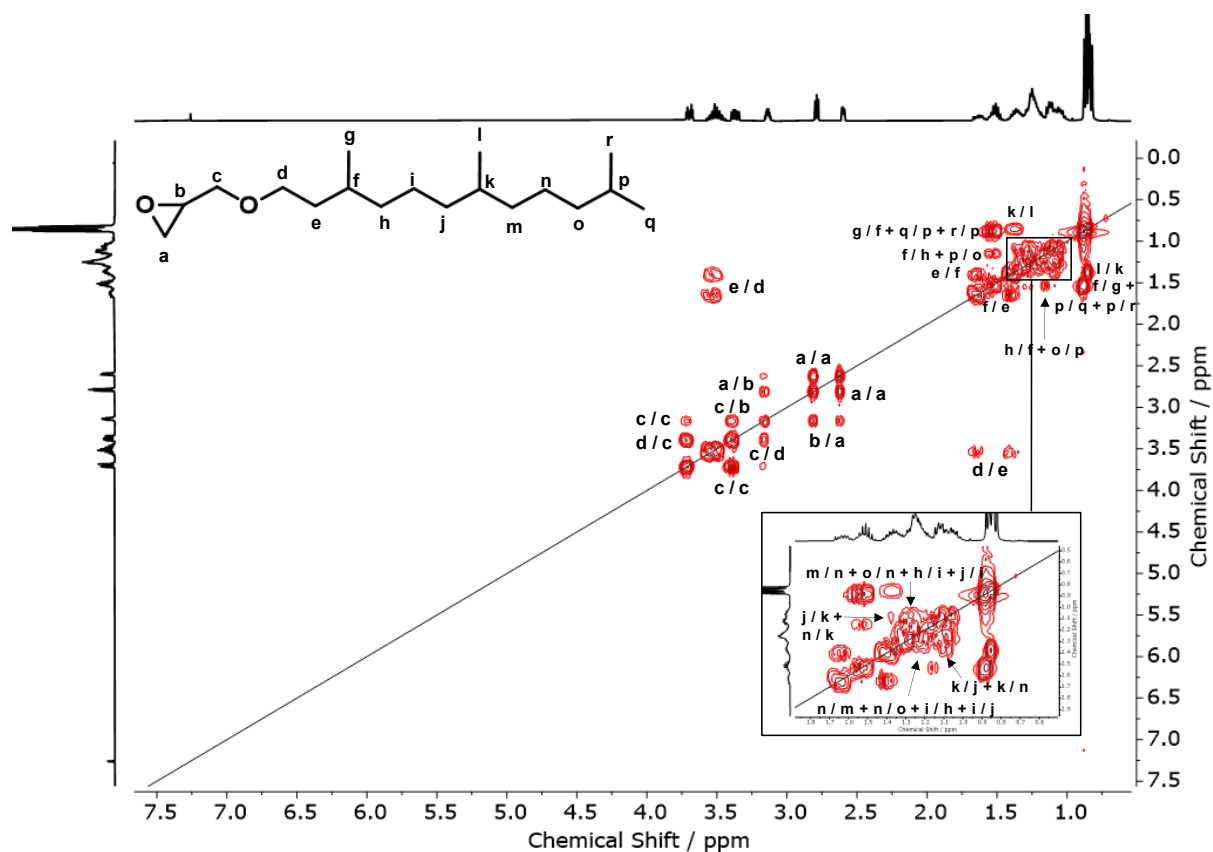
$T_g = -75 \text{ }^\circ\text{C}$

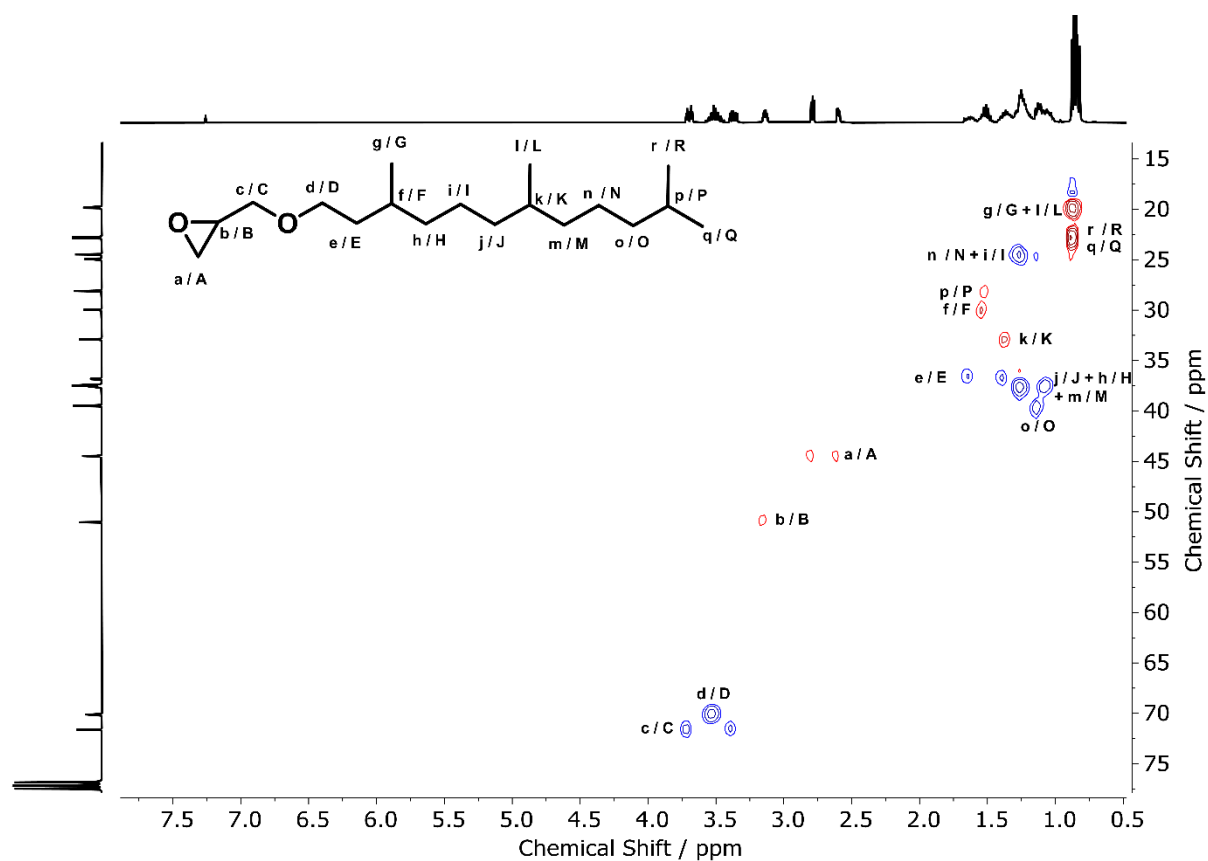
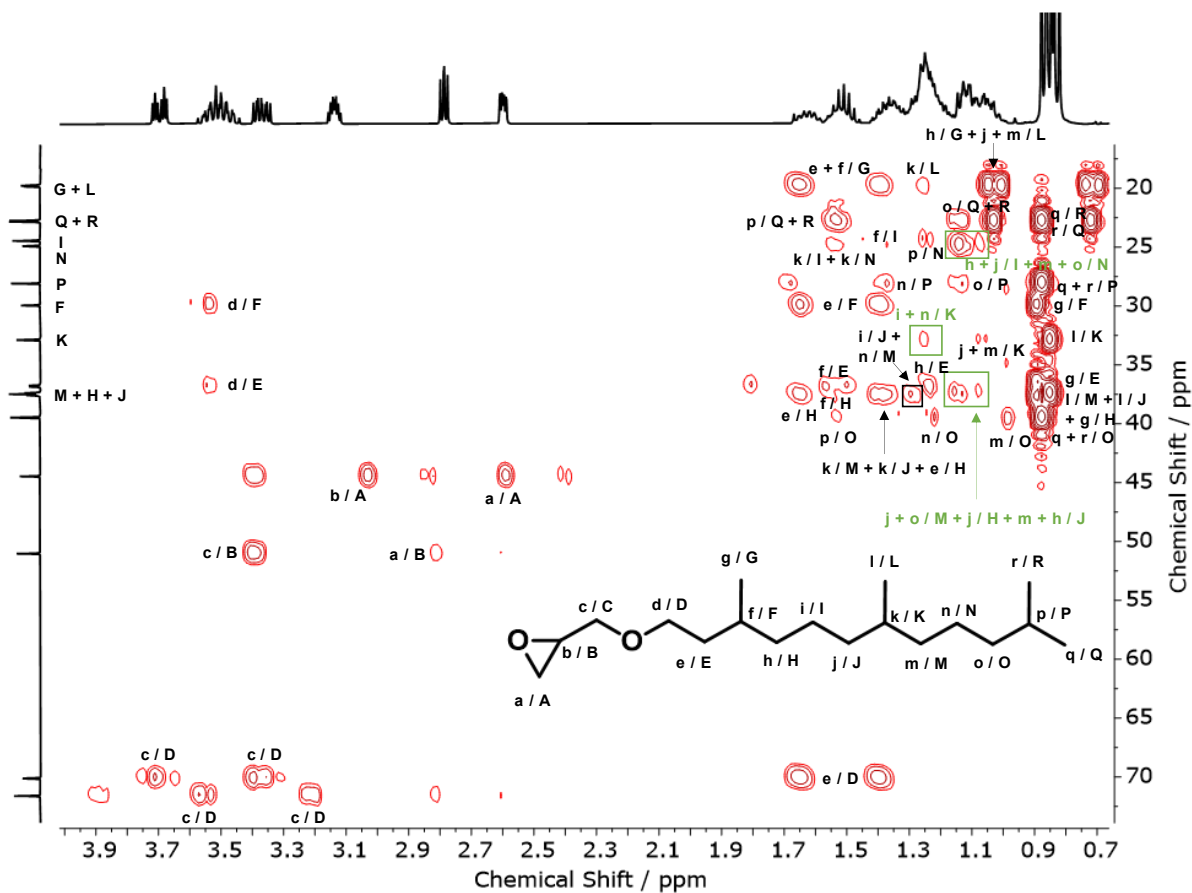
NMR and IR Spectra of HHF and HHFarGE

Figure S 1: ¹H NMR spectrum (400 MHz, CDCl₃) of HHF.Figure S 2: ¹³C NMR spectrum (100 MHz, CDCl₃) of HHF.

Figure S 3: ^1H - ^1H COSY NMR spectrum (400 MHz, CDCl_3) of HHF.Figure S 4: ^1H - ^{13}C HSQC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of HHF.

Figure S 5: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of HHF.Figure S 6: ^1H NMR spectrum (400 MHz, CDCl_3) of HHFarGE.

Figure S 7: ¹³C NMR spectrum (100 MHz, CDCl₃) of HHFarGE.Figure S 8: ¹H-¹H COSY NMR spectrum (400 MHz, CDCl₃) of HHFarGE.

Figure S 9: ^1H - ^{13}C HSQC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of HhFarGE.Figure S 10: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of HhFarGE.

NMR Characterization of Diblock Copolymers of HHFarGE and mPEG₁₁₄

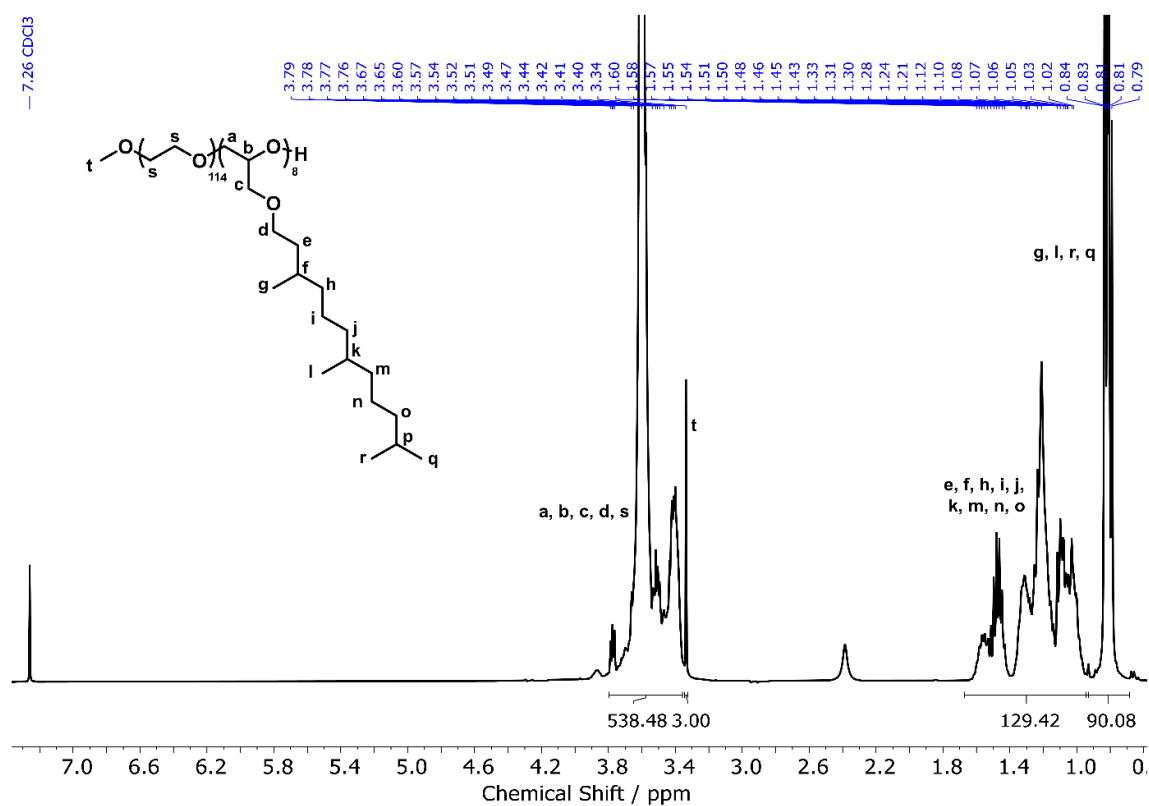


Figure S 11: ¹H NMR spectrum (400 MHz, CDCl₃) of mPEG₁₁₄-b-PHHFarGE₈.

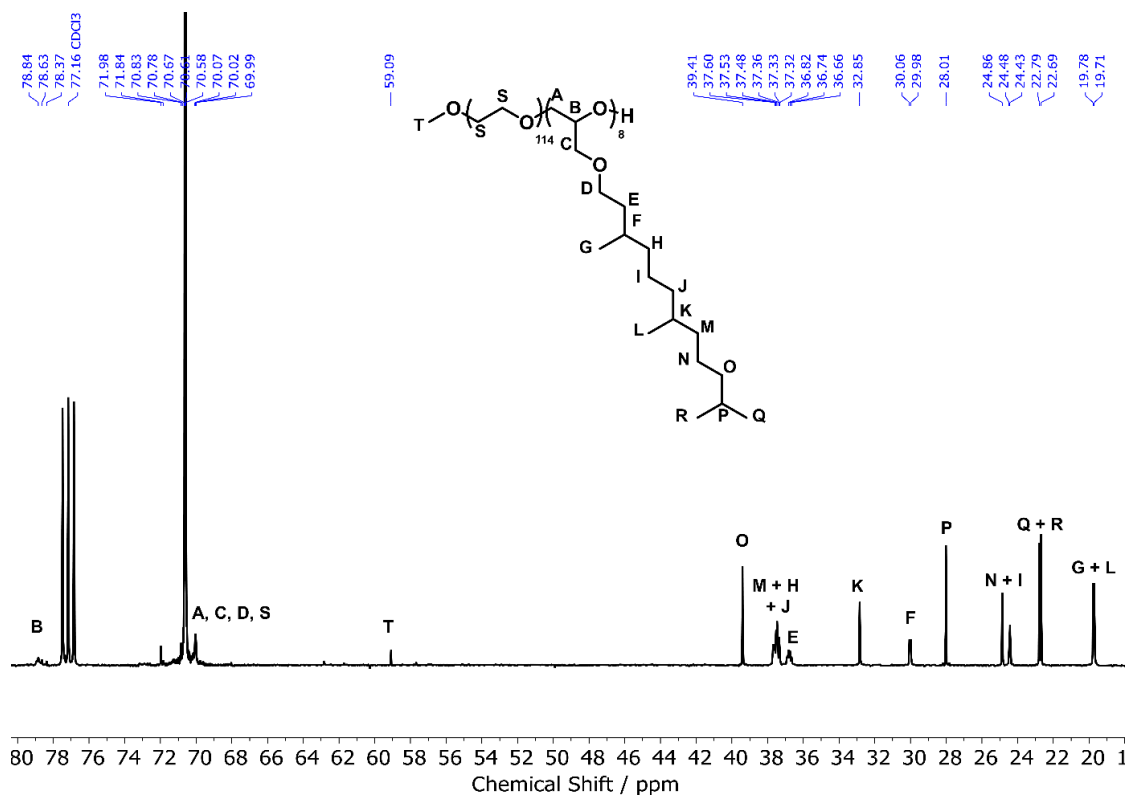
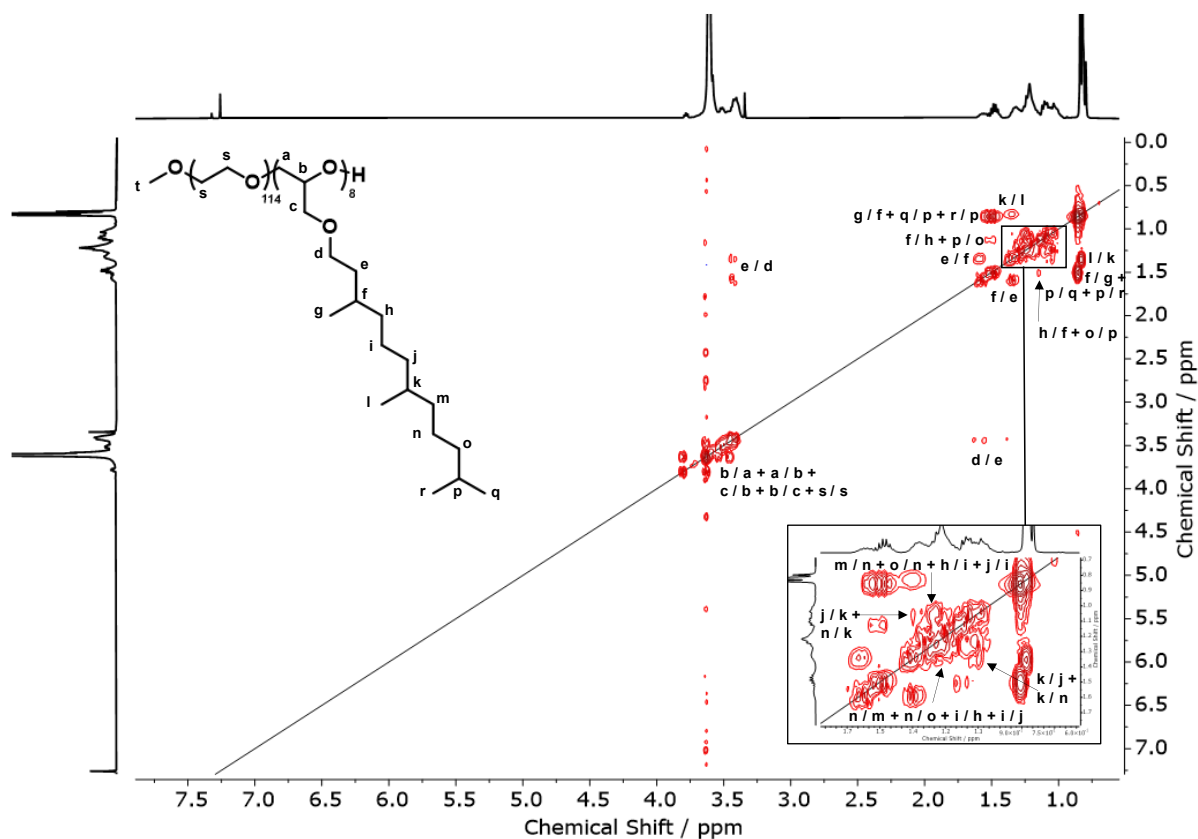
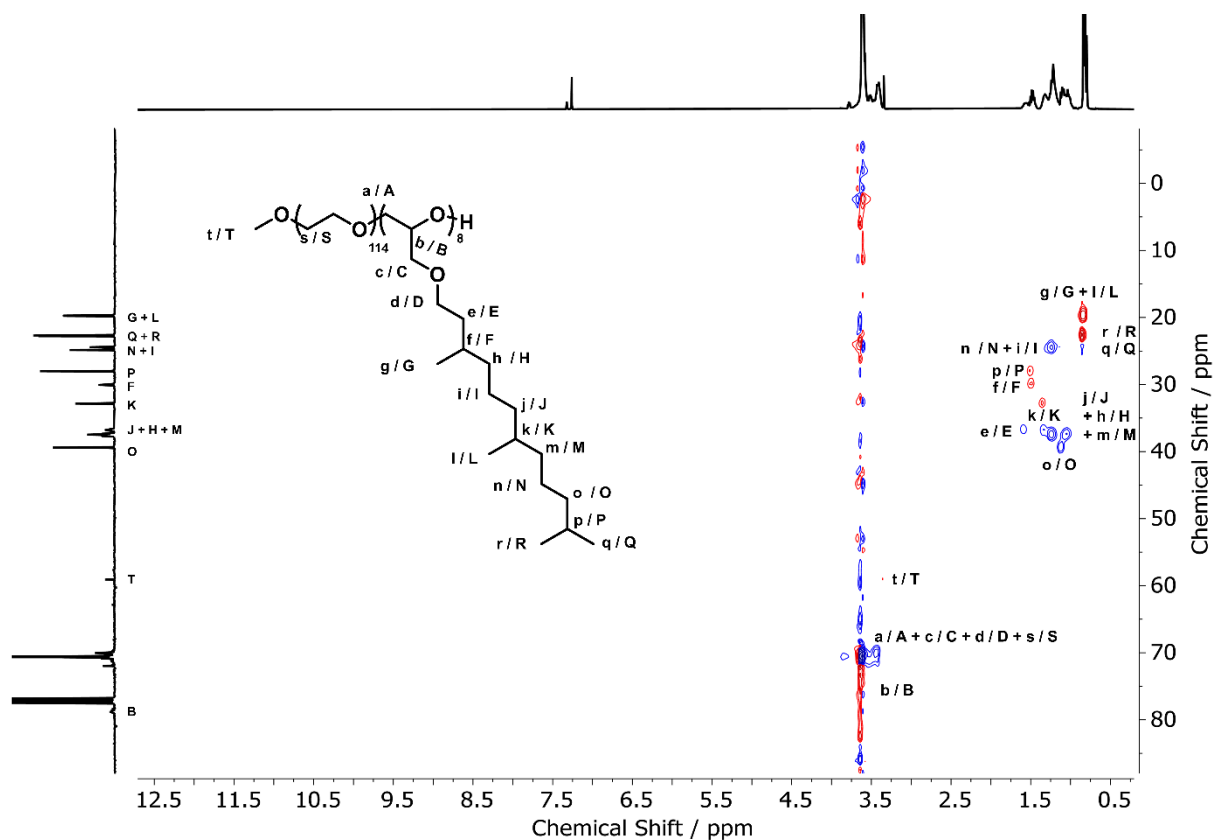


Figure S 12: ¹³C NMR spectrum (100 MHz, CDCl₃) of mPEG₁₁₄-b-PHHFarGE₈.

Figure S 13: ^1H - ^1H COSY NMR spectrum (400 MHz, CDCl_3) of mPEG_{114} - b -PHHFarGE $_8$.Figure S 14: ^1H - ^{13}C HSQC NMR spectrum (400 MHz/100 MHz, CDCl_3) of mPEG_{114} - b -PHHFarGE $_8$.

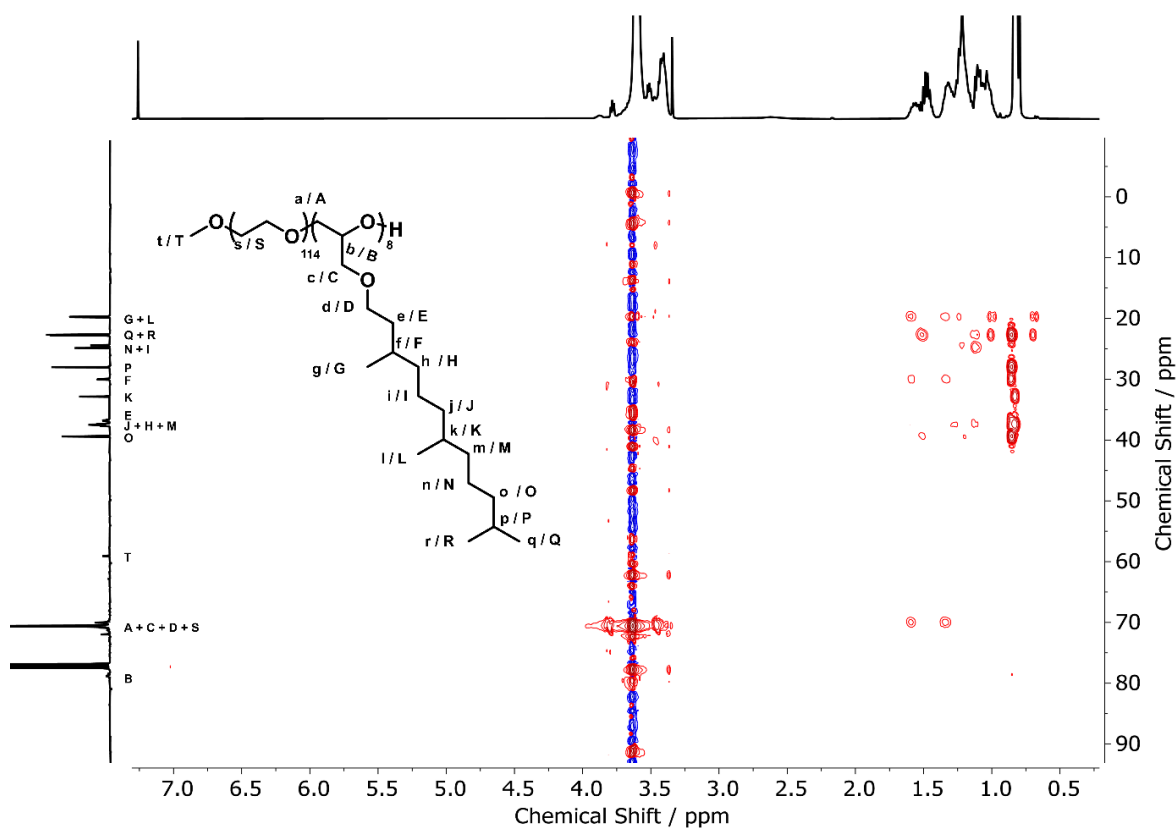


Figure S 15: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of $\text{mPEG}_{114}\text{-}b\text{-PHHFarGE}_8$. Coupling assignment was omitted for clarity reasons. Compare Figure S 10.

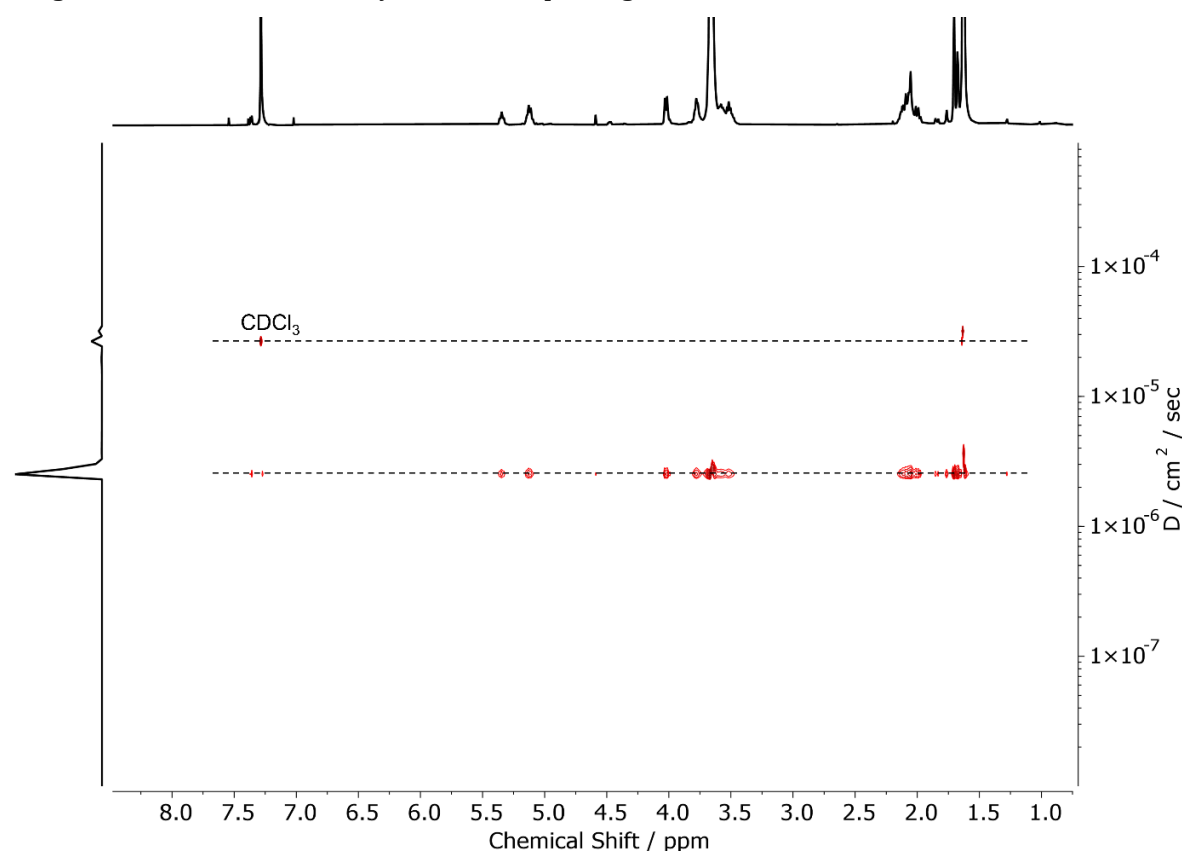
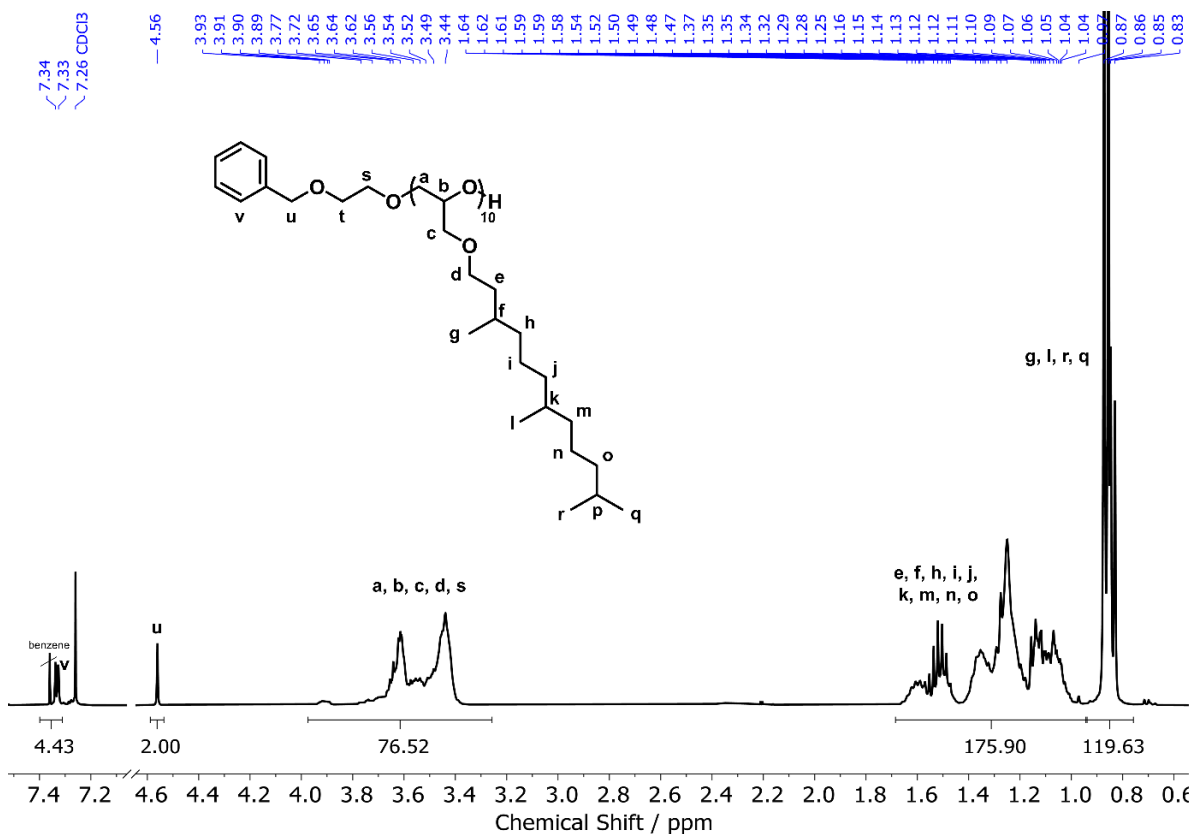
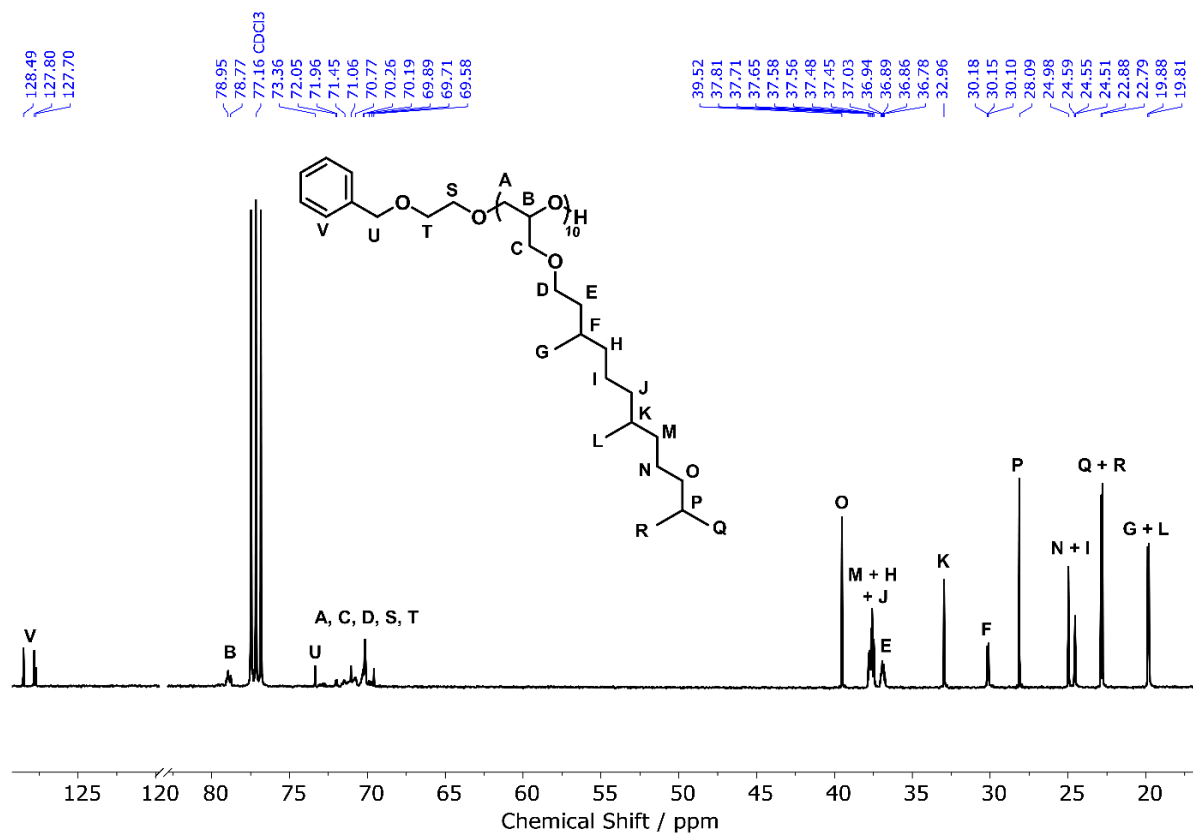
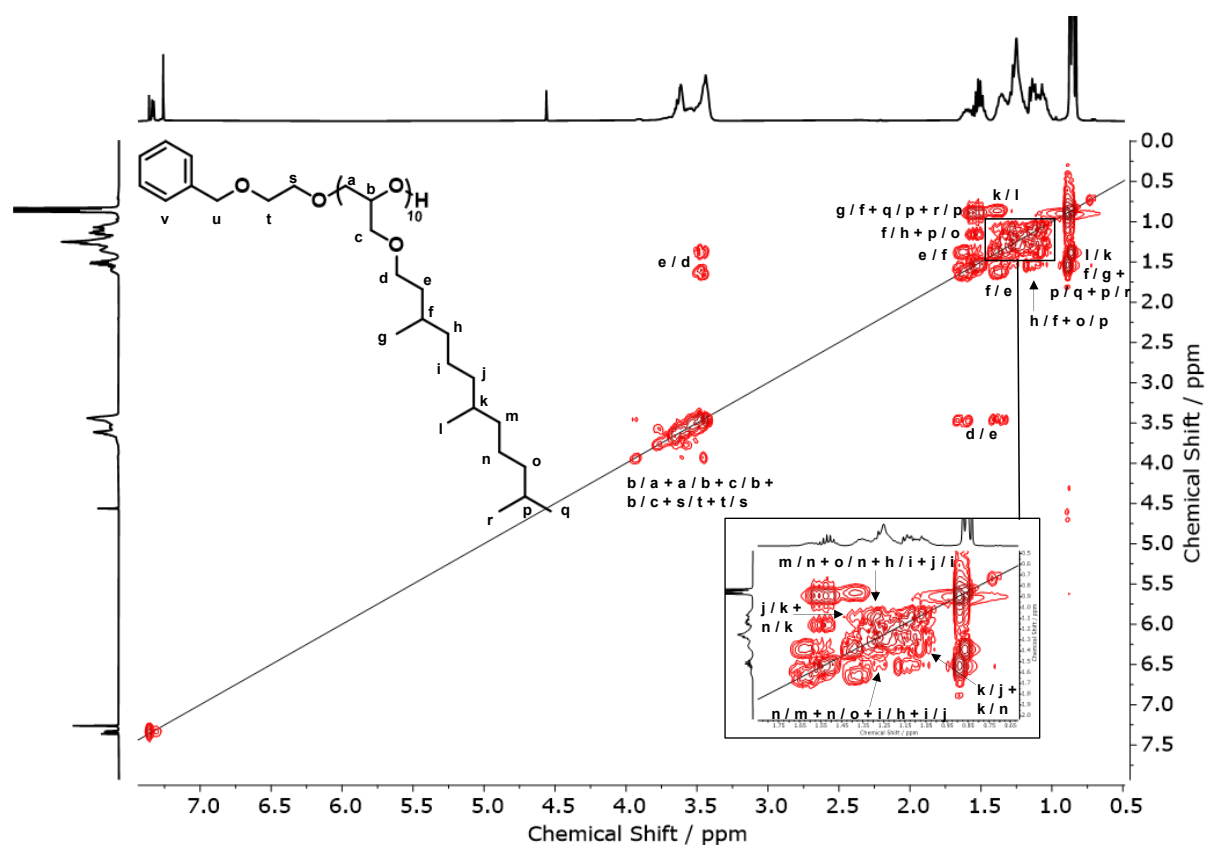
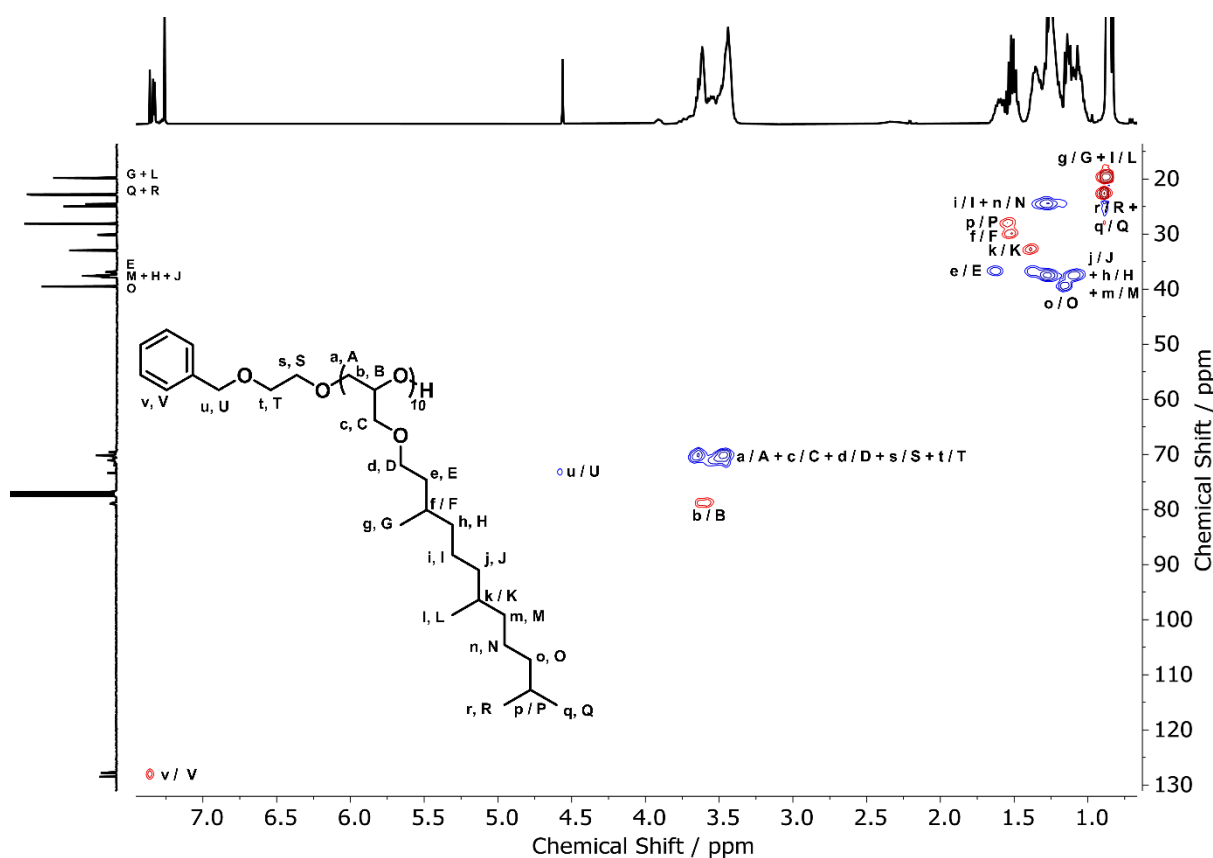


Figure S 16: DOSY NMR spectrum (400 MHz, CDCl_3) of $\text{mPEG}_{114}\text{-}b\text{-PHHFarGE}_5$, featuring a single diffusion coefficient for the block copolymer. The signal at 7.26 ppm and 1.60 ppm with a higher diffusion coefficient belong to the CDCl_3 solvent and water, respectively.

NMR Characterization of PHHFarGE_mFigure S 17: ¹H NMR spectrum (400 MHz, CDCl₃) of PHHFarGE₁₀.Figure S 18: ¹³C NMR spectrum (100 MHz, CDCl₃) of PHHFarGE₁₀.

Figure S 19: ^1H - ^1H COSY NMR spectrum (400 MHz, CDCl_3) of PHHFarGE₁₀.Figure S 20: ^1H - ^{13}C HSQC NMR spectrum (400 MHz/100 MHz, CDCl_3) of PHHFarGE₁₀

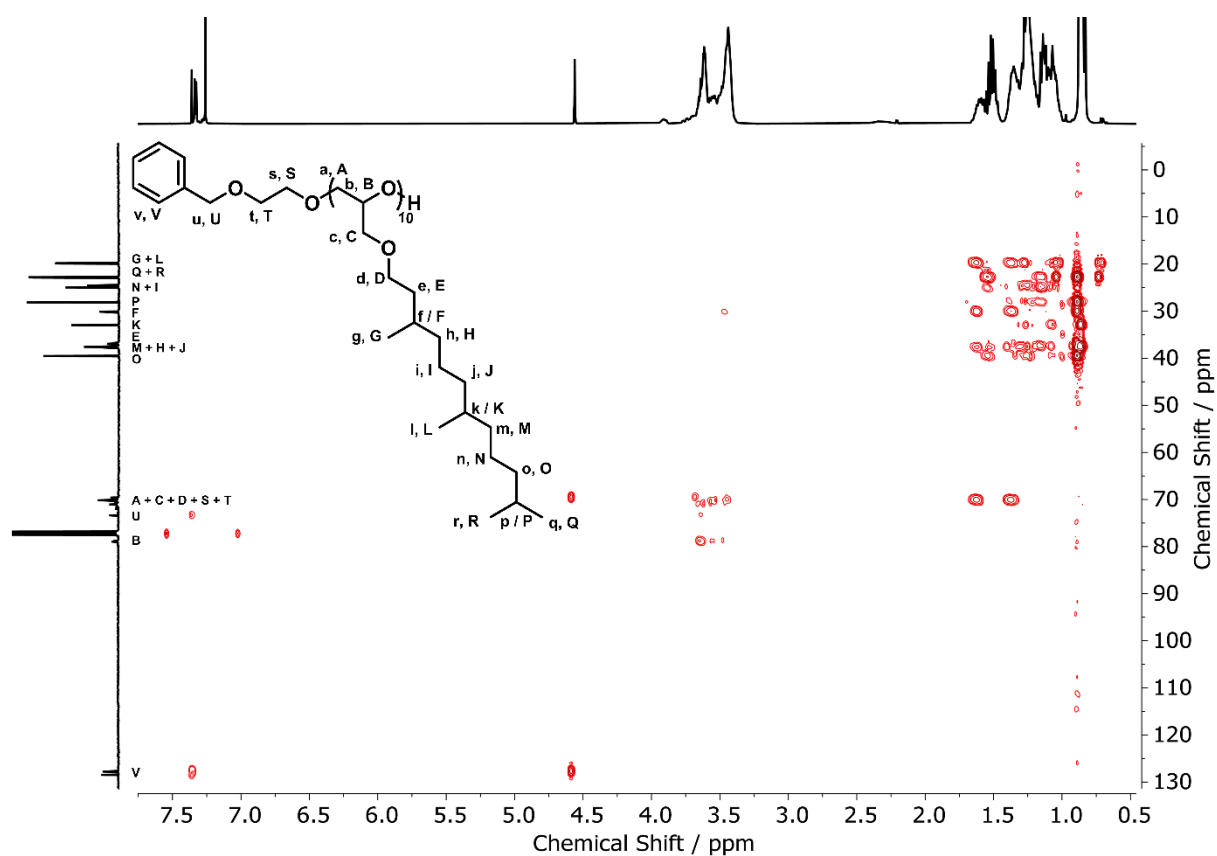


Figure S 21: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/ 100 MHz, CDCl_3) of PHHFarGE₁₀. Coupling assignment was omitted for clarity reasons. Compare Figure S 10.

Characterization of PHHFarGE_m and PFarGE_m Homopolymers

Table S 1 summarizes characterization data for homopolymers of HHFarGE and FarGE, which are to be investigated via SANS measurements. Due to the high hydrophobicity of HHFarGE_m, SEC analysis was conducted in THF as eluent (Figure S 22). Owing to the SEC resolution limits, the SEC traces of the homopolymers with a $P_n=5$ (Table S 1, entry 1 and 3) feature several humps towards higher elution volumes (smaller molecular weights), which can be ascribed to the discrete oligomeric species.

Table S 1: Characterization data of synthesized PHHFarGE_m and PFarGE_m homopolymers with respect to molecular weights, dispersity and thermal properties.

Entry	Sample	$M_n^a / \text{g} \cdot \text{mol}^{-1}$	$M_n^b / \text{g} \cdot \text{mol}^{-1}$	$\bar{D}^b$	$T_g^c / ^\circ\text{C}$
1	PHHFarGE ₅	1580	1800	1.12	-73
2	PHHFarGE ₁₀	3000	3300	1.12	-74
3	PFarGE ₅	1540	1800	1.13	-74
4	PFarGE ₁₂	3490	3500	1.20	-75

^aNumber-averaged molecular weight determined via ¹H NMR spectroscopy. ^bDetermined via SEC measurements using THF as eluent and PEG as standard. ^cGlass transition temperature determined by DSC at a heating rate of 10 °C/min. Extrapolation for entry 1 and 3 was limited due to the lower limit of the measurement. Errors are estimated as ± 2 °C.

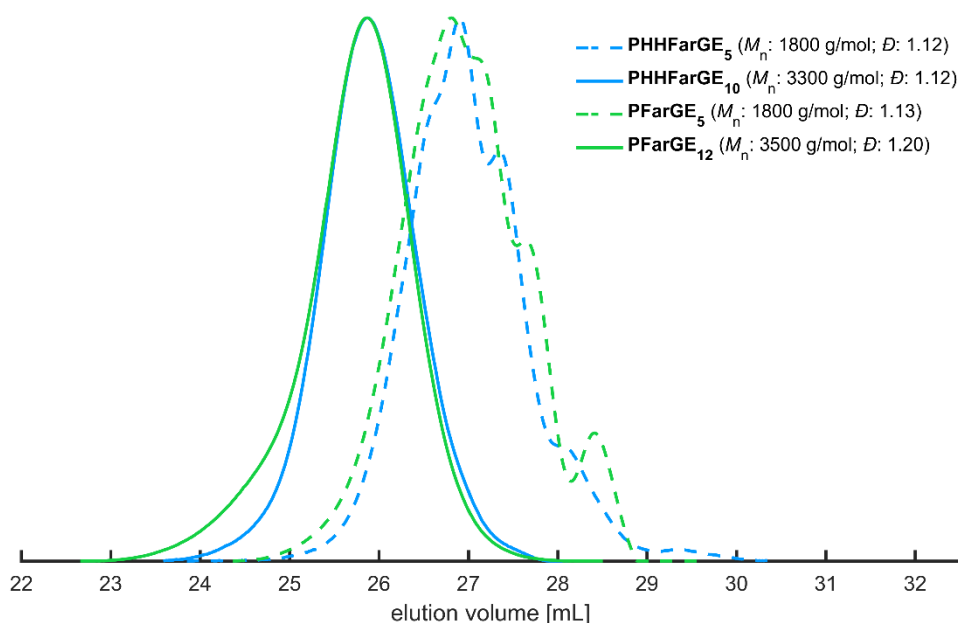


Figure S 22: SEC elution traces of the synthesized PHHFarGE_m and PFarGE_m homopolymers using BzEtOH as initiator (RI detector, eluent: THF, PEG calibration).

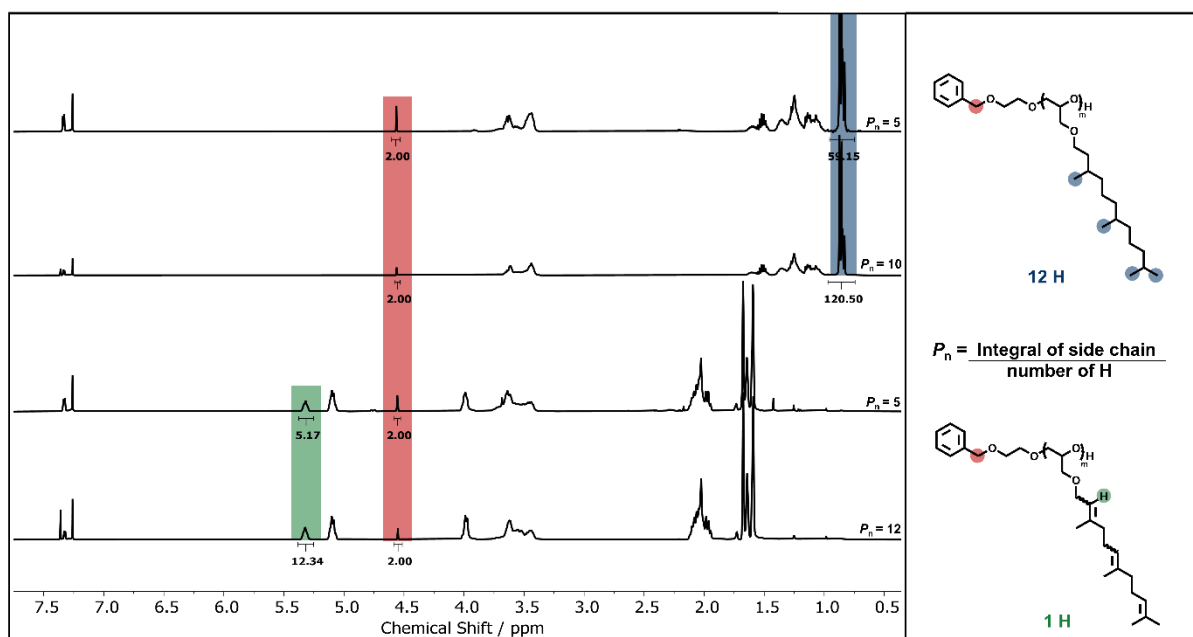


Figure S 23: Overlay of ^1H NMR spectra (400 MHz, CDCl_3) of PHHFarGE_m and PFarGE_m homopolymers.

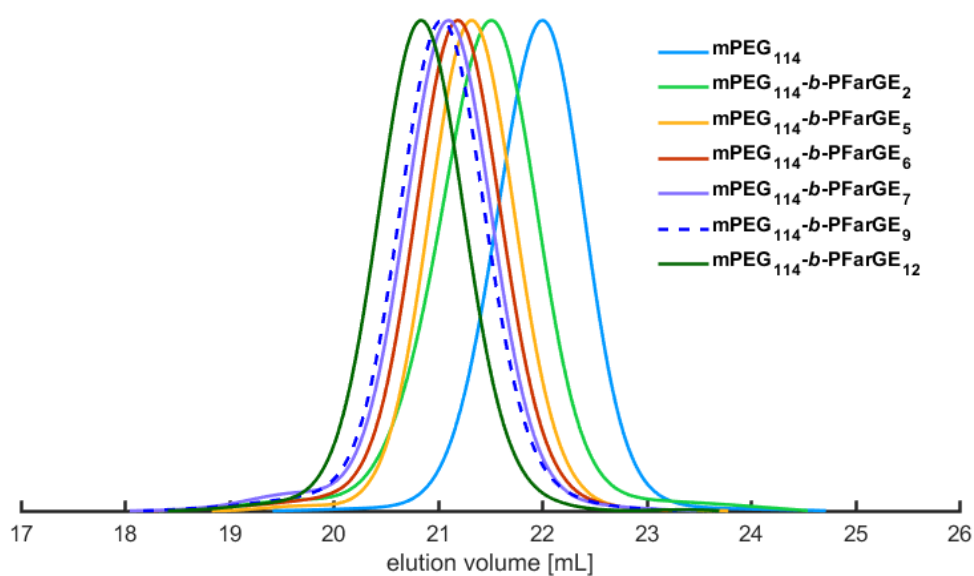
SEC Measurements of Diblock Copolymers of FarGE and mPEG₁₁₄

Figure S 24: SEC elution traces of selected mPEG₁₁₄-*b*-PFarGE_m diblock copolymers compared to initial the mPEG₁₁₄ macroinitiator (top) (RI detector, eluent: DMF, PEG calibration).¹²

DSC Thermograms of the Synthesized Diblock Copolymers and Homopolymers

All results of the thermal analysis are given in Table 1.

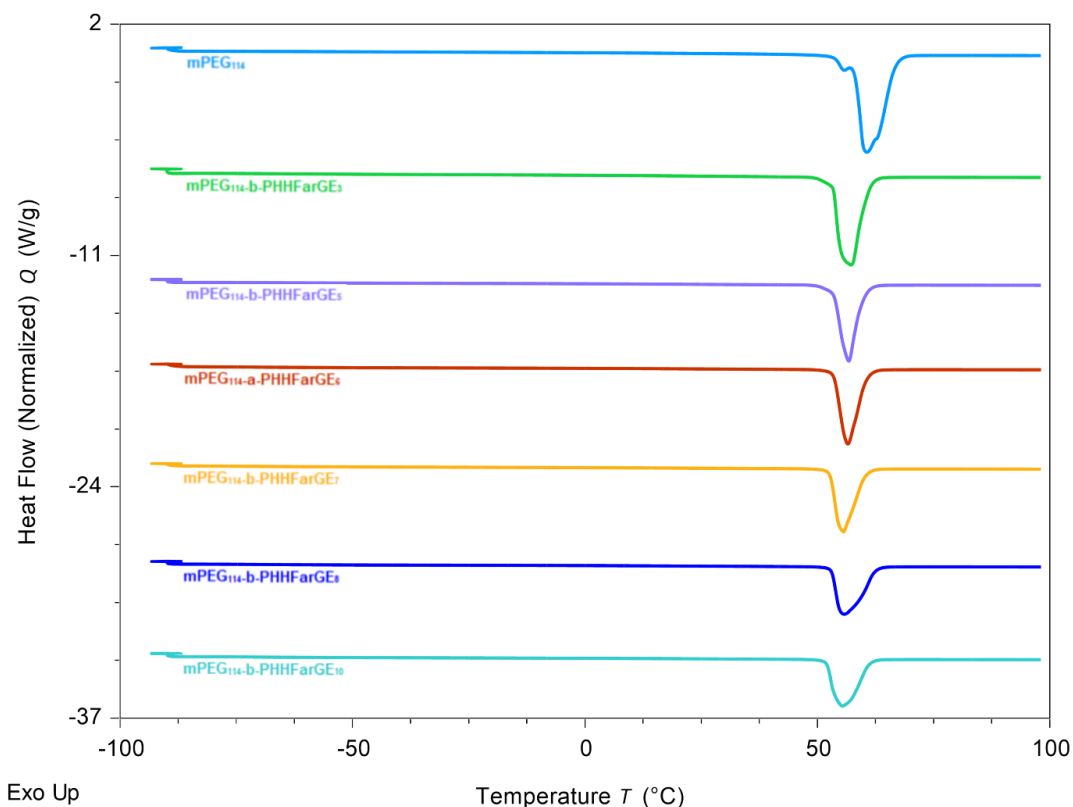


Figure S 25: DSC thermograms of mPEG₁₁₄-b-PHHFarGE_m diblock copolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

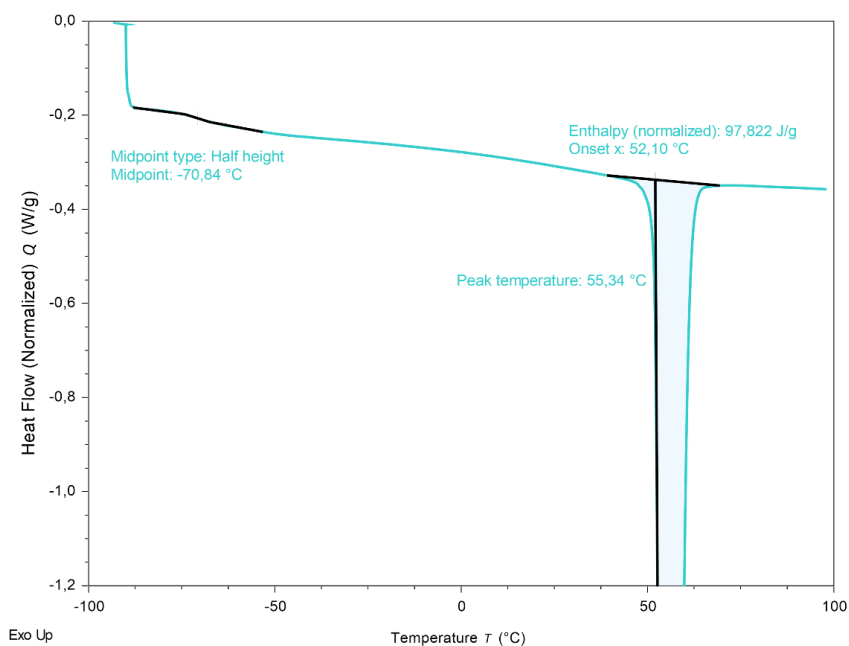


Figure S 26: Exemplary DSC thermogram of mPEG₁₁₄-b-PHHFarGE₁₀ diblock copolymer exhibiting a weak glass transition feature (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

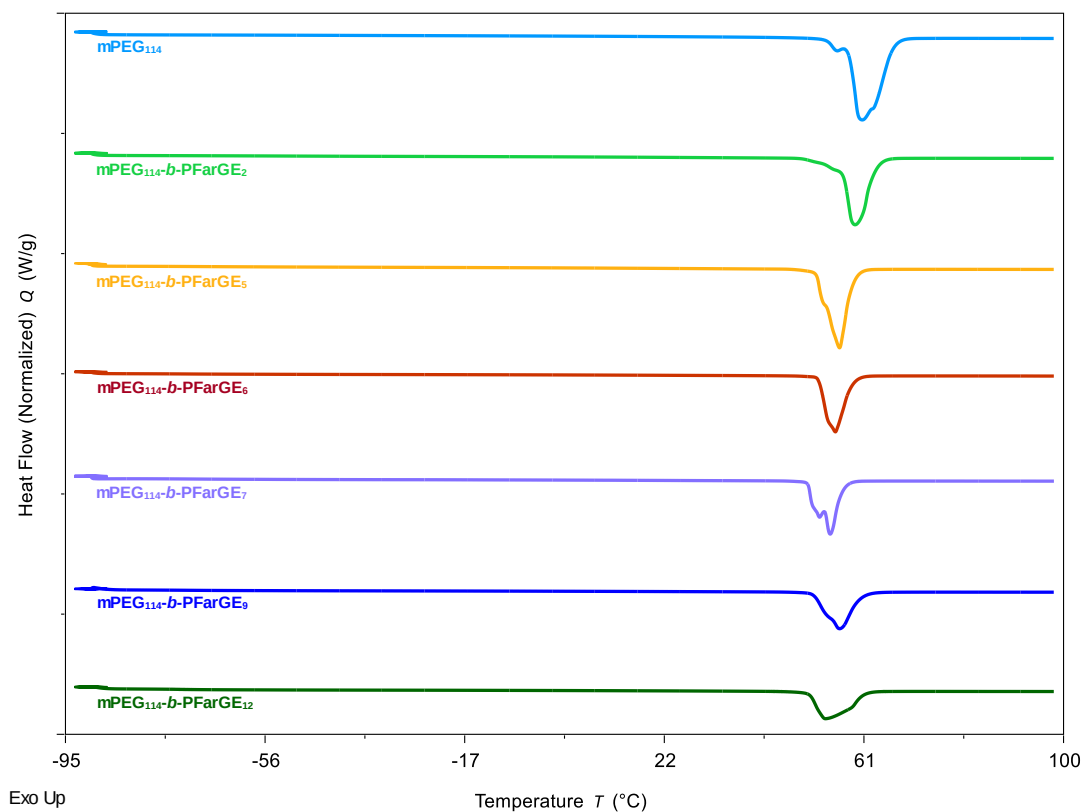


Figure S 27: DSC thermograms of mPEG₁₁₄-b-PFarGE_m diblock copolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹). Thermal analyses have been previously reported.¹²

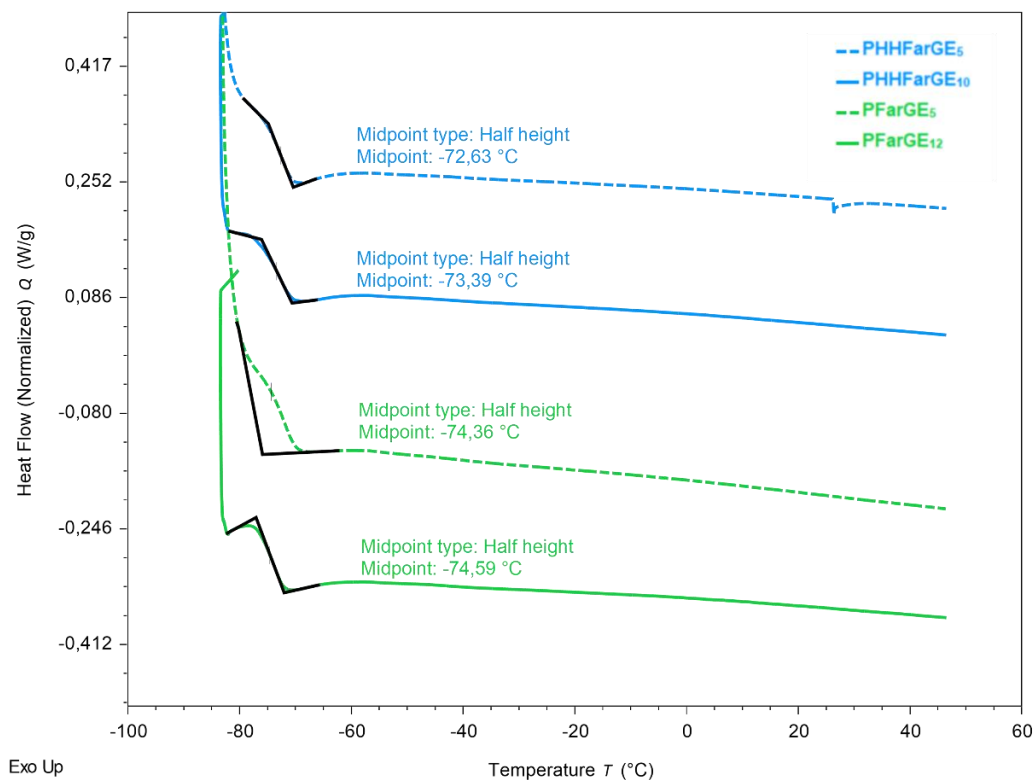


Figure S 28: DSC thermograms of PHHFarGE_x and PFarGE_x homopolymers (second heating cycle, from -90 to 50 °C, 10 °C·min⁻¹). Extrapolation for PHHFarGE₅ and PFarGE₅ was limited due to the lower limit of the measurement. Errors are estimated as ± 2 °C.

Determination of CMCs via Fluorescence Spectroscopy

We previously reported on a power law equation to calculate the CMC of the diblock copolymer:¹²

$$I_1/I_3 = \frac{A_1 - A_2}{1 + (c/c_0)^f} + A_2, \quad (5)$$

A_1 and A_2 are the upper and lower limits of the sigmoid (I_1/I_3 for $c \rightarrow 0$ and $c \rightarrow \infty$, respectively), f represents the steepness of the sigmoid and c_0 is defined as the concentration at the inflection point of the sigmoid, also known as the CMC. The advantage of this altered version of the exponential-based approach by Aguiar et al. is its applicability to determine solely positive concentrations and lower χ^2 .⁵ FS data for all FarGE (Figure S30) and HHFarGE polymers (Figure S31) are shown below. Note that the hydrophobicity of the pyrene surroundings influences the fluorescence intensity ratio I_1/I_3 . However, the I_1/I_3 ratio approximates a value of $I_1/I_3 \approx 1.2$ for all diblock copolymers of varying length as the hydrophobic core always consists of FarGE and HHFarGE, which are similar in their side chain structure. The dependence of the CMC on copolymer hydrophobicity is presented in Figure 4 and Figure S 29. All CMC values are summarized in Table 2.

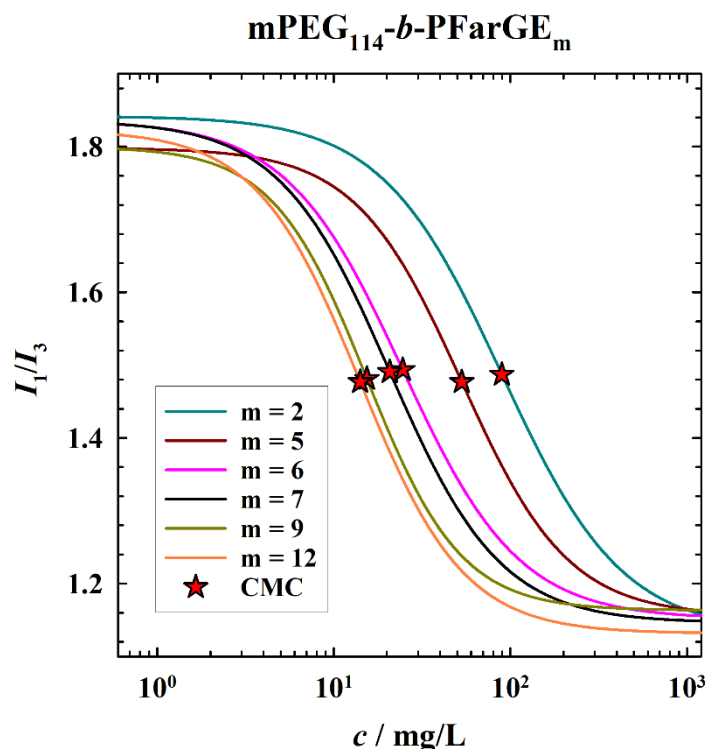


Figure S 29: Overlay of intensity ratio I_1/I_3 plots versus diblock copolymer concentration for the mPEG₁₁₄-b-sPFarGE_m diblock copolymer series, visualizing the anticipated shift to lower CMC values with increasing FarGE block size. CMCs are depicted with stars. To maintain clarity, only the fitting curves are depicted without the respective data points.^{12,14}

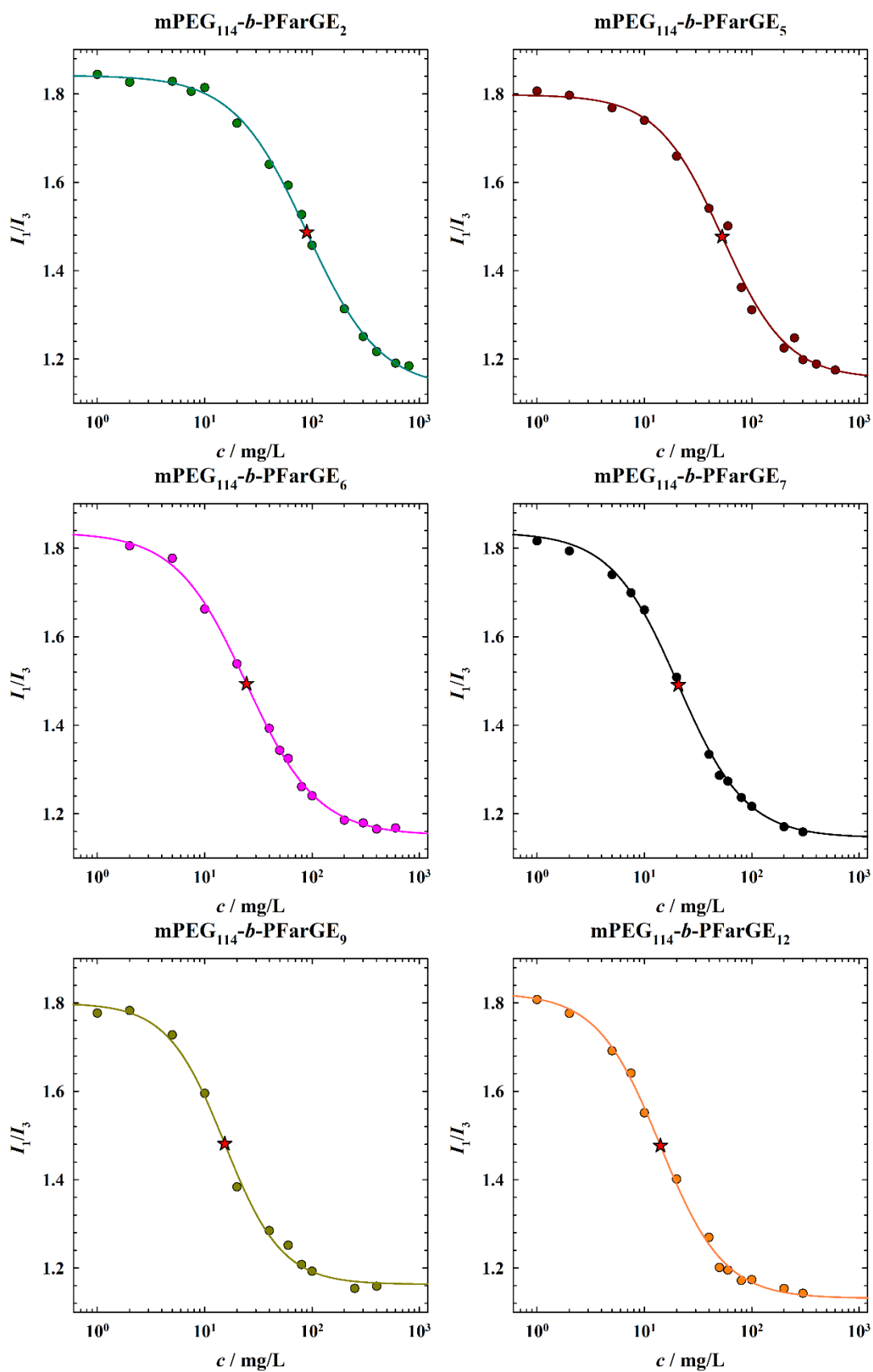


Figure S 30: Plots of the pyrene intensity ratio I_1/I_3 ($c_{\text{pyrene}} = 7 \cdot 10^{-7}$ M) versus polymer concentration, allowing for determination of the CMCs via fluorescence spectroscopy for the series of mPEG₁₁₄-b-PFarGE_m diblock copolymers. CMCs are depicted with stars.^{12,14}

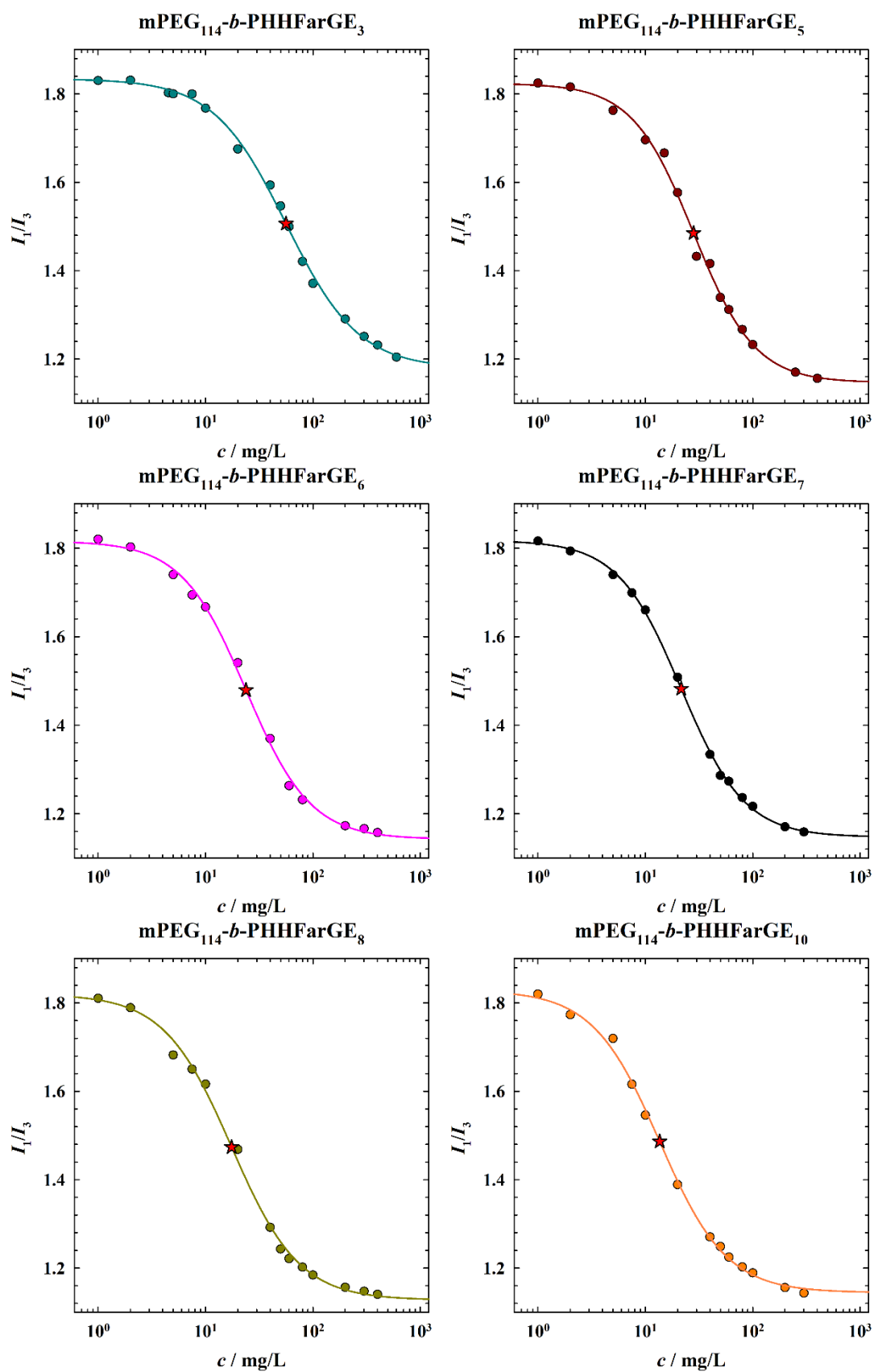


Figure S 31: Plots of the pyrene intensity ratio I_1/I_3 ($c_{\text{pyrene}} = 7 \cdot 10^{-7}$ M) versus polymer concentration, allowing for determination of the CMCs via fluorescence spectroscopy for the series of mPEG₁₁₄-b-PHHFarGE_m diblock copolymers. CMCs are depicted with stars.¹⁴

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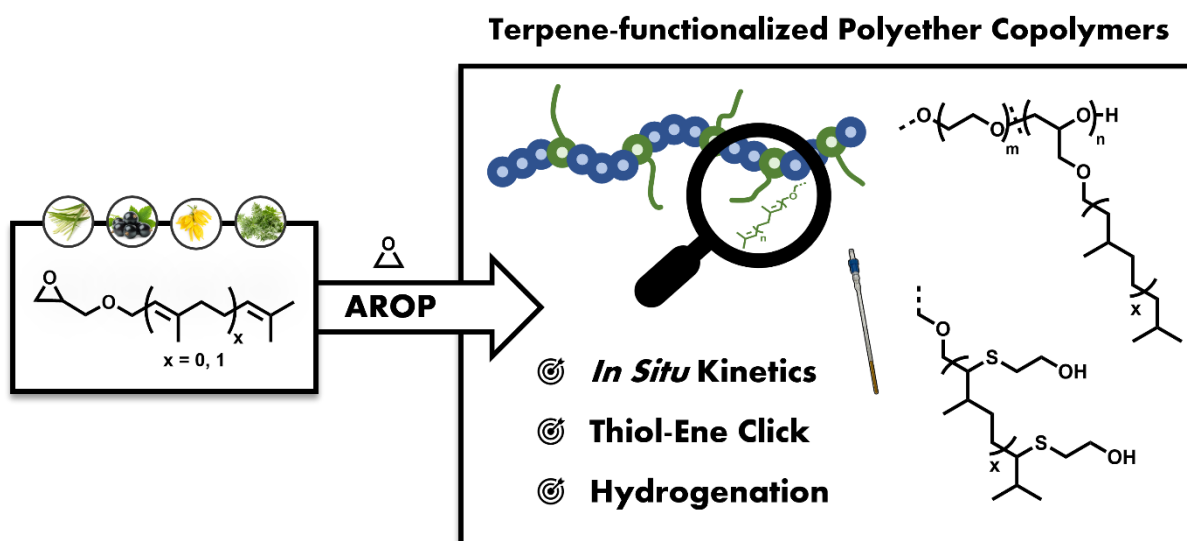
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2.3 Poly(Terpenyl Glycidyl Ether)s: Copolymerization with Ethylene Oxide, Properties, and Functionalization

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To be submitted.



Abstract

Multifunctional poly(ethylene glycol)s (*m*/PEGs) are accessible via the anionic copolymerization of functional epoxides with ethylene oxide (EO). Glycidyl ethers are conveniently synthesized from bio-renewable alcohols and epichlorohydrin (ECH). Herein, we present the synthesis of a series of acyclic terpenyl glycidyl ethers (TGEs) and their subsequent copolymerization with ethylene oxide (EO) via anionic ring opening polymerization (AROP). The resulting library of copolymers with varying side chain length and comonomer composition comprises molecular weights in the range of 4800 to 8300 g mol⁻¹ and narrow molecular weight distributions ($\bar{D} = 1.06 - 1.13$). For the copolymerization of the TGEs with EO, detailed ¹H NMR *in situ* kinetic studies revealed a change from ideally random to slight gradient copolyether microstructures, with increasing chain length and hydrophobicity of the respective TGE. The living nature of AROP provides control of molecular weights, and optimized reaction conditions, such as low temperatures and a weakly bound cesium counterion, suppress the well-known proton abstraction of monosubstituted epoxides. Since the incorporation of the terpenyl side chains impedes crystallization, thermal properties can be tailored by the monomer feed ratio. Subsequently, hydrogenation and thiol-ene click reactions at the side chain double bonds were carried out as post-polymerization modifications. The application of potassium azodicarboxylate (PADA) in the diimide reduction of polymers was demonstrated to possess immense potential for the full hydrogenation of the novel copolymers, offering facile purification options. Overall, the copolymerization of EO and TGEs give access to biobased, tailormade polyethers with pathways to post-functionalization.

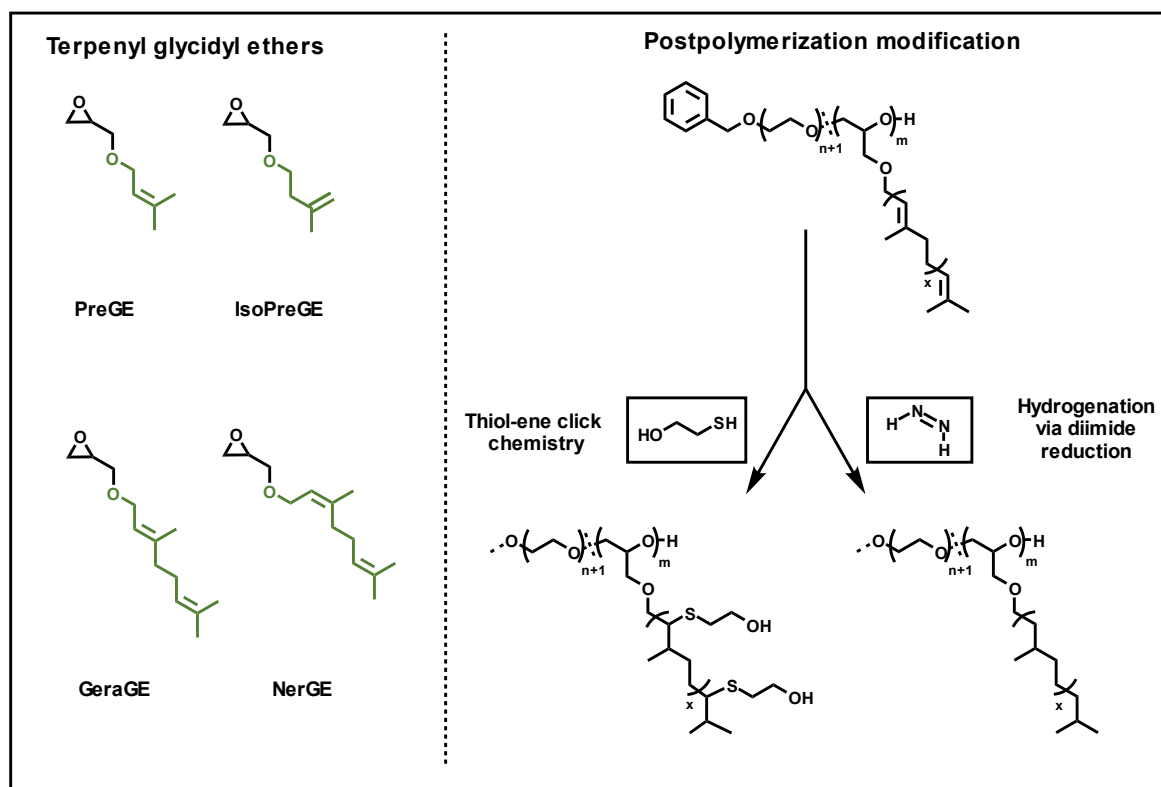
Introduction

Poly(ethylene glycol) (PEG) marks a high-value polyether owing to its excellent biocompatibility and extraordinary solubility in aqueous media. Known as the gold standard for pharmaceutical and biomedical polymers, the application range of PEG also includes cosmetics, surface-active materials and polymer electrolytes.^{1–4} To overcome the limited backbone functionality, the copolymerization of ethylene oxide (EO) with functional epoxide building blocks allows for the synthesis of multifunctional PEG (*mf*-PEG) featuring tailormade material properties.^{1,5} Particularly glycidyl ethers (GE) represent an underrated monomer class, which is available via a plethora of alcohols and epichlorohydrin (ECH).^{6,7} Alternatively, the reaction of an alcohol with allyl bromide, followed by the epoxidation using *meta*-chloroperoxybenzoic acid affords the respective GE.⁸ However, despite aiming at transitioning toward the use of renewable resources for polymer synthesis, bio-derived epoxides in general and specifically glycidyl ethers have scarcely been exploited for more sustainable polyethers.⁹ Simultaneously, several efforts have been reported that aim at more sustainable sources of conventional polyether building blocks. Intriguingly, Sargent and coworkers have recently improved the electrochemical production of ethylene oxide (EO) from CO₂ and water.¹⁰ Alternatively, “green ethylene” can be transformed into EO utilizing the conventional silver-catalyzed epoxidation.¹¹ Furthermore, “green ECH” is readily available from glycerol, a byproduct in the bio-fuel production from biomass.^{12,13}

The use of natural product-based building blocks in the glycidyl ether synthesis is a key objective. Fatty acids extracted as value-added chemical from plant oils, have been a long-standing raw material for the chemical industry and polymer synthesis.^{14,15} Relevant parameters, which affect the chemical and physical properties, are the length and the degree of unsaturation of the fatty acid chain as well as the stereochemistry of the double bond.¹⁶ Relying on fatty acids, the respective alcohols for glycidyl ether synthesis are accessible via a reductive transformation into an alcohol and subsequent phase transfer catalysis.¹⁵ Verkoyen et al. published an extensive overview of available long-chain alkyl epoxides and glycidyl ethers, characterized by their hydrophobicity, including some examples of fatty acid analogues.^{7,17}

As another class of relevant, bio-mass derived building blocks, terpenoids and terpenes have been established as attractive monomer precursors.^{14,18} Following the “isoprene rule”, acyclic terpenoids vary in their chain length based on the number of linear, head-to-tail condensed (C₅H₈)_n units they are comprised of. Thus, the number of repeat

isoprene units allows for the classification into hemi- (C_5), mono- (C_{10}) and sesquiterpenoids (C_{15}).^{19,20} Linear, acyclic terpenoids are abundant in ethereal oils of fruits and plants and their application ranges from pharmaceutical products, flavors, fragrances and pheromones.^{21,22} Producing GEs from a range of acyclic terpenoids gives rise to a diverse platform of bio-renewable epoxide monomers (Scheme 1, left). The proposed terpenyl glycidyl ethers (TGEs) are characterized by their unsaturated, hydrophobic side chains. In general, their branched nature impedes crystallization, in stark contrast to their linear fatty acid analogues.⁸ To date, only a handful of publications on polyether and polycarbonates have capitalized on these terpene-derived epoxide building blocks, being suitable for anionic and catalytic polymerization techniques.^{23–28} On one hand, the hydrophobic character of farnesyl glycidyl ether in combination with PEG enables the facile synthesis of amphiphilic polyethers.^{25,26} On the other hand, the terpenyl side chain flexibility leads to a low glass transition temperature (T_g), thus permitting the generation of low- T_g polycarbonates.^{27,28} Moreover, replacement of the commonly applied propylene oxide as a hydrophobic building block takes effect on the copolymer microstructure. It has to be emphasized that the copolymerization of EO with PO entails a strong gradient microstructure, whereas GE and EO are expected to produce a random copolymer.^{29–31}



Scheme 1: Scope of prepared bio-renewable TGEs for copolyether synthesis (left). The TGE copolymers are amenable for post-polymerization modification such as hydrogenation and thiol-ene click (right).

In addition, the unsaturated side chains of such acyclic TGEs with chemically differing double bonds serve as chemoselective handles due to the chemically differing double bonds and, in turn, enable tailor-made materials via post-functionalization.^{14,18,22,32} For TGEs, cross-metathesis has been demonstrated by Morris and coworkers, who were the first to report on TGEs for polyether synthesis utilizing prenyl glycidyl ether (PreGE) and isoprenyl glycidyl ether (IsoPreGE).²³ In this context, PreGE and IsoPreGE can be considered as a bio-renewable analogue of the commonly applied allyl glycidyl ether (AGE). Moreover, successful click-TAD chemistry on a citronellyl glycidyl ether side chain has made terpene-derived polyether-based organo- and hydrogels available.²⁴ Yet, the plentiful modification opportunities have not been investigated extensively. For instance, the thiol-ene click reaction of polymers offers flexible means to create custom materials, as documented in Lowe's comprehensive review.^{33,34} Thiol-ene addition has already found its place in the synthesis of bio-based polymers due to its facile "click" characteristic.^{35,36} Additionally, polymer structures that are usually difficult to access can be achieved by post-polymerization modification. Walter *et al.* were able to produce a variety of dendritic polymers by incorporating a reactive thiol into the core of the macro-thiols, followed by coupling with allylic precursors.³⁷ By employing cysteamine, polyisoprene was partially modified to produce a polymer containing amine groups. This amine-containing polymer was then protonated or quaternized, resulting in a positively charged polymer with antibacterial activity.³⁸ In addition, hydrogenation is a widely adopted approach that enhances the thermal and oxidative stability of polyisoprene by using gaseous hydrogen and metal catalysts at high temperatures in a reactor.³⁹ Another modification method is hydrogenation using diimide, which can be generated from various sources and does not require high pressure equipment.^{40,41} Typically, the production of diimide involves the thermal decomposition of *para*-toluenesulfonyl hydrazide (*p*TSH). Despite its effectiveness, the use of this reagent is accompanied by several limitations. These include the requirement for reflux in solvents with a high boiling point such as *ortho*-xylene, inefficient byproduct removal, and the occurrence of undesirable reactions towards polyisoprene, such as chain degradation, cyclization, and nucleophilic attack of *para*-tolylsulfinate anion.^{42,43} Chain degradation can be reduced by the addition of a tertiary amine and, conclusively, the *p*TSH route represents a reasonable alternative to catalyzed hydrogenation.

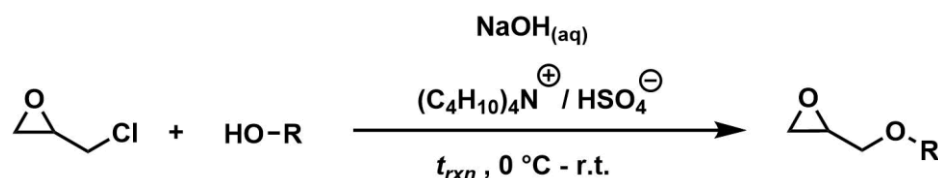
In this work, we present the use of different bio-based terpenyl glycidyl ethers for the synthesis of *mf*-PEGs. Applying hemi- and monoterpenoids in the synthesis of terpenyl glycidyl ethers (TGEs, Scheme 1), we expanded the available bio-derived TGE library for polyether design and synthesis. Statistical polyether copolymers P(EG_n-*co*-TGE_m) were

prepared via living AROP of EO and the TGEs of varying acyclic chain length. The resulting polyethers exhibit the targeted molecular weights and low dispersity $\bar{D}$ (≤ 1.12), while the thermal properties can be fine-tuned by the applied TGE content. ^1H NMR *in situ* kinetic was employed to study the impact of the glycidyl ether sides on the copolymerization behavior of the respective EO/TGE comonomer pairs. Furthermore, the structural variety regarding side chain length and double bond configuration was explored with respect to post-polymerization functionalization (Scheme 1). Aiming at introducing hydroxyl-functionalities, photochemical thiol-ene click chemistry was performed. Further, the double bond was hydrogenated via potassium azodicarboxylate (PADA) diimide reduction, which involves the *in situ* generation of the diimide via acidic decomposition of PADA. Subsequently, we address some of the limitations associated with the use of *p*TSH.

Results and Discussion

Monomer Synthesis

The presented TGEs have all been prepared in a phase transfer catalysis, starting from epichlorohydrin and the respective terpenoid.^{25,28} The products were isolated in high purity after distillation work up, which was performed subject to the monomer boiling temperature T_b .

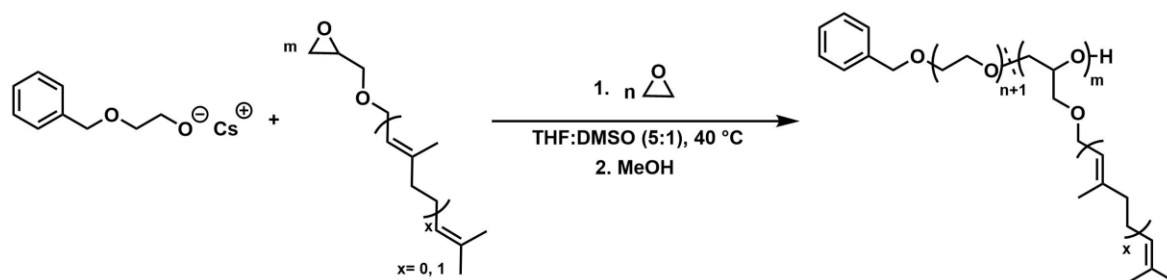


Scheme 2: General monomer synthesis via phase transfer catalysis.

During the phase transfer catalysis, elimination and substitution reactions lead to the formation of side products, specifically 3-chloro-allyl glycidyl ether and diglycidyl ether.^{25,28} While the resulting side products can be easily separated from the long-chain TGEs (C_{10} and C_{15}) due to a significant difference in boiling points, the C_5 -analogues, namely PreGE, IsoPreGE and DHPreGE, required an altered synthetic protocol.^{25,28} To suppress the side product formation, the synthesis approach utilizing the C_5 -alcohols was performed under prolonged cooling and for shorter reaction times, ultimately resulting in lower overall yields (51 – 64%) compared to the C_{10} and C_{15} -analogues (78 – 83%). We designed a synthesis protocol that circumvented the purification step via column chromatography and improved the C_5 -monomer yields compared to literature.²³ Detailed NMR characterization for all TGEs (Figures S 1 – S 14) as well as an explicit synthetic protocol are provided in the SI.

Statistical Copolymerization of EO and TGEs

The living statistical copolymerizations of bio-renewable TGEs with EO were performed in a THF-DMSO solvent mixture ($V_{\text{THF}}:V_{\text{DMSO}} = 5:1$) at 40 °C, using conventional AROP conditions, employing cesium 2-benzyloxy ethoxide as initiator salt (Scheme 3). In order to maintain the remarkable properties of PEG while extending its functionality, we designed a series of copolymers for each TGE by varying the comonomer content between 3.0 and 9.6 mol%. The rationale for this low amount of TGE comonomer encompasses significant property changes at small TGE amounts, while increasing functionality and maintaining the aqueous solubility of the copolymers.



Scheme 3: Synthetic strategy for the copolymerization of EO with TGEs of varying terpenyl chain length, resulting in terpenyl-functionalized PEGs.

Table 1: Overview of polymer characterization of P(EG_m-co-TGE_n) statistical copolymers

No	Sample	$X_{\text{TGE,exp}}^a$ / (mol%)	$M_{n,\text{NMR}}^a$ / g·mol ⁻¹	$M_{n,\text{SEC}}^b$ / g·mol ⁻¹	$\bar{D}^b$	T_g^c / °C	T_m^c / °C	ΔH_m^c / J·g ⁻¹
1	P(EG ₁₂₁ -co-PreGE ₅)	4.0	6190	4800	1.08	-59	39	79
2	P(EG ₁₁₃ -co-PreGE ₅)	4.2	5840	4600	1.06	-60	31	74
3	P(EG ₁₀₇ -co-PreGE ₁₀)	8.5	6290	4700	1.09	-63	21	47
4	P(EG ₁₀₂ -co-PreGE ₁₀)	8.9	6070	4900	1.07	-62	18	43
5	P(EG ₉₆ -co-IsoPreGE ₃)	3.0	4810	4700	1.07	-61	40	76
6	P(EG ₁₁₇ -co-IsoPreGE ₇)	5.6	6300	5200	1.07	-64	29	56
7	P(EG ₁₀₀ -co-IsoPreGE ₁₀)	9.1	5980	4400	1.10	-66	18	44
8	P(EG ₁₂₆ -co-IsoPreGE ₁₂)	8.7	7410	4800	1.11	-65	15	44
9	P(EG ₁₂₃ -co-GeraGE ₄)	3.1	6250	4700	1.07	-61	40	77
10	P(EG ₁₁₇ -co-GeraGE ₆)	4.9	6540	4800	1.08	-65	26	37
11	P(EG ₁₁₀ -co-GeraGE ₈)	6.8	6680	4200	1.07	-66	23	40
12	P(EG ₁₂₀ -co-GeraGE ₁₂)	9.1	7960	5400	1.10	-63	14	35
13	P(EG ₁₀₉ -co-NerGE ₄)	3.5	5640	4400	1.07	-63	38	70
14	P(EG ₁₂₅ -co-NerGE ₈)	6.0	7180	5100	1.07	-65	32	51
15	P(EG ₁₁₅ -co-NerGE ₁₀)	8.0	7160	5600	1.07	-67	21	48
16	P(EG ₁₂₃ -co-NerGE ₁₃)	9.6	7980	5500	1.08	-	-	-

^aNumber averaged molecular weight and experimental monomer content determined via ¹H NMR spectroscopy. ^bDetermined via SEC measurements (RI detector, eluent: DMF, calibration: PEG). ^cDetermined from second heating cycle at a heating rate of 10 °C·min⁻¹.

Table 1 contains the copolymerization results as well as the thermal characterization of the statistical P(EG_n-co-TGE_m) copolymers. Number averaged molecular weights (M_n) were calculated via ¹H NMR end group analysis by referencing to the methylene group

of the benzyloxy ethanol initiator (Figures S 19, S 21, S 23 and S 25), in the range of 4800 to 8300 g·mol⁻¹.

The representative ¹H NMR spectra show the anticipated signals of the polyether backbone and the terpenyl side chain, which can be clearly distinguished from one another. Notably, we observed side chain isomerization for all polymers, which is a known phenomenon when applying the general basic conditions of AROP.^{44–46} We will briefly readdress the isomerization in the kinetic investigation section. Size exclusion chromatography (Figures S 15 – S 18) indicates well-defined copolymers with monomodal distributions and low dispersity $\bar{D}$ (1.06 – 1.11). Deviations of the M_n determined by SEC from ¹H NMR characterization are ascribed to the structural and polarity difference of the P(EG_n-co-TGE_m) copolymers compared to the PEG calibration standards for SEC.

***In situ* ¹H NMR Copolymerization Kinetics of TGEs with EO**

Glycidyl ethers can be applied in the copolymerization with EO, introducing functionality along the polyether backbone. To understand copolymer properties, it is pivotal to elucidate the copolymer microstructure for a detailed understanding of the material's properties.³⁰ Capitalizing on *in situ* ¹H NMR kinetic investigations in combination with suitable copolymerization models, it is possible to translate monomer conversion into the respective reactivity ratios of a given comonomer pair.^{30,47,48} Motivated by the different structure of the terpenyl side chains, we systematically performed *in situ* ¹H NMR copolymerization kinetics in vacuum-sealed NMR tubes to compare the copolymerization behavior for all TGE/EO comonomer pairs. It is important to note that we additionally investigated the fully hydrogenated analogues of the C₅, C₁₀ and C₁₅ side chains to evaluate the influence of hydrophobicity on the copolymerization behavior, also aiming at further understanding the role of the allylic double bond. Based on the living AROP copolymerization without chain transfer and termination, we accurately tracked the monomer conversion, specifically for EO at 2.59 ppm (blue) and PreGE at 3.05 ppm (green, Figure 1 and Figure S 39, left). As previously reported, the ideal non-terminal model is known to be valid for the copolymerization of EO and glycidyl ethers. The copolymerizations tend to follow ideal copolymerization behavior, which is expressed by the simple relation: $r_1=r_2^{-1}$.^{30,49,50} Plotting the individual monomer conversion versus total conversion (Figure S 39, right), we applied the ideal Jaacks fit (Figure S 27) to obtain reactivity ratios of $r_{\text{PreGE}}=0.94$ and $r_{\text{EO}}=1.06$, revealing an almost ideally random copolymerization for PreGE and EO.⁵¹

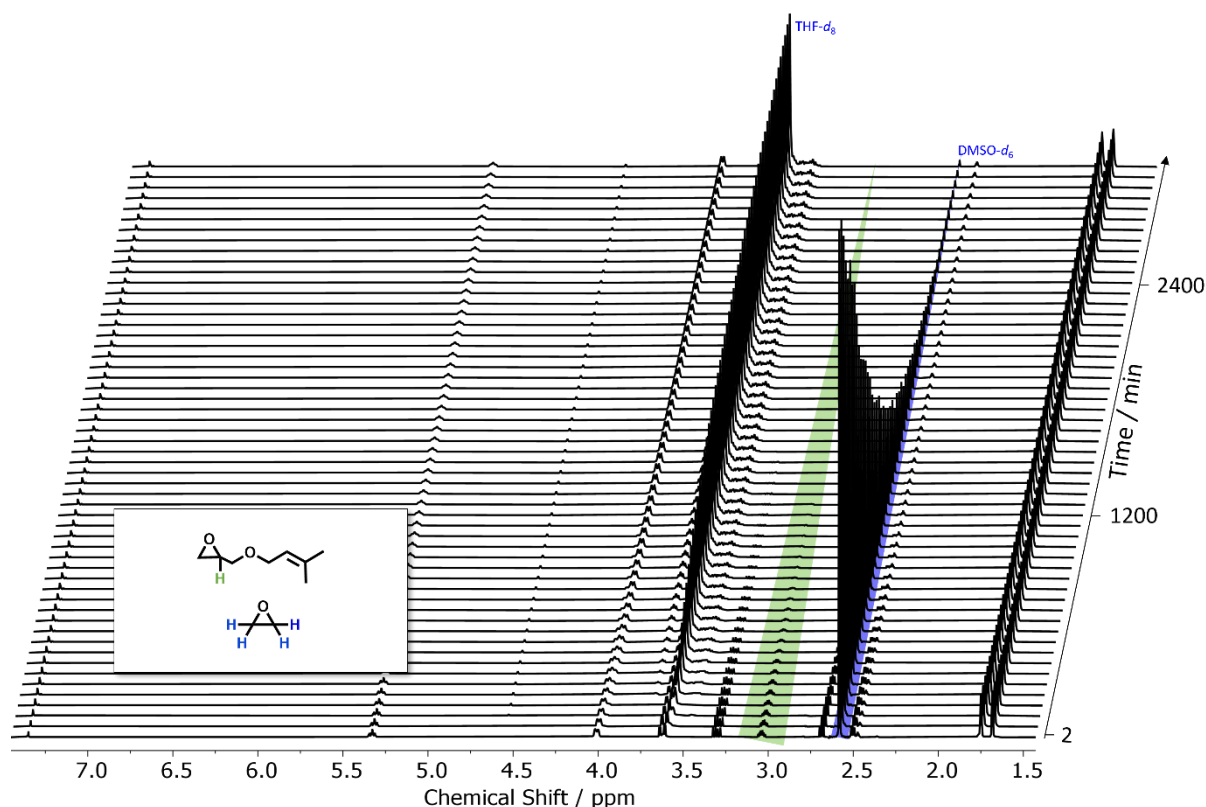


Figure 1: Selection of ^1H NMR spectra (400 MHz, $\text{THF-}d_8$: $\text{DMSO-}d_6$ = 5:1) of the *in situ* copolymerization kinetics of PreGE with EO at 40 °C. Relevant proton signals are highlighted in green (PreGE) at 3.05 ppm and blue (EO) at 2.59 ppm. As spectra were collected every 2 min over a period of 51.5 h, only every 30th spectrum is displayed.

Table 2 summarizes the reactivity ratios determined in the statistical copolymerization of EO with the TGEs employed in this work. Detailed *in situ* kinetic data, characterization as well as the respective SEC traces ($\mathcal{D} \leq 1.13$) are compiled in the Supporting Info, Figures S 27 – 33 and S 39 – 58. In general, the copolymerization behavior is governed by steric and electronic properties of the epoxide monomers.³⁰ The side chain impact on reactivity ratios is manifest as a collective of three parameters: (i) length, (ii) hydrophobicity and (iii) flexibility. At first glance, an increase in chain length and hydrophobicity leads to more pronounced incorporation of EO at the start of the copolymerization. PreGE and IsoPreGE manifest no significantly different copolymerization behavior, although the isoprenyl main chain is more flexible. Both copolymerizations show almost ideally random behavior. On the other hand, the reactivity ratio of EO is higher for all other comonomer pairs, resulting in a (soft) monomer gradient in the copolymer chain. The difference in *cis*- and *trans*-stereoconformation of NerGE and GeraGE, respectively, appear to be a negligible factor during the copolymerization. In contrast, an increase in side chain hydrophobicity by full hydrogenation appears to be the most influential parameter for the copolymer microstructure, affording a stronger gradient. Altogether, the observed trends are in

good agreement with previously reported results, as GEs generally copolymerize in an ideally random manner with EO.^{30,31} Due to the additional oxygen in the GE side chain, Lynd and coworkers postulated a “crown ether-effect” at the active polymer chain end, enhancing the GE reactivity.³¹ Following our findings, we hypothesize that the steric demand of the branched structures impedes counterion complexation and, in turn, leads to an inversion of the comonomer reactivity.²⁵ Furthermore, a slight deviation could also be due to solvent and counterion effects.^{30,52}

Table 2: Reactivity ratios for the AROP of various TGEs with EO in a mixture of THF-*d*₈ and DMSO-*d*₆ (5:1) at 40 °C, evaluated by the non-terminal model and the ideal Jaacks fit.

Monomer	Pendant group	r_{EO}^a	r_{TGE}^a	R^2
IsoPreGE	C ₅ H ₉ O	1.03 ± 0.01	0.97 ± 0.01	0.99
PreGE	C ₅ H ₉ O	1.06 ± 0.01	0.94 ± 0.01	0.99
GeraGE	C ₁₀ H ₁₇ O	1.08 ± 0.01	0.93 ± 0.01	0.99
NerGE	C ₁₀ H ₁₇ O	1.07 ± 0.01	0.93 ± 0.01	0.99
FarGE^b	C ₁₅ H ₂₅ O	1.18 ± 0.01	0.85 ± 0.01	0.99
DHPreGE	C ₅ H ₁₁ O	1.18 ± 0.01	0.85 ± 0.01	0.99
THGeraGE	C ₁₀ H ₂₁ O	1.21 ± 0.01	0.83 ± 0.01	0.99
HHFarGE	C ₁₅ H ₃₁ O	1.25 ± 0.01	0.80 ± 0.01	0.99

^aErrors for reactivity ratios have been rounded up to the last significant digit. ^bReactivity ratios of the FarGE/EO comonomer pair have been previously published for identical polymerization conditions.²⁵

In our kinetic study, IsoPreGE and HHFarGE show the strongest discrepancy in their copolymerization behavior. To visually demonstrate the difference between the ideally random and gradient structures, we simulated the molar-based composition diagram of a statistical copolymer for EO with IsoPreGE and HHFarGE at an equimolar monomer ratio, respectively. Figure 2 demonstrates the effect of the reactivity ratio difference on the polymer microstructure. While the isoprenyl side chains are randomly distributed along the polyether chain, the copolymerization with HHFarGE produces a noticeable, but weak gradient copolyether, which determines the nature of the terminal units. HHFarGE units are slightly less incorporated at the onset of the growing polymer chain, whereas the gradient shows a noticeable increase towards the chain terminus. Based on a previous kinetic study by Heatley et al., for comparison purposes we additionally depict the molar composition diagram for the highly relevant EO/PO comonomer pair (Figure 2, bottom).²⁹ While statistical P(EG_n-*co*-PO_m) copolymers features a significantly

stronger gradient composition profile, a nearly random microstructure can be realized by simply substituting PO by a TGE.

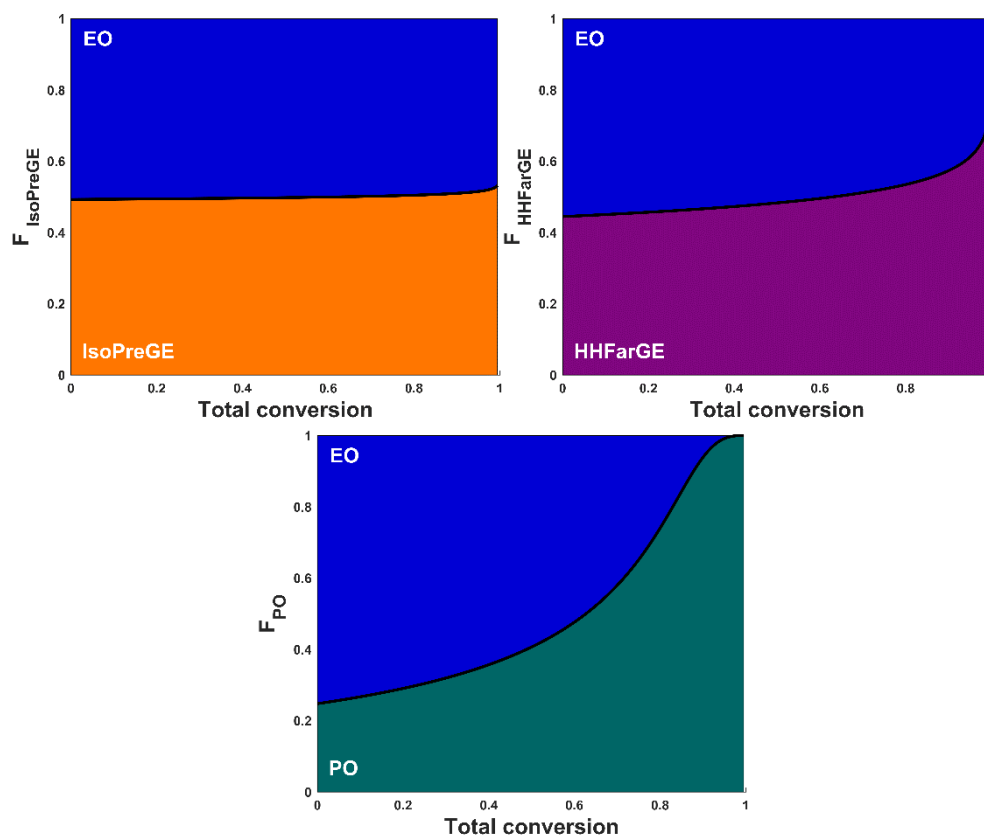


Figure 2: Molar-based composition diagrams of a $P(EG_n\text{-}co\text{-}IsoPreGE_m)$ (top, left); a $P(EG_n\text{-}co\text{-}HHFarGE_m)$ (top, right) and a $P(EG_n\text{-}co\text{-}PO_m)$ copolymer (bottom), respectively, modelled at an equimolar monomer ratio, with F_X = molar fraction of TGE or PO. Calculations for TGEs are based on the reactivity ratios derived from a linear Jaacks fit⁵¹ (top, right), whereas reactivity ratios for the EO/PO comonomer pair are derived from literature ($r_{EO} = 2.80$; $r_{PO} = 0.25$).²⁹

Having revealed the reactivity difference of the available TGEs, we directed our attention to unraveling the unexpected appearance of novel signals during the *in situ* kinetics of the unsaturated C_5 -TGEs. Figure 3 depicts a zoom-in of the time-resolved overlay of 1H NMR spectra between 4.6 and 6.6 ppm, documenting the unexpected appearance of new signals during the copolymerization. Chain transfer to the monomer is a well-known drawback of the alkali metal mediated AROP of substituted epoxides, leading to the formation of new allylic species with signals in a similar down-field region, as evidenced by 1H NMR spectroscopy.⁵³ More importantly, chain transfer would simulate an inaccurate PreGE consumption in our study, falsifying the determined reactivity ratios. Owing to the similarity of the signals' shifts, we sought to obtain a deeper understanding of our observations regarding (i) signal elucidation and (ii) validity of the determined reactivity ratios. Interestingly, our findings indicate the occurrence of base-catalyzed γ -elimination of the prenyl protective group (Scheme S 2) and formation of isoprene during the copolymerization ($\leq 0.5\%$ of overall monomer,

Figure S 34) rather than chain transfer.^{54–56} A cryotransfer of all volatile compounds following our kinetic study corroborated our hypothesis, as we identified isoprene via GC and NMR analysis (Figures S 35 – S 37). Concurrently, a hydroxyl functionality is released (glycidol or within the polymer chain), which can act as an additional initiating species due to the degenerative proton transfer in the AROP.¹ Yet, as the elimination occurs in trace amounts of less than 1%, a hyperbranched structure is not expected. The aforementioned observations and conclusions are conferrable for the copolymerization of EO and IsoPreGE as a structural isomer of PreGE (Figure S 41).

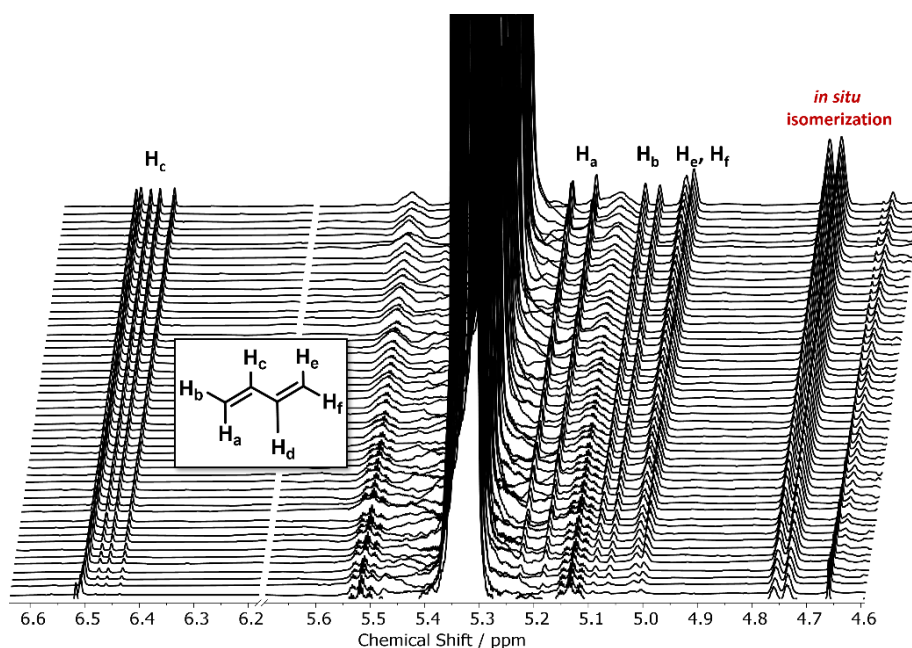


Figure 3: Zoom-in region of stacked ^1H NMR spectra (400 MHz, $\text{THF-}d_8$: $\text{DMSO-}d_6$ = 5:1) of the copolymerization kinetic investigation of PreGE and EO, validating the elimination of isoprene in small quantities. The doublet forming between 4.71 and 4.77 ppm shows the concurrent prenyl-to-isoprenyl isomerization under basic AROP conditions.

Nevertheless, decreasing the base concentration in the NMR tube leads to a decrease in the overall isoprene formation by base-catalyzed elimination. This is in line with the results of the significantly more dilute copolymerization conditions in a flask, for which no isoprene formation has been observed. Additionally, we used dihydroprenyl glycidyl ether (DHPreGE) as a saturated model compound in an *in situ* kinetic measurement (Figures S 50 – S 52), for which, as anticipated, no new signals are witnessed (Figure S 50). Intriguingly, the elimination reaction was only observed for the unsaturated C_5 -TGEs, which is presumably favored by a six-membered transition state (Scheme S 2). Conclusively, the chosen copolymerization conditions suppress chain transfer reactions whilst trace elimination does not impact the accurate determination of the reactivity ratios. An additional finding is the partial base-catalyzed prenyl-to-isoprenyl isomerization of the side chain under basic conditions (and vice versa for IsoPreGE), as evidenced in Figure 3 and Figure S 38.⁵⁷ In contrast, the copolymerization EO with neryl

and geranyl glycidyl ether (NerGE, GeraGE), respectively, shows little to no isomerization. The different degree of isomerization is further supported by ^{13}C NMR analysis of $\text{P}(\text{EG}_n\text{-co-PreGE}_m)$ and $\text{P}(\text{EG}_n\text{-co-IsoPreGE}_m)$ copolymers, which show more pronounced carbon shifts of the isomerized side chain (compare Figures S 20 and S 22 vs. Figures S 24 and S 26). Similar *in situ* isomerization has already been reported during the AROP of EO with AGE, which undergoes a transformation from allyl- to *cis*-prop-1-enyl ether.^{44,45} Due to the degree of substitution, PreGE isomerization is sterically promoted towards the isoprenyl structure. Overall, the different copolymerization behavior renders TGE highly promising building blocks to fine-tune the microstructure of *mf*-PEGs under the established AROP conditions.

Thermal Properties of Statistical $\text{P}(\text{EG-co-TGE})$ Copolymers

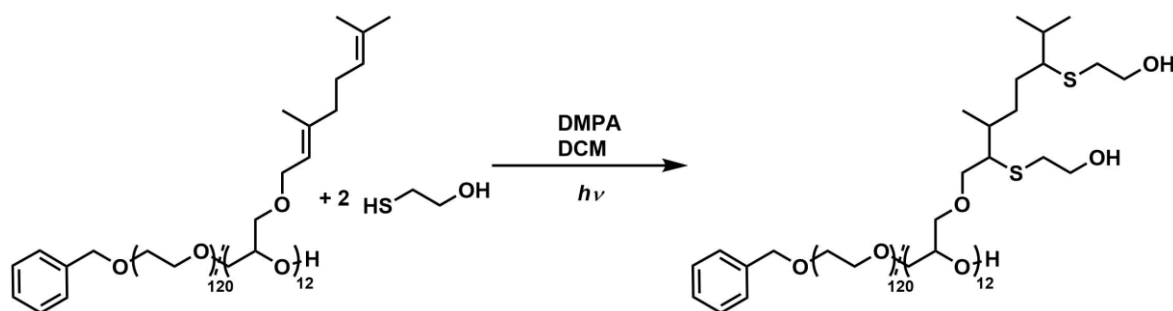
Differential scanning calorimetry (DSC) of the copolymers not only reveals the thermal properties (Figures S 78 – S 81), but also provides indirect support for the copolymer microstructure. PEG is a semicrystalline polyether with a melting temperature (T_m) of 65 °C. Generally, all synthesized copolymers exhibit a T_m that can be tailored by the comonomer content. Accordingly, a gradual TGE increase results in an incremental decrease of T_m and the respective melting enthalpy. In contrast to block-like structures, statistical copolymers with side chain functionalization show significant reduction of the PEG crystallization.^{5,25} The branched terpenyl side chains lead to regular interruptions along the PEG chain, prohibiting the packing of PEG in highly ordered crystalline domains. For instance, incorporation of approximately 3 mol% TGE reduces the T_m by ~ 25 °C. Melting points in the range of 30 °C to 40 °C, i.e., in a physiological temperature range are promising for a variety of pharmaceutical applications. Furthermore, the steric demand of branched side chain groups does also not allow for side chain crystallization for the longer terpenyl side chains (C_{10}), as indicated by the absence of a second T_m .⁸ As expected for statistical copolymers with a random or soft gradient microstructure, only a single glass transition temperature T_g in the range of -59 and -67 °C is observed.⁵⁸ The prenyl side chain leads to a slightly higher T_g than isoprenyl, resulting from decreased chain flexibility. The results show that the difference in chain length or conformation of the incorporated C_5 and C_{10} TGE chain does not represent a key parameter in tailoring the thermal properties. Overall, the thermal properties of the copolymers are a consequence of the almost ideally random microstructure.

Post-polymerization Modification

The unsaturated side chains of the P(EG-*co*-TGE) copolymers are characterized by chemically different double bonds. Therefore, we next sought to investigate the different copolymer structures focusing on their post-polymerization potential capitalizing on thiol-ene click and hydrogenation.

Thiol-ene click reaction

Thiol-ene click photo reactions were carried out overnight in DCM using 2,2-dimethoxy-2-phenylacetophenone (DMPA) as a radical photoinitiator and 2-mercaptoethanol as a functional thiol, exemplifying the general applicability. As trisubstituted, internal double bonds represent a particular challenge with respect to modification, P(EG₁₂₀-*co*-GeraGE₁₂) was used as the model copolymer (Scheme 4). The ratios of double bonds/DMPA/thiol were varied to receive fully functionalized copolymers with monomodal molecular weight distributions. After the photoreaction, residual 2-mercaptoethanol was removed via aqueous extraction, followed by further purification via dialysis.



Scheme 4: Thiol-ene modification of P(EG₁₂₀-*co*-GeraGE₁₂) employing 2-mercaptoethanol as a functional thiol. The copolymers in entry 4, 8 and 16 were modified in the same manner. For experimental details see Table S 1, Supporting Information.

Generally, the reactivity of double bonds towards hydrothiolation decreases from terminal towards internal and subsequently multiple substituted double bonds.^{59–61} As the formation of the carbon-sulfur bond is reversible and dependent on the olefin and thiol structures, it is anticipated that the reverse reaction will be more pronounced for olefins with trisubstituted internal double bonds than less substituted olefins. Terpene-based small molecules with terminal double bonds can be modified with one-digit equivalents of thiol.²² Yet, these modification conditions commonly used for small molecules induce cross-linking of double bond-containing polymers, leading to multimodal molecular weight distribution. This is evidenced in the high M_n of the yielded polymer as determined by SEC (Figure 4, gray curve). A strategy to overcome crosslinking is the use of excess thiol equivalents (Figure 4, compare red, cyan and

purple curve) while keeping the required amount of the photoinitiator DMPA at a minimum (Figure 4, red and green curve). When 200 equivalents of thiol per double bond are applied, a monomodal molecular weight distribution is achieved. Comparing the functionalized copolymers to the starting P(EG₁₂₀-co-GeraGE₁₂) copolymer, a shift of the SEC elugrams toward higher molecular weights indicates the successful functionalization (dotted blue and purple curve).

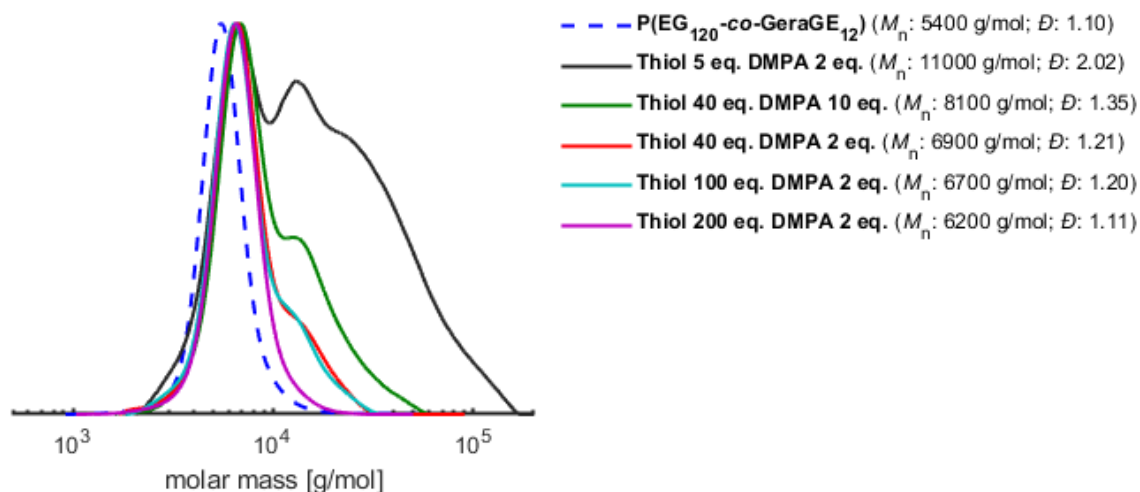


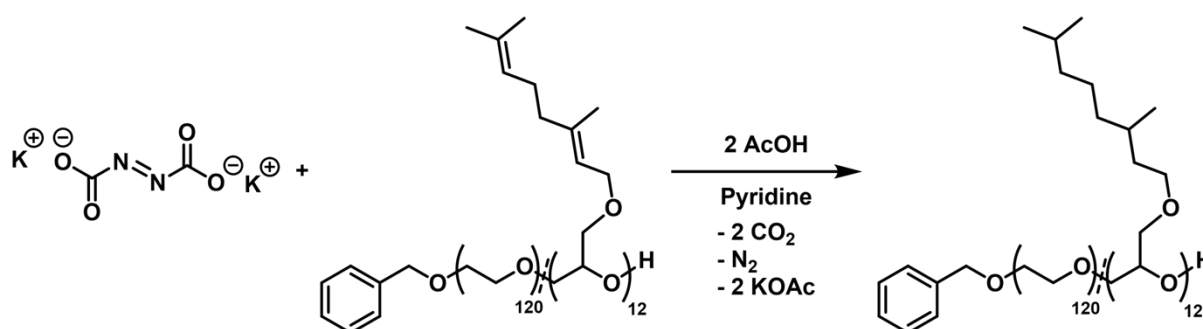
Figure 4: SEC traces of P(EG₁₂₀-co-GeraGE₁₂) modified with different equivalents of the thiol 2-mercaptoethanol and DMPA with respect to one double bond (Eluent DMF, RI detector, PEG calibration). Purple line represents the SEC curve of the successful modification without crosslinking.

Furthermore, ¹H NMR analysis revealed complete conversion of both double bonds in all experiments (Figures S 63 – S 66). The incisive protons at 2.75 and 2.36 ppm refer to the methine protons from the anti-Markovnikov product of the two double bonds (Figure S 65). The infrared spectrum illustrates a broad band at approximately 3400 cm⁻¹ due to the added hydroxyl functionalities. The absence of the R-S-H band at 2500 cm⁻¹ indicates the complete removal of 2-mercaptoethanol by dialysis (Figure S 69). MALDI-ToF analysis provides further proof for complete modification, as the peak intervals solely correspond to the EO unit and the double functionalized GeraGE unit with 366 gmol⁻¹ (Figure S 73). It is noteworthy that unreacted 2-mercaptoethanol was recovered by fractional distillation in yields of 80% (see Supporting Information for details), reducing the overall thiol equivalents required for functionalization. Equally, we modified P(EG₁₂₆-co-IsoPreGE₁₂), requiring 600 eq. of thiol per double bond to suppress cross-linking (Figure S 59). Surprisingly, SEC characterization still indicated a shoulder towards higher molecular weights, even when 300 equivalents of thiol were used. P(EG₁₂₃-co-NerGE₁₃) required similar reaction conditions, despite its similarity to GeraGE. A different reactivity towards hydrothiolation of those species was not expected, however, adjusting the modification

conditions enabled us to obtain monomodal distributions for both copolymer types (Figure S 62).

Hydrogenation via diimide reduction

While the diimide reduction using *p*TSH is a well-known hydrogenation method, the use of PADA as a *in situ* hydrogenation agent has been scarcely investigated to date.⁶² Thus, we investigated the post-polymerization hydrogenation of terpenoid structures employing PADA with respect to (i) hydrogenation temperature, (ii) applied PADA equivalents and (iii) the solvent volume required. Detailed experimental procedures and further results (Table S 2) are provided in the Supporting Information. PADA was utilized to generate the diimide, which upon decomposition produced potassium acetate as a byproduct. The general procedure involved dissolving the dry polymer in dry pyridine, followed by the addition of PADA. A slurry was created, into which dry glacial acetic acid was added dropwise to induce decomposition. It is important to note that the decomposition of PADA is strongly influenced by the concentration of acid.⁶³



Scheme 5: Hydrogenation of P(EG₁₂₀-co-GeraGE₁₂) employing potassium azodicarboxylate (PADA). Intermediate steps towards diimide are omitted but can be found in the introduction.

First experiments showed that decreasing the temperature from RT to 0 °C only affects the degree of hydrogenation in concentrated solutions, yet the efficiency was only at a maximum of 53% (Table S 2, entry 1-4). Next, we increased the volume of the solvent to 3 ml, which increased the degree of hydrogenation from 25% to 53% according to ¹H NMR analysis (Table S 2, entry 4 and 8). As the slower decomposition of PADA directly correlates with the slower dosage and reduced concentration of acetic acid in the reaction mixture, improved hydrogenation and reduction of side reactions is observed. A similar effect was observed upon increasing the PADA equivalents from 2.5 to a maximum of 15 per double bond (Table S 2, entry 4 and 8). Figure 5 illustrates the polymer's double bond resonances before and after hydrogenation, respectively, showing a decrease in double bond signals (full analysis in Figures S 75 and S 76 in the Supporting Information).

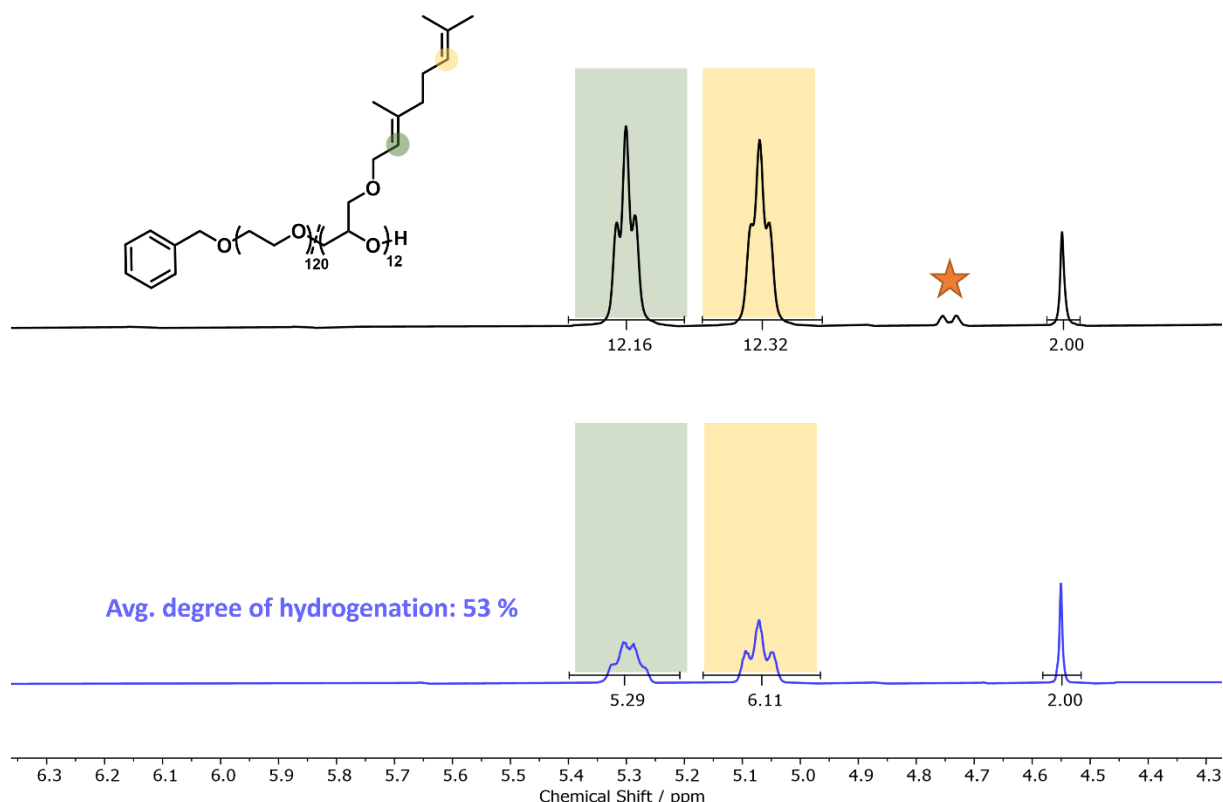


Figure 5: Stacked ^1H NMR spectra of P(EG₁₂₀-co-GeraGE₁₂) before (top) and after (bottom) hydrogenation employing PADA. The double bond with a deficiency of electrons (colored green, resonating at 5.30 ppm) undergoes hydrogenation with a slight preference. The orange star denotes the terminal double bond of the isomerized product and is not considered in the calculations.

This described method of producing diimide using PADA is suitable for post-polymerization hydrogenation, even with partial hydrogenation. We would like to emphasize that the structures presented are difficult to hydrogenate, both due to the trisubstituted double bonds and the attachment to a polymer chain. The reactivity of a double bond is lowered significantly by the presence of alkyl substitution of the alkene.⁶⁴ Exemplarily, the relative hydrogenation rate constant of 2-methyl-1-pentene, which represents a terminal disubstituted substrate, is 7.3 times higher than that of 2-methyl-2-butene, which is comparable to a terpene unit.^{40,65} Additionally, upon an increase of acetic acid equivalents (> 2 equivalents), we observed a broadening of the molecular weight distribution in SEC analysis (Figure S 77). Similar observation have been reported during the hydrogenation of polyisoprene-based polymers using *para*-toluenesulfonyl hydrazide, caused by the formation of *para*-toluene-sulfonic acid as a byproduct.⁴² Ultimately, the diimide reduction of P(EG-co-TGE) copolymers requires further optimization, but PADA already shows good hydrogenation efficiencies of less substituted double bonds in polymers in model experiments. Nevertheless, it is a particularly interesting method for the hydrogenation of amphiphilic structures, as facile purification is enabled due to the volatile coupling product, i. e., carbon dioxide.

Conclusion

TGEs represent a bio-derived class of epoxide monomers, which as yet have been hardly employed. The easy-to-synthesize nature and structural variety leads to a versatile monomer platform for polyether, polycarbonate and polyester synthesis. We demonstrated the successful copolymerization of EO with TGEs (PreGE, IsoPreGE, GeraGE, NerGE), introducing branched terpenyl side chains along the polyether backbone. Four systematic series of well-defined statistical copolymers with a TGE content up to 10 mol% have been prepared, maintaining aqueous solubility and crystallizability of PEG, while introducing backbone functionality. A molecular weights range between 4800 and 8300 g mol⁻¹ was explored, and the molecular weight distribution showed low dispersities $\bar{D}$ in the range of 1.05 – 1.13. The statistical distribution of terpenyl pendant groups gradually reduced PEG crystallization with increasing TGE content and, correspondingly, thermal properties can be tailored by varying the comonomer ratio. Melting points in the range of 14 to 40 °C were obtained. Only marginal differences in glass transition temperatures are observed, despite the differing side chain length.

In situ ¹H NMR kinetic investigations revealed a TGE reactivity trend and unraveled the copolymer microstructure. TGE reactivity only slightly decreases with increasing side chain length, flexibility and hydrophobicity. Ideally random behavior was determined for the EO/IsoPreGE comonomer pair, whereas HHFarGE features the strongest, but mild gradient in the copolyether series.

The unsaturated double bonds of the terpenyl side chains allow for a post-polymerization modification, tapping the full potential of a single polymer precursor to expand the application scope.³² Both modification reactions, thiol-ene click and hydrogenation, addressed the unsaturated double bonds (di- and trisubstituted) of the terpenyl side chains. Representative thiol-ene click reaction was performed using 2-mercaptoethanol on all four types of synthesized copolyethers, comprised of ~ 10 mol% of TGE units. We achieved full functionalization for all copolymers, however, the thiol equivalents had to be varied between 200 and 600, depending on the respective TGE side chain in order to prevent crosslinking. Yet, recycling of the thiol equivalents was possible by up to 80%. Furthermore, the diimide reduction using PADA for polyether hydrogenation has been studied for the first time. Despite the difficulty of the hydrogenation of trisubstituted double bonds, we were able to achieve a hydrogenation

of 53%, while the gaseous release of CO₂ as the coupling product did not require further purification.

In contrast to commonly reported *para*-toluenesulfonyl hydrazide for hydrogenation purposes, PADA may have been overlooked as a hydrogenation agent in previous research. However, if side chains double bonds are not desired, the utilization of fully hydrogenated TGEs may prove advantageous, given the low hydrogenation efficiency.

Altogether, we consider the extended TGE library as a versatile platform, allowing for the well-controlled synthesis of P(EG_n-*co*-TGE_m) copolymers as promising PEG derivatives of a partially bio-based nature. The structural variety and potential for postfunctionalization enables a diverse scope of applications, ranging from surfactants to polymeric drug carriers and microgels.^{1,5,66,67}

Acknowledgments

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Supporting Information

Experimental Sections

Reagents

All chemicals and solvents were acquired from commercial suppliers (*Sigma-Aldrich*, *Fluka*, *Alfa Aesar*, *Acros*, *TCI*) and used without prior purification, unless otherwise stated. Deuterated solvents were purchased from *Deutero GmbH*. Ethylene oxide (EO) was obtained by *Air Liquide*. All terpenoids were purchased from *Sigma-Aldrich*. The long-chain terpenyl glycidyl ethers (TGEs), farnesyl glycidyl ether (FarGE) and hexahydrofarnesyl glycidyl ether (HHFarGE), were dried azeotropically with benzene overnight under reduced pressure. All others TGEs were dried by cryo-transfer after stirring over calcium hydride (CaH_2) for 2 h prior to polymerization. Tetrahydrofuran (THF) was dried over diphenylhexyllithium (adduct of sec-butyllithium and 1,1-diphenylethylene), degassed by three freeze-pump-thaw cycles and stored under vacuum until distilled into the polymerization flask. Anhydrous dimethyl sulfoxide (DMSO) stored over molecular sieves was used for the statistical copolymerizations. Prior to all *in situ* ^1H NMR kinetics, deuterated THF ($\text{THF-}d_8$) was cryo-transferred after stirring over CaH_2 overnight. For each kinetic, a new bottle of deuterated DMSO ($\text{DMSO-}d_6$) was utilized to ensure the absence of water residues.

Instrumentation

Nuclear Magnetic Resonance (NMR) Spectroscopy.

Standard NMR spectra were recorded at 23 °C either on a *Bruker Avance II HD 400* spectrometer or on a *Bruker Avance III HD 300* spectrometer, referenced internally to residual protium signals of the deuterated solvent (^1H NMR spectra) and the deuterated solvent itself (^{13}C NMR spectra).

2D NMR analysis and *in situ* ^1H NMR copolymerization kinetics were investigated on a *Bruker Avance III HD 400* spectrometer operated at 400 MHz (5 mm BBFO-SmartProbe (Z-gradient), an ATM and a SampleXPress 60 auto sampler). Diffusion-Ordered Spectroscopy (DOSY) spectra were collected using a *Bruker Avance III HD 400* spectrometer at 23 °C. Spectra were processed using *MestReNova* software 14.2.0. NMR spectroscopy data is reported as follows: chemical shift, multiplicity and integration. Spectra annotation uses lowercase letters for proton signals and capital letters for carbon signals.

Fourier-Transformations-Infrared Spectroscopy (FT-IR Spectroscopy).

FT-IR spectroscopy was performed on a *Nicolet iS10* FT-IR spectrometer (Thermo Scientific, Waltham, MA, USA) equipped with a diamond ATR unit. Spectra were recorded in a frequency range of 650–3500 cm⁻¹.

Size Exclusion Chromatography (SEC).

SEC analysis was performed with an Agilent 1100 series SEC system with a HEMA 300/100/40 Å column cascade, equipped with UV (254 nm) and RI detectors. Measurements were conducted with a flow rate of 1 mL·min⁻¹ with DMF as eluent (with 1 g·mL⁻¹ lithium bromide) at 50 °C. Toluene was used as a reference for the baseline. The SEC calibration was carried out with poly(ethylene glycol) standards provided from *Polymer Standard Service* (PSS). *PSS WinGPC UniChrom* software was used for all data recording and processing.

Matrix-Assisted Laser Desorption Ionization Time-of-Flight (MALDI-ToF) Mass Spectrometry.

MALDI-ToF was conducted on a *Bruker autoflex maX MALDI-ToF-MS/MS* with multi target plate in linear mode. *Trans*-2-[3-(4-*tert*-Butylphenyl)-2-methyl-2-propen-sylidene]malononitrile was used as a matrix (DCTB) and potassium trifluoroacetate (KTFA) as a salt additive.

Differential Scanning Calorimetry (DSC).

DSC measurements of the polymer samples were carried out on a *DSC 250, TA Instrument*, applying indium and *n*-octane as calibration standard. After drying all samples azeotropically, each sample was sealed in an aluminum pan and measured against an empty pan as reference under a nitrogen atmosphere. The DSC samples were cooled from 40 °C to -90 °C and then heated to 100 °C, followed by an additional cooling and heating cycle in the temperature range of -90 °C and 100 °C. Heating and cooling cycles were set to a rate of 10 °C/min. All melting temperatures (T_m s) and glass transition temperatures (T_g s) values were evaluated from the second heating cycle to ensure the removal of the thermal history.

Gas Chromatography (GC).

GC measurements were conducted using a Shimadzu GC-2010 (*Shimadzu*, Japan) with a *VWR Avantor™ Hichrom HI-5 MS* column (*VWR International GmbH*, Germany). Dimensions of the column: Length 30 m, inner diameter 0.25 mm, coating thickness 0.25 µm. Carrier gas hydrogen. Injector temperature 250 °C, start temperature 27 °C for

3 min. Heating rate 1 °C/min to 32 °C, heating rate 40 °C/min to 300 °C, hold for 4 min.
Detector temperature 330 °C. Total time 18.7 min.

Monomer Synthesis

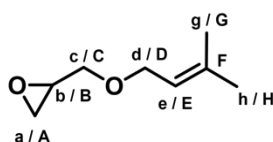
The phase transfer catalysis by Mouzin et al. was modified subject to the terpenyl side chain targeted.^{1,2} The presented synthesis for TGEs of hemiterpenoids has been altered to previously reported synthetic approaches.

Synthesis of TGEs from hemiterpenoids

The following synthesis protocol was used for the short-chain TGEs, namely prenyl glycidyl ether (PreGE), isoprenyl glycidyl ether (IsoPreGE) and dihydro glycidyl ether (DHPreGE).

An aqueous sodium hydroxide solution (33% (w/w) solution, $V_{\text{solution}} = 150.5$ mL; NaOH: 50.14 g, 1.25 mol, 12.7 equiv.), tetrabutylammonium hydrogen sulfate (TBAHS, 1.89 g, 0.006 mol, 0.04 equiv.) and epichlorohydrin (ECH, 57.9 mL, 68.32 g, 0.738 mol, 5.30 equiv.) were added to a three-necked flask, equipped with a dropping funnel and mechanical stirrer. The mixture was cooled to 0 °C using an ice bath and the prenol (3-methyl-2-buten-1-ol, 13.6 mL, 12.00 g, 0.139 mol, 1 equiv.) was added dropwise over 90 min whilst vigorously stirring the suspension. Note that it is imperative to keep the reaction temperature below 5 °C to avoid the augmented formation of side products. Stirring continued at 0 °C for 3.5 h, followed by another 90 min at r.t.. The reaction was quenched with ice and the crude product was extracted with diethyl ether (DEE). The combined organic phases were washed with brine until a neutral pH value was obtained and dried using magnesium sulfate (MgSO_4). DEE was removed under reduced pressure and a first distillation at 25 mbar enabled the removal of undesired side products. Fractionated distillation at high vacuum ($p = 6 \cdot 10^{-3}$ mbar, $T_{\text{b,PreGE}} = 30 - 33$ °C) afforded PreGE as a colorless liquid in yields of 64%.

Prenyl glycidyl ether



Yield: 64%

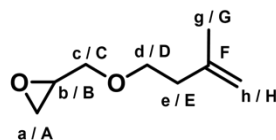
Purification by distillation: $p = 6 \cdot 10^{-3}$ mbar, $T_{\text{b,PreGE}} = 30 - 33$ °C

^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 5.26 (tdq, $J = 7.1, 2.8, 1.4$ Hz, 1H, H_e), 4.01 – 3.86 (m, 2H, H_d), 3.59 (dd, $J = 11.4, 3.2$ Hz, 1H, H_c), 3.29 (dd, $J = 11.4, 5.8$ Hz, 1H, H_c),

3.05 (ddt, $J = 5.9, 4.2, 2.9$ Hz, 1H, H_b), 2.69 (dd, $J = 5.1, 4.1$ Hz, 1H, H_a), 2.51 (dd, $J = 5.1, 2.7$ Hz, 1H, H_a), 1.66 (s, 3H, H_g), 1.59 (s, 3H, H_h).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 137.16 (C_F), 120.72 (C_E), 70.55 (C_C), 67.57 (C_D), 50.71 (C_B), 44.20 (C_A), 25.63 (C_G), 17.86 (C_H).

Isoprenyl glycidyl ether



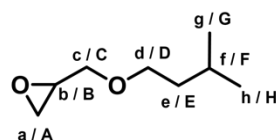
Yield: 59%

Purification by distillation: $p = 11 \cdot 10^{-3}$ mbar, $T_{b,\text{IsoPreGE}} = 32 - 35$ °C

^1H NMR (300 MHz, chloroform- d_1): δ (ppm) = 4.81 – 4.67 (d, 2H, H_h), 3.72 (dd, $J = 11.6, 3.0$ Hz, 1H, H_d), 3.59 (qt, $J = 9.4, 6.9$ Hz, 2H, H_c), 3.37 (dd, $J = 11.6, 5.8$ Hz, 1H, H_d), 3.12 (ddt, $J = 5.8, 4.1, 2.9$ Hz, 1H, H_b), 2.77 (dd, $J = 5.1, 4.1$ Hz, 1H, H_a), 2.58 (dd, $J = 5.0, 2.7$ Hz, 1H, H_a), 2.35 – 2.23 (m, 2H, H_e), 1.73 (s, 3H, H_g).

^{13}C NMR (75 MHz, chloroform- d_1): δ (ppm) = 142.72 (C_F), 111.65 (C_H), 71.56 (C_C), 69.98 (C_D), 50.94 (C_B), 44.33 (C_A), 37.82 (C_E), 22.74 (C_G).

Dihydroprenyl glycidyl ether



Yield: 51%

Purification by distillation: $p = 3.5 \cdot 10^{-2}$ mbar, $T_{b,\text{DHPreGE}} = 27 - 28$ °C

^1H NMR (300 MHz, chloroform- d_1): δ (ppm) = 3.68 (dd, $J = 11.5, 3.1$ Hz, 1H, H_c), 3.58 – 3.40 (m, 2H, H_d), 3.35 (dd, $J = 11.5, 5.8$ Hz, 1H, H_c), 3.11 (ddt, $J = 5.8, 4.2, 2.9$ Hz, 1H, H_b), 2.76 (dd, $J = 5.1, 4.1$ Hz, 1H, H_a), 2.58 (dd, $J = 5.1, 2.7$ Hz, 1H, H_a), 1.81 – 1.57 (m, 1H, H_f), 1.46 (q, $J = 6.7$ Hz, 2H, H_e), 0.88 (d, $J = 6.6$ Hz, 6H, H_g, H_h).

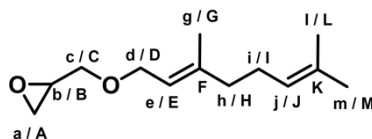
^{13}C NMR (75 MHz, chloroform- d_1): δ (ppm) = 71.56 (C_C), 70.10 (C_D), 50.98 (C_B), 44.38 (C_A), 38.56 (C_E), 25.10 (C_F), 22.71 (C_G, C_H).

Synthesis of TGEs from mono- and sesquiterpenoids

The procedure refers to the synthesis of geranyl glycidyl ether (GeraGE), neryl glycidyl ether (NerGE), tetrahydrogeranyl glycidyl ether (THGeraGE) and hexahydrofarnesyl glycidyl ether (HHFarGE).^{2,3}

A three-necked flask, equipped with a mechanical stirrer and dropping funnel, was charged with an aqueous sodium hydroxide solution (50% (w/w) solution, $V_{\text{solution}} = 96.26 \text{ mL}$; NaOH: 48.13 g, 1.20 mol, 12.7 equiv.), tetrabutylammonium hydrogen sulfate (TBAHS, 1.29 g, 0.004 mol, 0.04 equiv.) and epichlorohydrin (ECH, 39.38 mL, 46.47 g, 0.738 mol, 5.30 equiv.). The reaction mixture was cooled to 0 °C with an ice bath, followed by the dropwise addition of tetrahydrogeraniol (3,7-dimethyloctan-1-ol, 15.0 mL, 17.05 g, 0.095 mol, 1 equiv.) within 30 min under vigorous stirring. Stirring was continued at r.t. until complete consumption of the terpenoid (20 – 24 h). After quenching the reaction with ice, the crude product was extracted with DEE and the combined organic phases were washed with brine until neutrality, then dried over MgSO_4 . DEE was removed using rotary evaporation and subsequent Kugelrohr distillation served as a first purification step. A high vacuum distillation ($p = 5 - 12 \cdot 10^{-3} \text{ mbar}$) enables the removal of potential side products (3-Chloroallyl glycidyl ether (3-Chloro-AGE), diglycidyl ether). Finally, Kugelrohr distillation ($p = 12 \cdot 10^{-3} \text{ mbar}$, $T_{\text{Kugelrohr, THGeraGE}} = 130 - 135 \text{ °C}$) isolated purified THGeraGE as a colorless liquid in yields of 81%.

As previously established for long-chain TGEs, we pretreated the TGEs with methyl iodide (MeI) and sodium hydride (NaH), deactivating any residual protic impurities while extensively drying the monomer.² Therefore, a flame-dried Schlenk flask, charged with NaH (0.22 equiv.), was cooled to 0 °C, followed by the addition of the TGE (1.00 equiv.). MeI (0.10 equiv.) was syringed into the flask after 2 h and the reaction mixture was allowed to warm up to r.t.. After 22 h, the mixture was diluted with hexane and filtered multiple times to remove accrued sodium iodide. The TGEs were isolated in quantitative yields after Kugelrohr distillation.

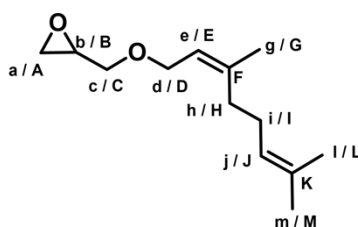
Geranyl glycidyl ether

Yield: 83%

Purification by Kugelrohr distillation: $p = 7 \cdot 10^{-3}$ mbar, $T_{\text{Kugelrohr, GeraGE}} = 130 - 135$ °C

^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 5.32 (ddq, $J = 6.8, 5.4, 1.3$ Hz, 1H, H_e), 5.06 (ddp, $J = 6.9, 5.7, 1.5$ Hz, 1H, H_j), 4.10 – 3.95 (m, 2H, H_d), 3.65 (dd, $J = 11.4, 3.2$ Hz, 1H, H_c), 3.36 (dd, $J = 11.4, 5.8$ Hz, 1H, H_c), 3.12 (ddt, $J = 5.9, 4.2, 3.0$ Hz, 1H, H_b), 2.76 (dd, $J = 5.1, 4.1$ Hz, 1H, H_a), 2.57 (dd, $J = 5.1, 2.7$ Hz, 1H, H_a), 2.13 – 1.96 (m, 4H, H_i, H_h), 1.64 (dt, $J = 2.3, 1.2$ Hz, 6H, H_g, H_l), 1.57 (d, $J = 1.4$ Hz, 3H, H_m).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.64 (C_F), 131.66 (C_K), 123.98 (C_J), 120.53 (C_E), 70.63 (C_C), 67.77 (C_D), 50.89 (C_B), 44.45 (C_A), 39.62 (C_H), 26.37 (C_I), 25.71 (C_M), 17.70 (C_L), 16.49 (C_G).

Neryl glycidyl ether

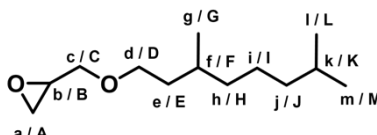
Yield: 81%

Purification by Kugelrohr distillation: $p = 7 \cdot 10^{-3}$ mbar, $T_{\text{Kugelrohr, NerGE}} = 135 - 145$ °C

^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 5.35 (tq, $J = 6.9, 1.5$ Hz, 1H, H_e), 5.08 (ttd, $J = 5.9, 3.0, 1.5$ Hz, 1H, H_j), 4.09 – 3.94 (m, 2H, H_d), 3.66 (dd, $J = 11.3, 3.3$ Hz, 1H, H_c), 3.38 (dd, $J = 11.3, 5.8$ Hz, 1H, H_c), 3.14 (ddt, $J = 5.9, 4.1, 3.0$ Hz, 1H, H_b), 2.78 (dd, $J = 5.0, 4.1$ Hz, 1H, H_a), 2.59 (dd, $J = 5.0, 2.7$ Hz, 1H, H_a), 2.12 – 1.99 (m, 4H, H_i, H_h, H_l), 1.74 (s, 3H, H_g), 1.68 (s, 3H, H_m), 1.59 (s, 3H, H_l).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 140.97 (C_F), 132.08 (C_K), 123.90 (C_J), 121.59 (C_E), 70.79 (C_C), 67.60 (C_D), 50.97 (C_B), 44.56 (C_A), 32.35 (C_H), 26.79 (C_I), 25.80 (C_M), 23.59 (C_G), 17.74 (C_L).

Tetrahydrogeranyl glycidyl ether



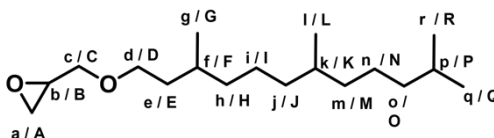
Yield: 81%

Purification by Kugelrohr distillation: $p = 12 \cdot 10^{-3}$ mbar, $T_{\text{Kugelrohr, THGeraGE}} = 130 - 135$ °C

^1H NMR (300 MHz, chloroform- d_1): δ (ppm) = 3.71 (dt, $J = 11.5, 2.9$ Hz, 1H, H_C), 3.63 – 3.42 (m, 2H, H_D), 3.38 (ddd, $J = 11.5, 5.8, 3.0$ Hz, 1H, H_C), 3.15 (ddt, $J = 5.8, 4.1, 2.9$ Hz, 1H, H_B), 2.80 (dd, $J = 5.1, 4.1$ Hz, 1H, H_A), 2.61 (dd, $J = 5.1, 2.7$ Hz, 1H, H_A), 1.73 – 1.01 (m, 8H, $\text{H}_\text{E}, \text{H}_\text{F}, \text{H}_\text{H}, \text{H}_\text{I}, \text{H}_\text{J}, \text{H}_\text{K}$), 0.88 (dd, $J = 6.6, 5.2$ Hz, 9H, $\text{H}_\text{G}, \text{H}_\text{L}, \text{H}_\text{M}$).

^{13}C NMR (75 MHz, chloroform- d_1): δ (ppm) = 71.59 (C_C), 70.07 (C_D), 51.00 (C_B), 44.41 (C_A), 39.36 (C_J), 37.46 (C_H), 36.79 (C_E), 29.91 (C_F), 28.06 (C_K), 24.76 (C_I), 22.80 ($\text{C}_\text{M}, \text{C}_\text{L}$), 19.76 (C_G).

Hexahydrofarnesyl glycidyl ether



Yield: 78%

Purification by Kugelrohr distillation: $p = 5 \cdot 10^{-3}$ mbar, $T_{\text{Kugelrohr, HHFarGE}} = 160$ °C

^1H NMR (400 MHz, chloroform- d_1): δ (ppm) = 3.70 (dt, $J = 11.5, 3.4$ Hz, 1H, H_C), 3.60 – 3.43 (m, 2H, H_D), 3.38 (ddd, $J = 11.5, 5.8, 4.2$ Hz, 1H, H_C), 3.14 (ddt, $J = 5.8, 4.1, 2.9$ Hz, 1H, H_B), 2.79 (dd, $J = 5.1, 4.1$ Hz, 1H, H_A), 2.60 (ddd, $J = 5.1, 2.8, 0.9$ Hz, 1H, H_A), 1.70 – 0.96 (m, $\text{H}_\text{E}, \text{H}_\text{F}, \text{H}_\text{H}, \text{H}_\text{I}, \text{H}_\text{J}, \text{H}_\text{K}, \text{H}_\text{M}, \text{H}_\text{N}, \text{H}_\text{O}$), 0.96 – 0.78 (m, $\text{H}_\text{G}, \text{H}_\text{L}, \text{H}_\text{R}, \text{H}_\text{Q}$).

^{13}C NMR (100 MHz, chloroform- d_1): δ (ppm) = 71.63 (C_C), 70.17, 70.14 (C_D), 51.05 (C_B), 44.50, 44.49 (C_A), 39.50 (C_O), 37.63, 37.59 (C_M), 37.51 (C_H), 37.47, 37.40 (C_J), 36.88, 36.80, (C_E), 32.91 (C_K), 30.00, 29.99, 29.97 (C_F), 28.12 (C_P), 24.96, 24.93 (C_N), 24.49 (C_I), 22.86, 22.77 (C_Q , C_R), 19.88, 19.84, 19.81, 19.78 (C_G , C_L).

Polymerization Procedures

Synthesis procedure for statistical copolymerization of TGEs with EO

The statistical copolymerization of TGEs and EO was conducted in an equal manner for all epoxide monomers applied. In the following, the general polymerization procedure is exemplified for P(EG₁₂₀-co-GeraGE₁₂) (Table 1, entry 12). In a flame-dried anionic polymerization flask, cesium hydroxide monohydrate (95.4 mg, 0.57 mmol, 0.9 equiv.) and 2-(benzyloxy)ethanol (91.0 mg, 0.59 mmol, 1.0 equiv., BzEtOH), were suspended in benzene (10 mL) under an argon atmosphere. After stirring the mixture for 1 h at 60 °C, the removal of benzene under reduced pressure afforded the partially deprotonated initiator salt. Subsequently, the dried initiator was dissolved in anhydrous DMSO (0.80 mL) and tetrahydrofuran (THF, 4.2 mL) ($V_{\text{DMSO}}/V_{\text{THF}}=1:5$) and stirred for 20 min at r.t.. THF was added via cryo-transfer to remove protic stabilizers. The reaction mixture was cooled to -82 °C using an ethanol/liquid nitrogen bath and previously dried GeraGE (1.63 mL, 1.43 g, 6.82 mmol, 11.4 equiv.) was syringed into the flask. Quantification of EO (2.82 mL, 2.70 g, 61.3 mmol, 102.6 equiv.) was realized via distillation into a graduated ampule under vacuum, followed by a cryo-transfer into the cooled polymerization flask. The polymerization was undertaken at 40 °C for 24 h and terminated with an excess of methanol (MeOH). All solvents were evaporated under reduced pressure and dialysis (MWCO = 1000 g·mol⁻¹) against a Milli-Q® water/MeOH mixture ($V_{\text{MeOH}}/V_{\text{water}}=5/1$) removed salt impurities and DMSO traces. Lyophilization afforded a brown viscous copolymer in yields of 77%. Table 1 summarizes the copolymer characterization data.

In situ ¹H NMR kinetic study of a statistical copolymerization of TGEs with EO

In situ ¹H NMR kinetic investigations for the copolymerization of a variety of TGEs with EO were performed in a sealable Norell S-500-VT-7 NMR tube subject to a procedure by Herzberger et al.⁴ In general, the polymerization set up in an NMR tube is restricted by its volume. To reproduce the optimized polymerization conditions (40 °C, THF-*d*₈/DMSO-*d*₆ = 5/1 ($V_{\text{THF}}/V_{\text{DMSO}}$)) for the TGE copolymerizations, batch calculations and theoretical comonomer ratios vary with each monomer in dependance of its chain length. This results from the varying molecular weights and densities of the applied TGEs. Note that EO is a highly toxic, flammable gas, which requires careful handling. As small amounts of EO are required for the *in situ* kinetic measurements, comonomer ratios are further impacted by small variations of the measured EO volumes.

The pre-dried initiator salt, cesium 2-(benzyloxy)ethanolate (degree of deprotonation: 95%), was prepared in a 10-fold excess and dissolved in anhydrous DMSO- d_6 under stirring for 30 min (initiator stock solution). Its preparation was carried out in accordance with the statistical copolymerization protocol described in the previous section. After evacuating the oven-dried NMR tube, using a Teflon stopcock using Schlenk-line vacuum, EO was cryo-transferred into the NMR tube under static vacuum at -45 °C with an acetone/nitrogen bath. Subsequently, an aliquot of the initiator stock solution and THF- d_8 were syringed into the tube under argon atmosphere while cooling was maintained. After a final evacuation cycle, the reaction mixture was allowed to warm to room temperature and shaken vigorously to homogenize the solution. Then, the NMR tube was placed in the preheated NMR spectrometer (40 °C) and a control spectrum was recorded once a stable temperature in the probe head was reached (~10 min, $\Delta T = 0.1$ K). The sample rotation was turned off and ^1H NMR spectra with 1 scan per spectrum were recorded in 2 min intervals. After the kinetic study, the copolymer was characterized via SEC analysis.

Monitoring the integrals of the epoxide functionality of EO and the respective TGE renders the calculation of the monomer consumption with preceding copolymerization possible. Therefore, the normalized monomer consumption was analyzed using the NIREVAL software from Johann et al.⁵ For the evaluation of the reactivity ratios of the comonomer pair the Jaacks method was applied for a 90% TGE conversion to ensure a significant signal-to-noise ratio.⁶

Procedures for Post-polymerization Functionalizations

Thiol-Ene Click

The following procedure was applied to all double bond containing monomers. As an example, the modification of P(EG₁₂₀-co-GeraGE₁₂) is described. The polymer (50 mg, 6.76 μ mol) and 2,2-dimethoxy-2-phenylacetophenone (DMPA, 83.1 mg, 0.324 mmol, 48 eq., 0.01 eq. to the thiol) were added to a Schlenkflask equipped with a magnetic stirrer and rubber septum. 8 ml of DCM was added, followed by 2-mercaptoethanol (2.53 g, 32.4 mmol, 4800 eq., 200 eq. per double bond). After mixing, three freeze-pump-thaw cycles were applied. Subsequently, an argon-filled balloon was attached to the Schlenkflask through the septum. The stirred mixture was irradiated overnight using a UV lamp (254 nm) at a distance of 5 cm. After the reaction the mixture was extracted against water (20 ml) thrice. Additionally, the polymer was purified by dialysis against MeOH (*Orange Scientific*, Molecular weight cut-off 1000 g/mol, 1 L, solvent changed thrice). The solvents were evaporated obtaining the modified polymer in typical yields of 80%.

Since every copolymer needed slightly different ratios of DMPA and 2-mercaptoethanol the set-ups are displayed in the following table. The authors would like to emphasize that the quantities mentioned are not necessarily the lowest possible. The experimental procedure was optimized for P(EG₁₂₀-co-GeraGE₁₂) first. The amounts were adjusted to the polymers. DMPA was modified and/or 2-mercaptoethanol was increased to suppress crosslinking.

Table S 1: Precursor polymers and the respective equivalents of Thiol and DMPA in the thiol-ene click post-polymerization modification.

Entry	Polymer	Thiol/Double bond	DMPA eq./Thiol
1	P(EG ₁₀₂ -co-PreGE ₁₀)	600	0.010
2	P(EG ₁₂₆ -co-IsoPreGE ₁₂)	200	0.010
3	P(EG ₁₂₀ -co-GeraGE ₁₂)	200	0.010
4	P(EG ₁₂₃ -co-NerGE ₁₃)	600	0.015

Recovery of unreacted 2-mercaptoethanol

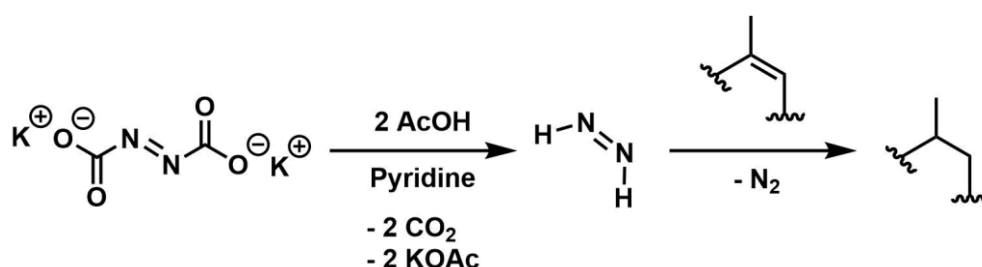
After the reaction, the volatile compounds, mainly DCM and 2-mercaptoethanol, were cryotransferred into a schlenkflask equipped with a magnetic stirrer. The volatile compounds were fractionally distilled, 2-mercaptoethanol was received in a yield of 80%.

Synthesis of potassium azodicarboxylate (PADA)

PADA was synthesized according to Groves and Ma.⁷ 30 mL of a 40 w.-% aqueous potassium hydroxide solution was added to a 50 mL round-bottom flask equipped with a magnetic stirrer. The flask was immersed into a water bath at 6 °C. Azodicarboxylate (4.84 g, 41.7 mmol) was added portion wise over 2 h. The precipitate was filtered off using a glass frit and washed 20 times with ice cold methanol. The product was dried in a desiccator over 1.5 d employing vacuum, giving an intense yellow powder. The yield was 7.18 g, 37.0 mmol, 89%.

Hydrogenation

Hydrogenation of polymers with potassium azodicarboxylate (PADA) is rarely employed.⁸ The described procedure was developed during the optimization experiments and represents the best result. We oriented on the procedures described from Groves and Ma⁷ as well as Snyder and Hamersma.⁹



Scheme S 1: Acidic decomposition of potassium azodicarboxylate (PADA) to generate diimide and subsequent polymer hydrogenation. Gaseous carbon dioxide and nitrogen as well as readily water-soluble potassium acetate are produced as coupling products.

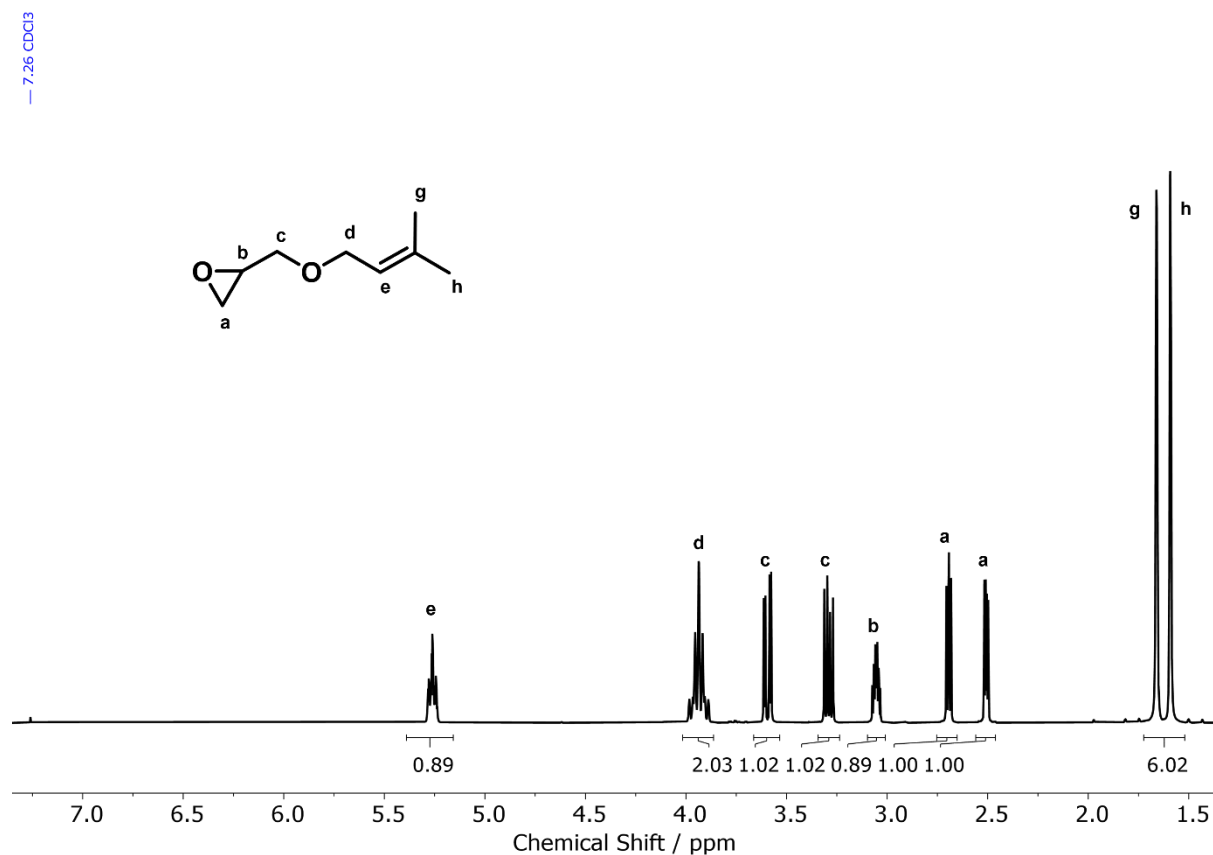
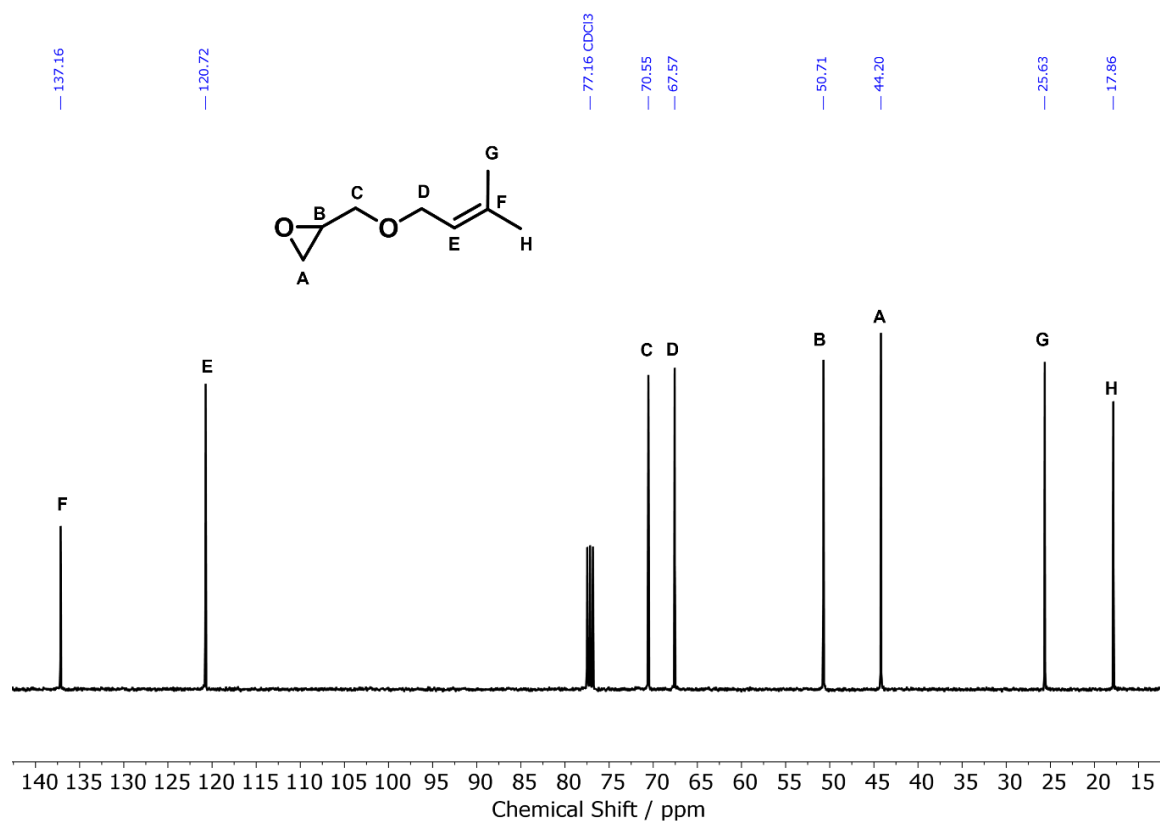
The hydrogenation was applied to P(EG₁₂₀-co-GeraGE₁₂). 50 mg (6.76 μmol) were transferred in a flame dried Schlenk flask equipped with a rubber septum and a magnetic stirrer using Toluene. The solvent was removed *in vacuo* yielding the dried polymer due to azeotropic distillation. PADA (423 mg, 360 eq., 15 eq. per double bond) and 3 ml of dry pyridine (stored over mole sieve, *Fisher Scientific*) were added. To the stirred slurry glacial acetic acid (distilled from P₄O₁₀ and stored over Argon, 0.28 ml, 720 eq., 2 eq. per PADA) was slowly added dropwise with a syringe. After complete

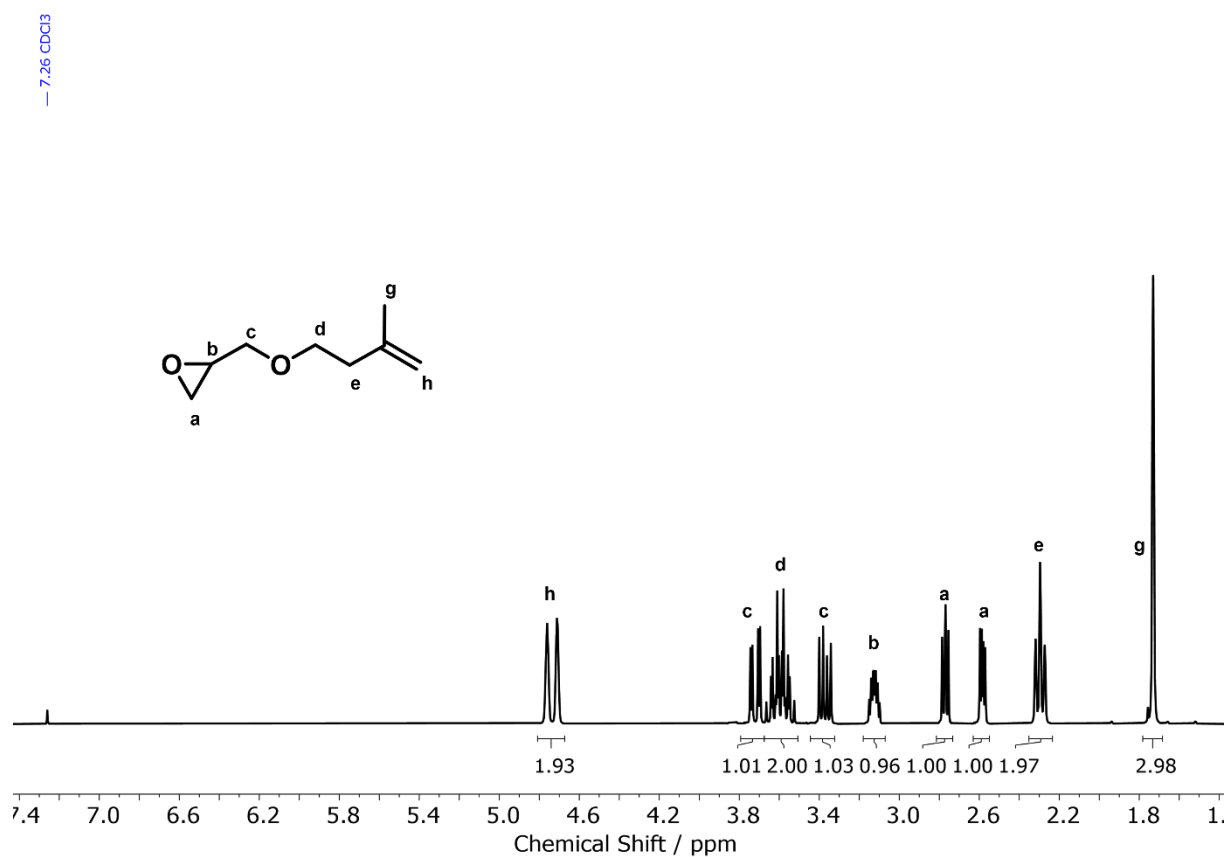
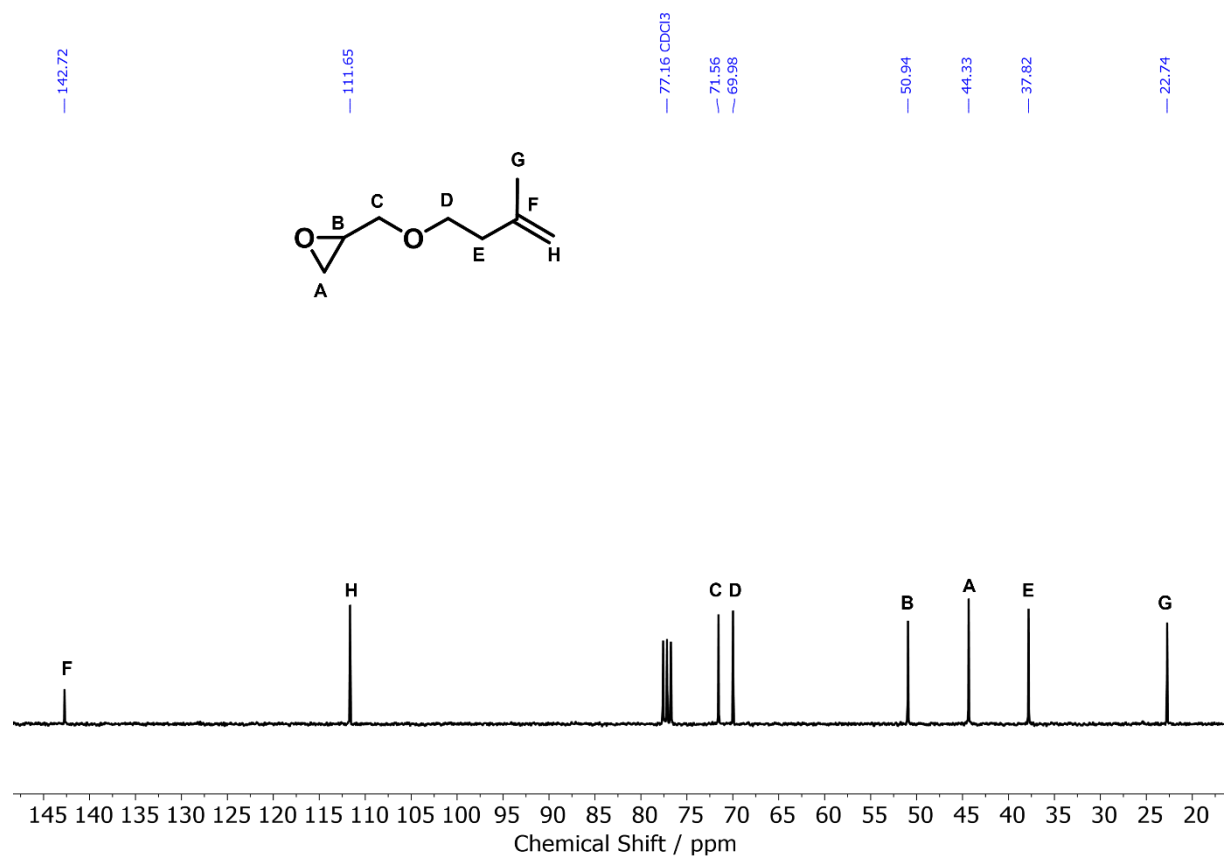
addition of the glacial acetic acid the mixture was allowed to react overnight. The now colorless suspension was suspended in CHCl_3 , solids were filtered off and the organic phase was washed with water twice (20 ml). The solvents were evaporated yielding the polymer in a yield of 85%.

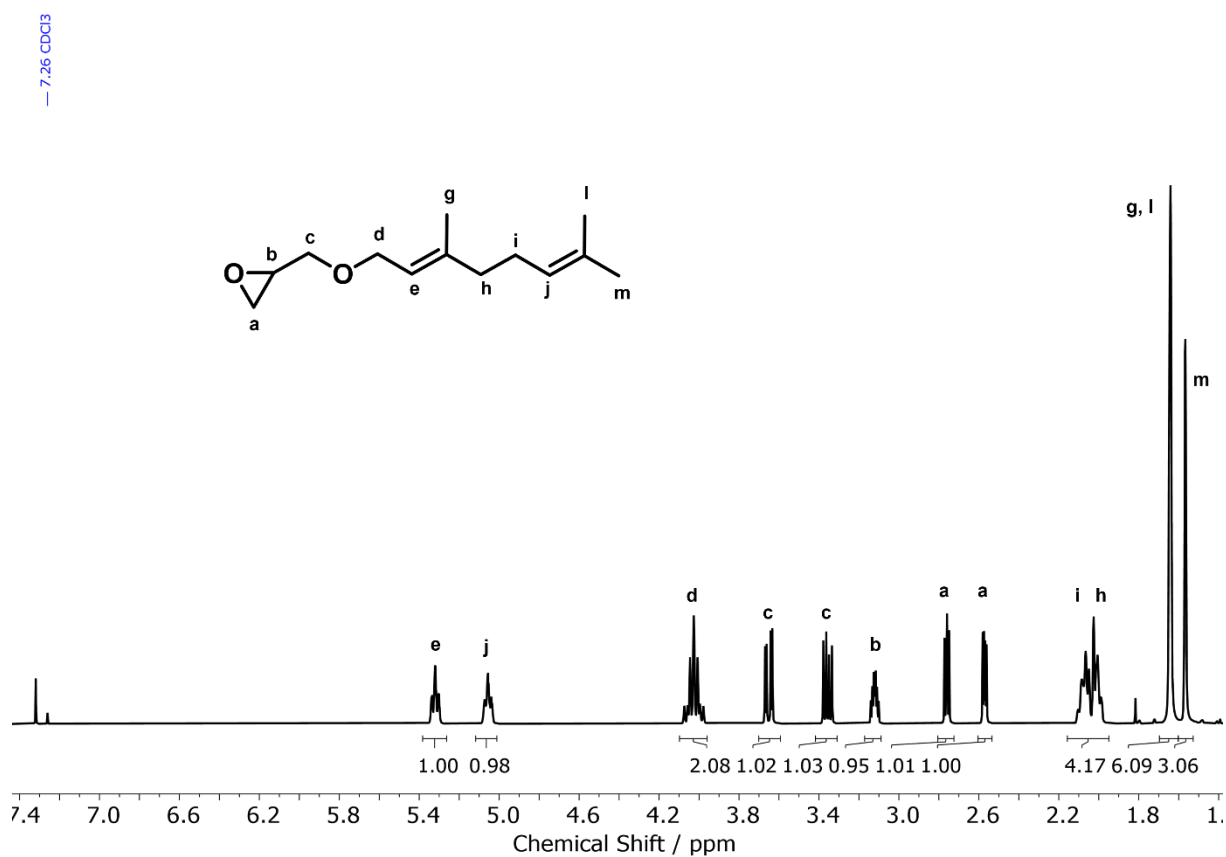
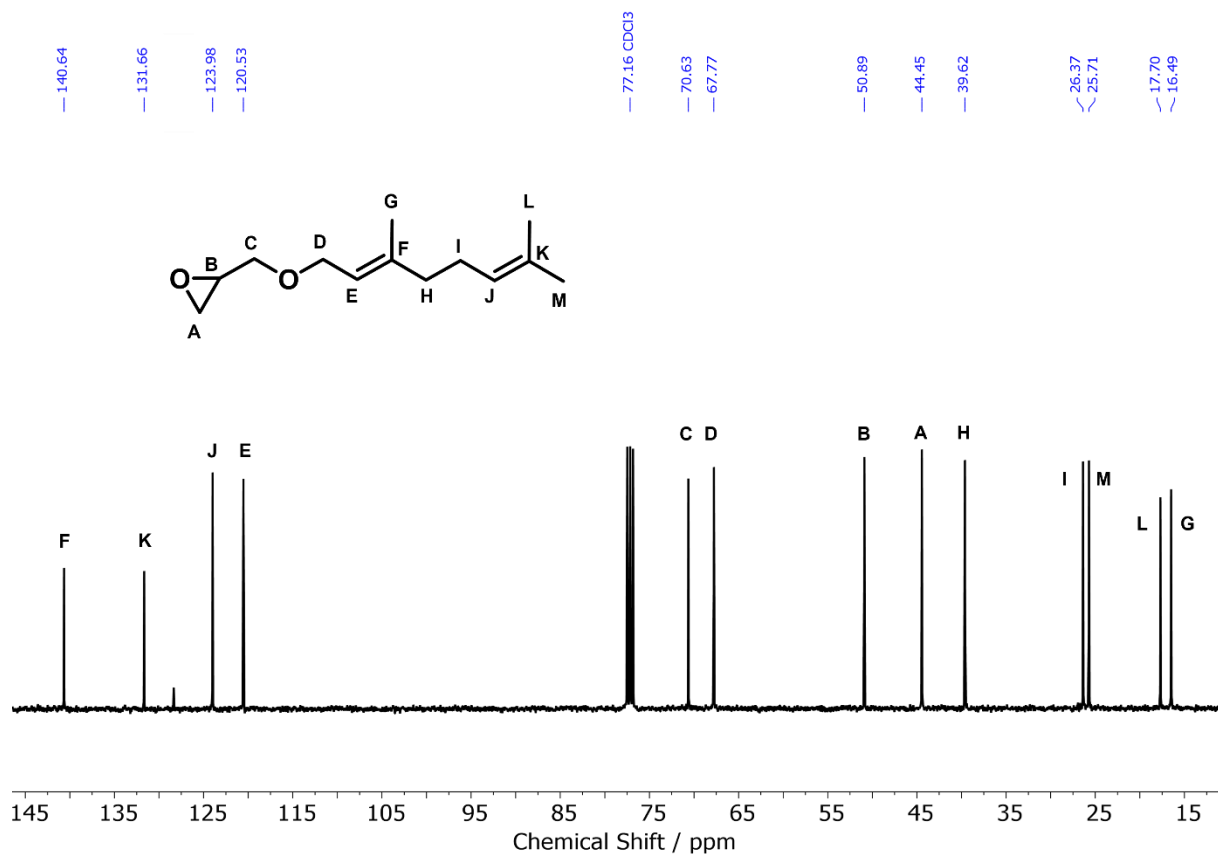
Table S 2: Reaction conditions of the hydrogenation of P(EG₁₂₀-co-GeraGE₁₂) employing potassium azodicarboxylate (PADA).

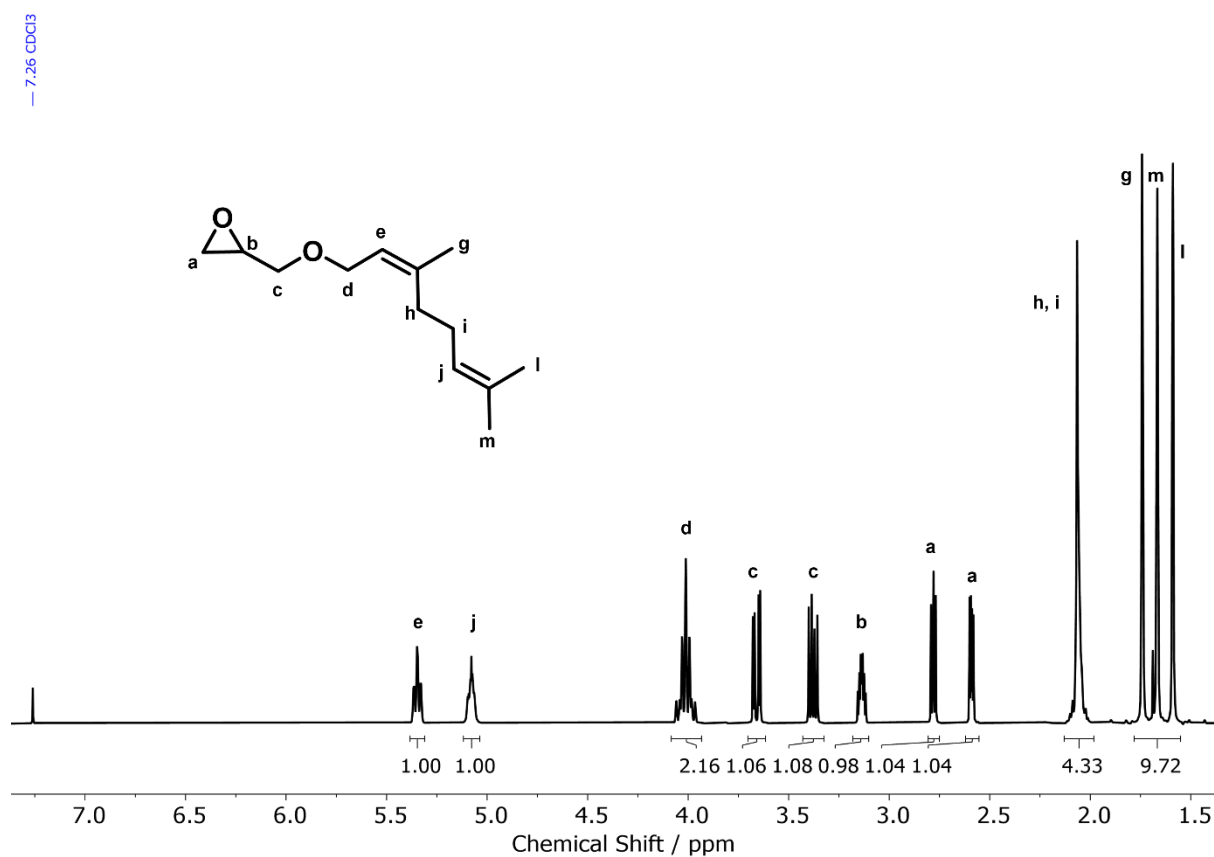
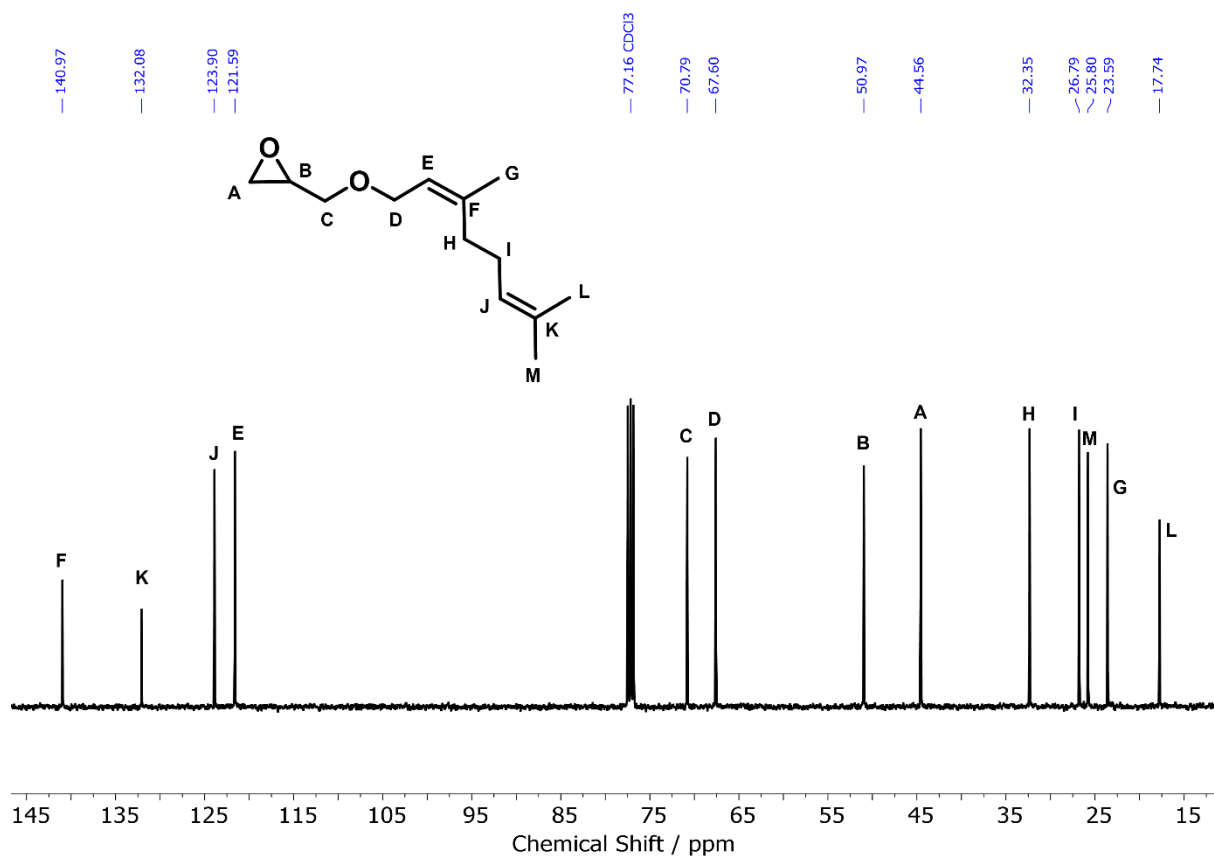
Entry	T / °C	Eq. PADA/DB	V(Py) / mL	Remaining signal of the DB		avg. efficiency
				5.30 ppm	5.08 ppm	
1	0	2.5	0.4	58%	64%	39%
2	25	2.5	0.4	92%	89%	10%
3	0	15	0.4	44%	49%	53%
4	25	15	0.4	73%	78%	25%
5	0	2.5	3	71%	74%	28%
6	25	2.5	3	74%	80%	23%
7	0	15	3	48%	55%	48%
8	25	15	3	43%	49%	53%

NMR Spectra of TGEs

Figure S 1: ¹H NMR spectrum (300 MHz, CDCl₃) of PreGE.Figure S 2: ¹³C NMR spectrum (75 MHz, CDCl₃) of PreGE.

Figure S 3: ¹H NMR spectrum (300 MHz, CDCl₃) of IsoPreGE.Figure S 4: ¹³C NMR spectrum (75 MHz, CDCl₃) of IsoPreGE.

Figure S 5: ¹H NMR spectrum (400 MHz, CDCl₃) of GeraGE.Figure S 6: ¹³C NMR spectrum (100 MHz, CDCl₃) of GeraGE.

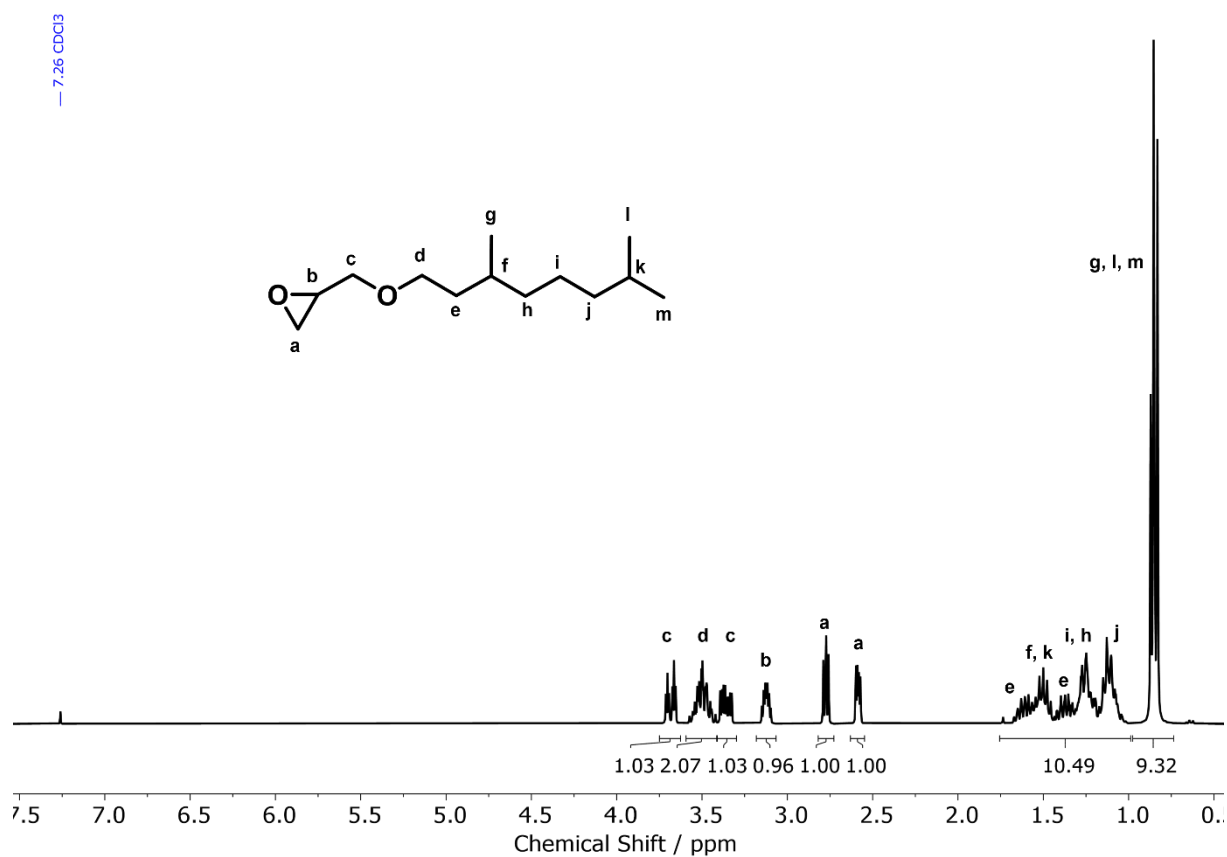
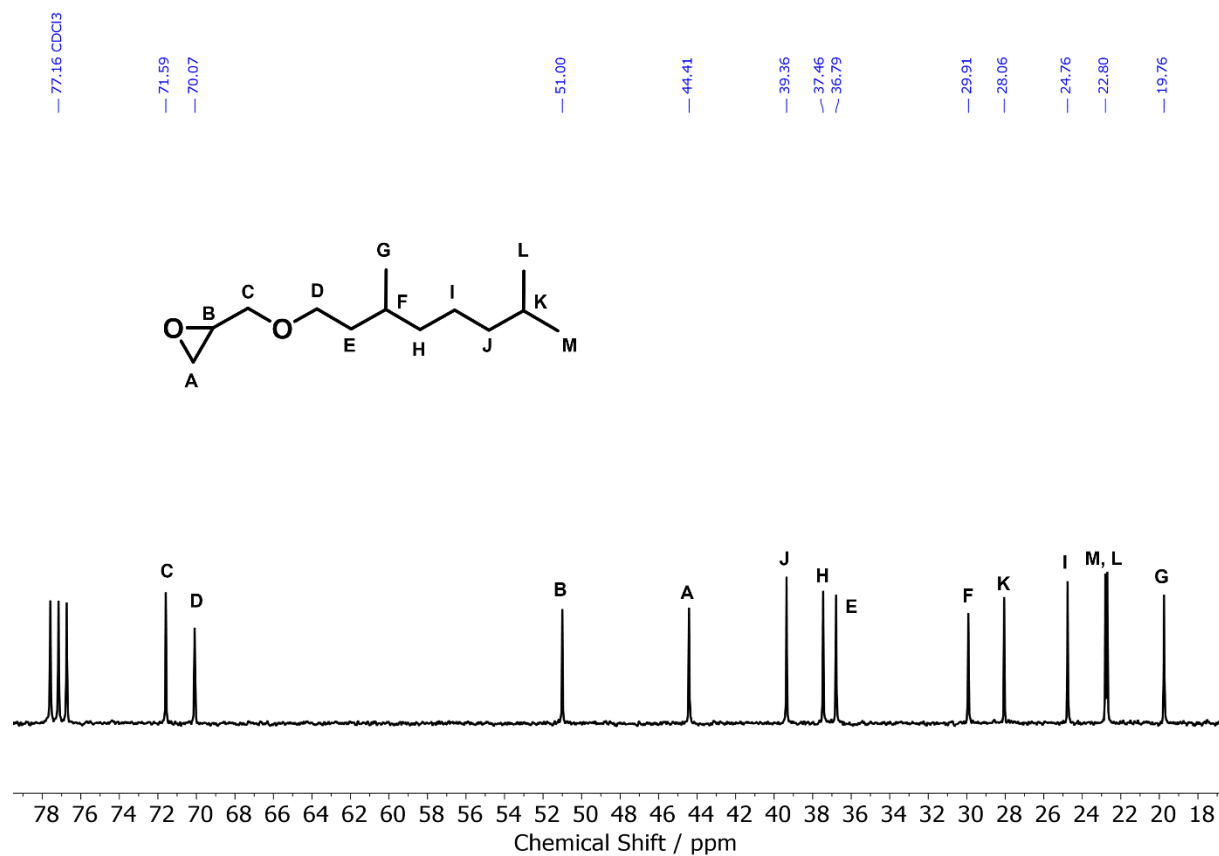
Figure S 7: ¹H NMR spectrum (400 MHz, CDCl₃) of NerGE.Figure S 8: ¹³C NMR spectrum (100 MHz, CDCl₃) of NerGE.

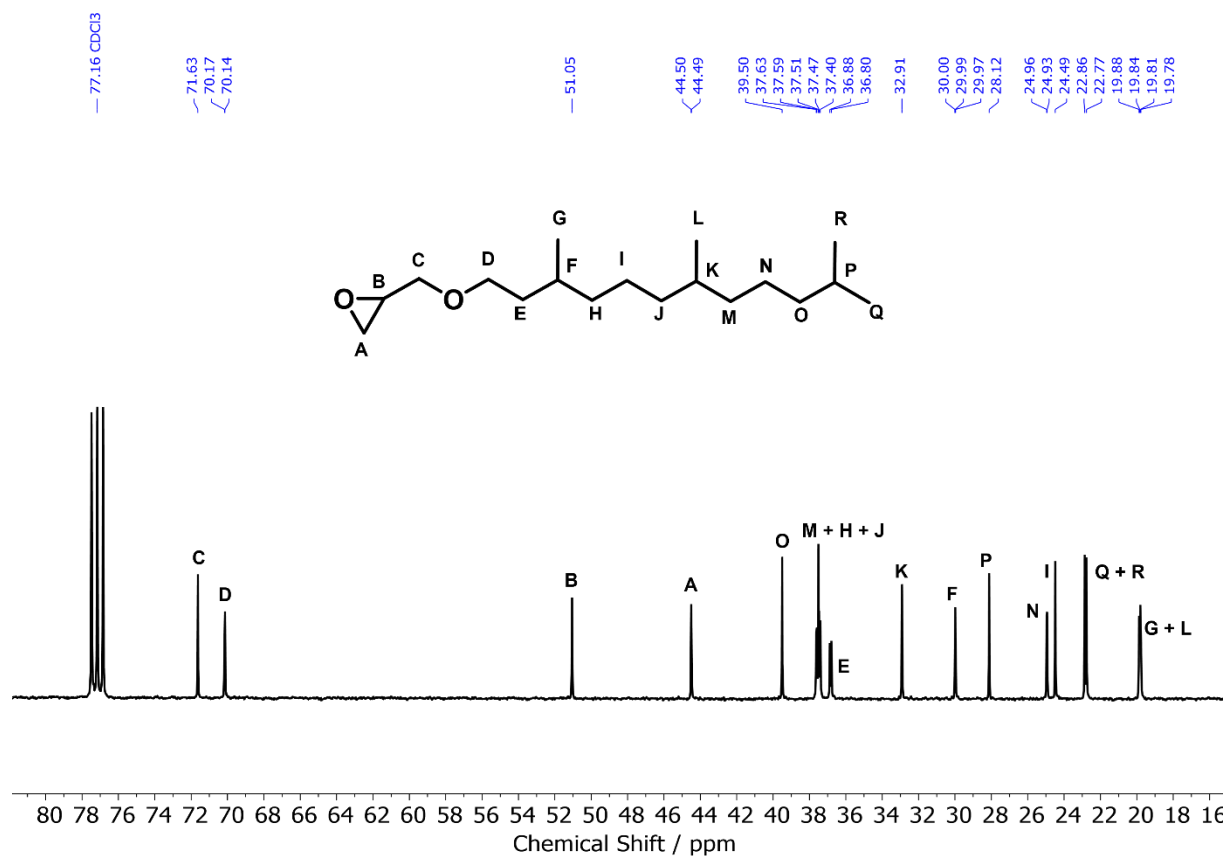
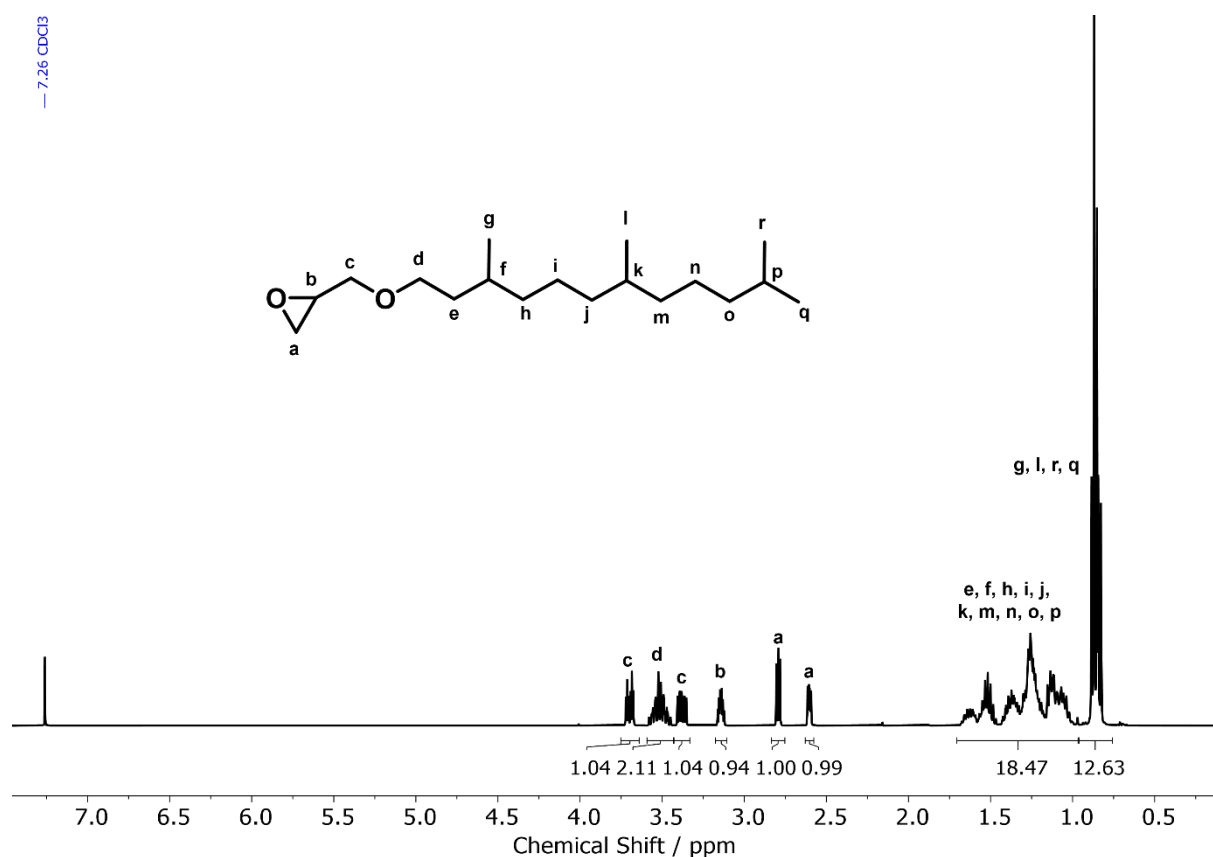
Chemical structure of 2-(2-ethoxy-2-methylpropyl)oxirane (labeled **1**) is shown above the spectrum. The structure is labeled with letters A through H indicating specific carbon environments for assignment.

¹³C NMR spectrum (CDCl₃) showing peaks assigned to the structure:

Peak Label	Chemical Shift (ppm)
A	44.38
B	50.98
C, D	70.10, 71.56
E	38.56
F	25.10
G, H	22.71

Figure S 10: ^{13}C NMR spectrum (75 MHz, CDCl_3) of DHPreGE.

Figure S 11: ¹H NMR spectrum (300 MHz, CDCl₃) of THGeraGE.Figure S 12: ¹³C NMR spectrum (75 MHz, CDCl₃) of THGeraGE.



Characterization of Statistical Copolymers of TGEs and EO

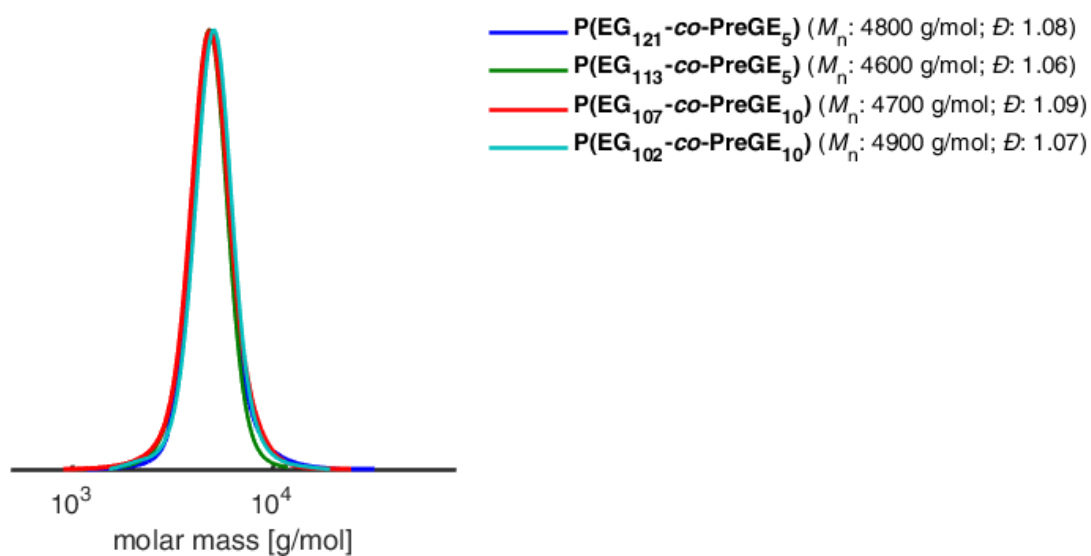


Figure S 15: SEC traces of $\text{P(EG}_n\text{-co-PreGE}_m)$ (RI detector, eluent: DMF, PEG calibration).

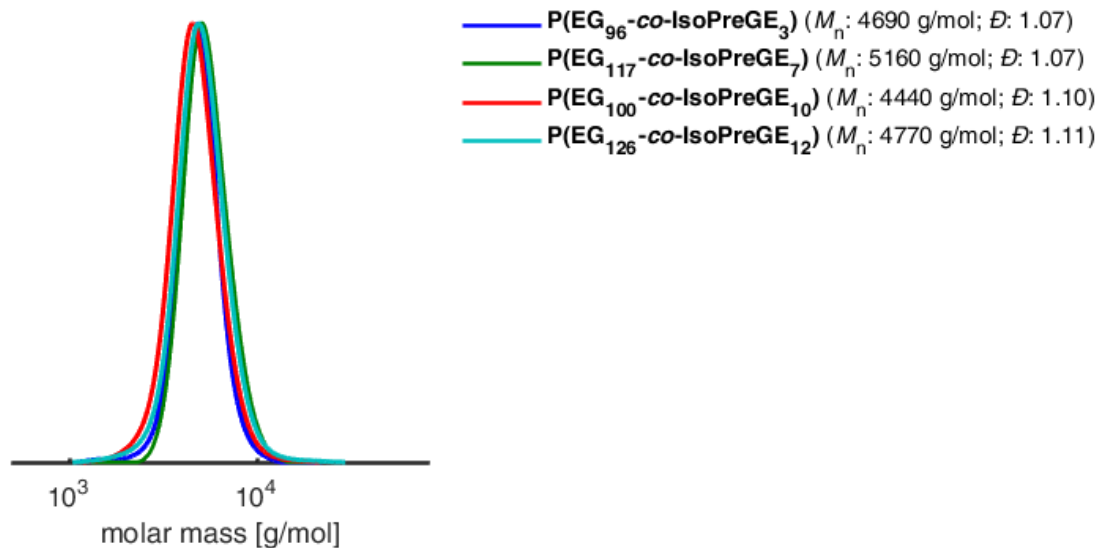


Figure S 16: SEC traces of $\text{P(EG}_n\text{-co-IsoPreGE}_m)$ (RI detector, eluent: DMF, PEG calibration).

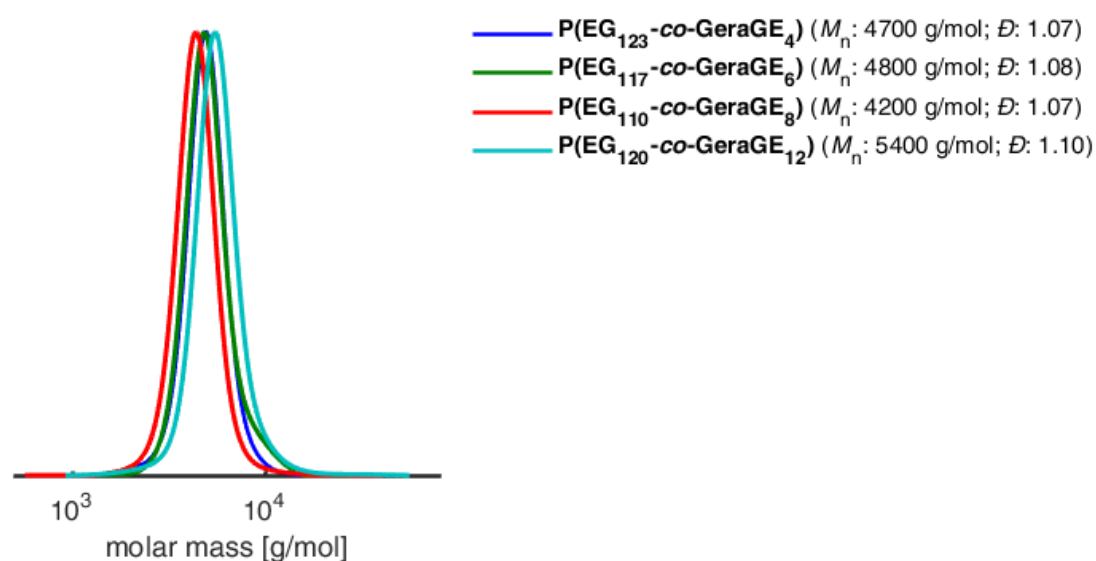


Figure S 17: SEC traces of $P(EG_n\text{-}co\text{-}GeraGE_m)$ (RI detector, eluent: DMF, PEG calibration).

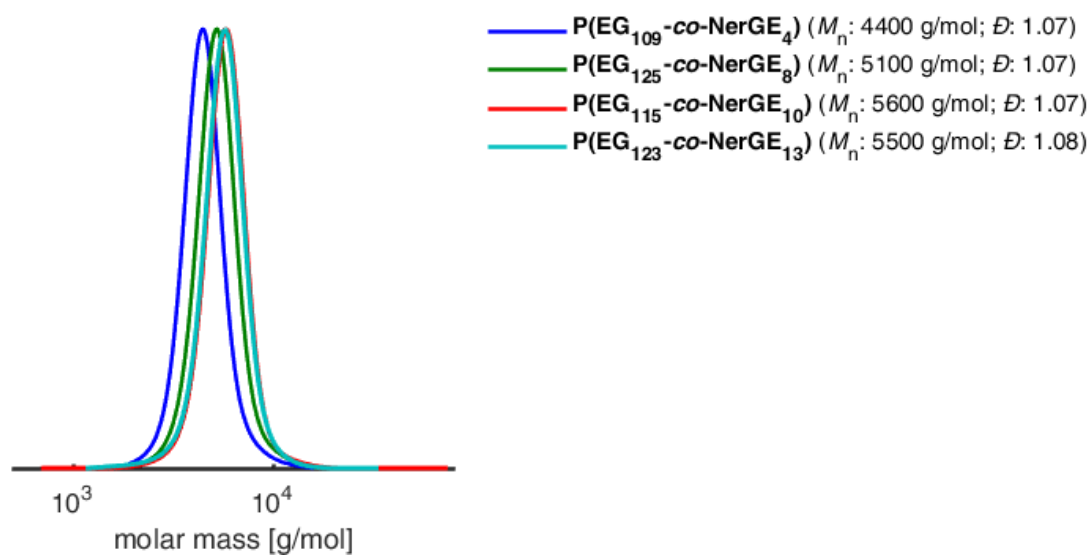
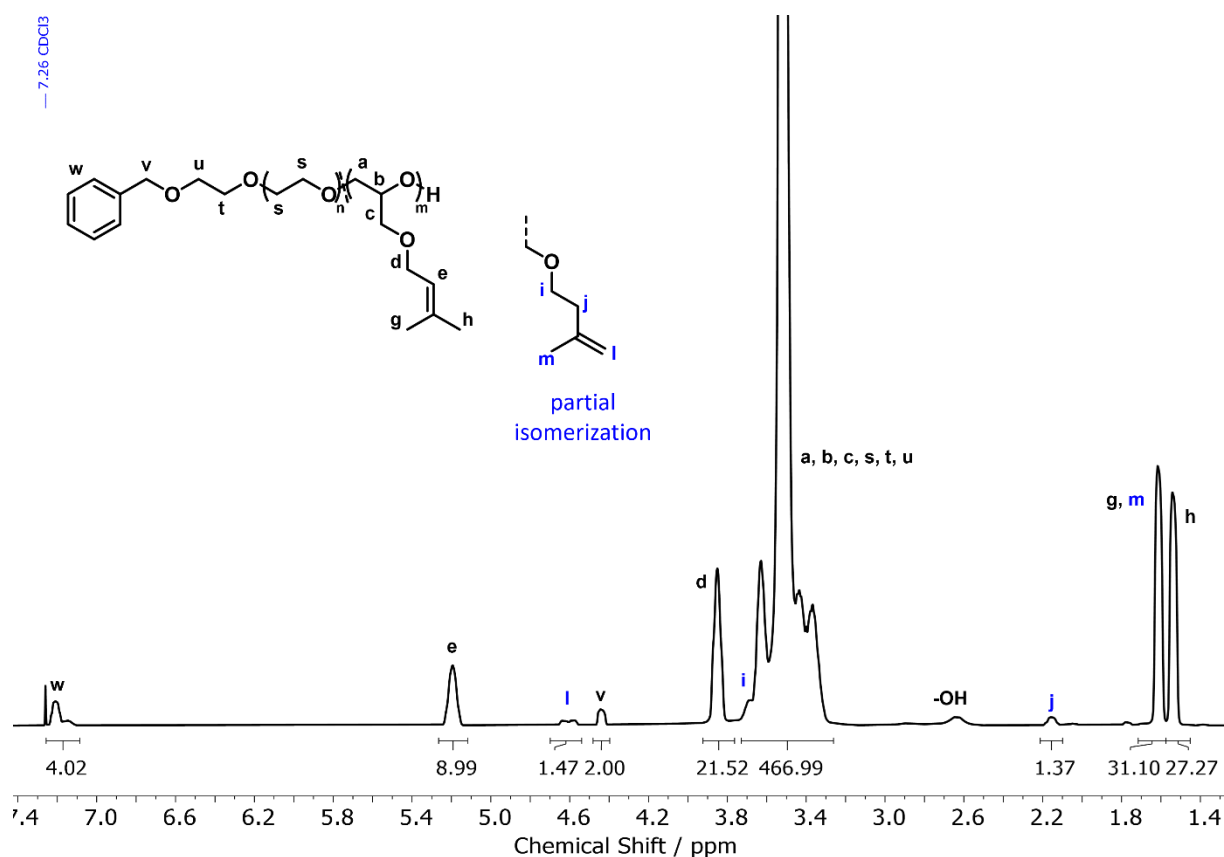
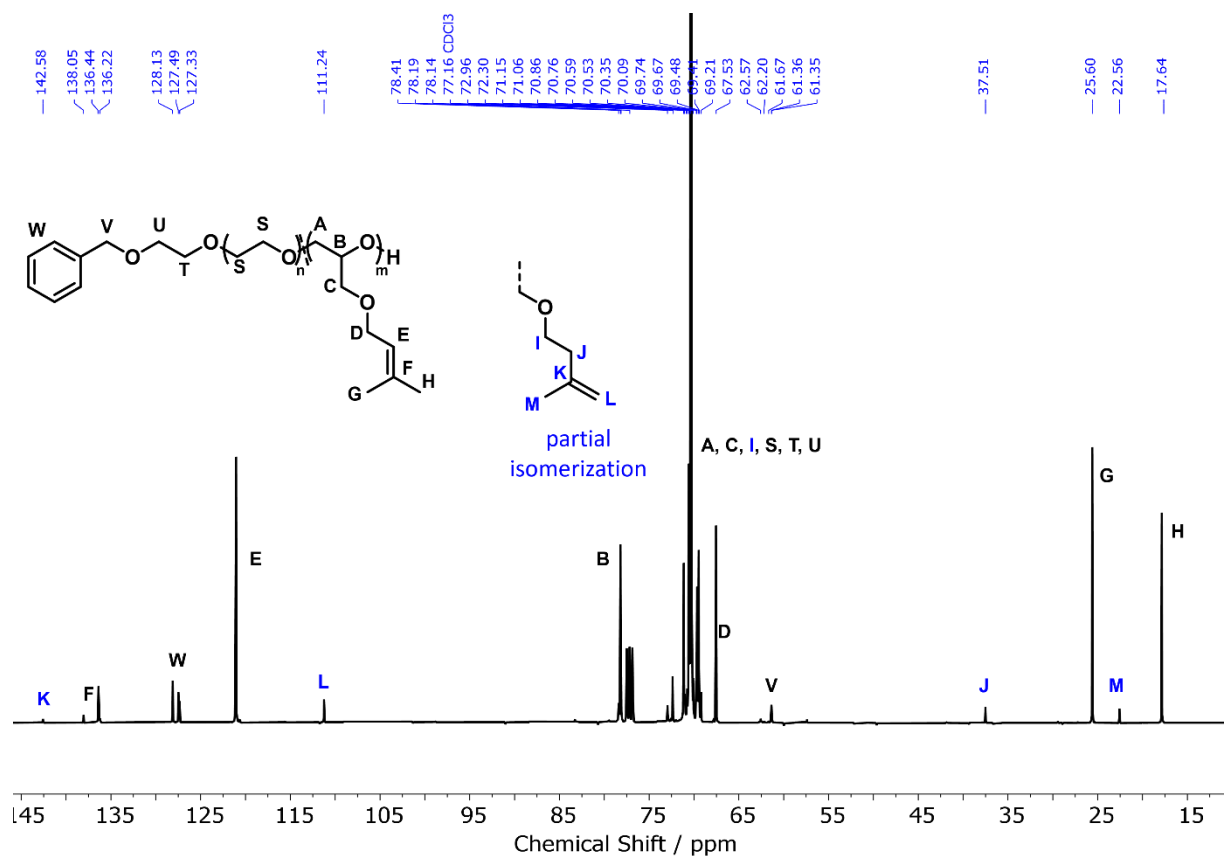
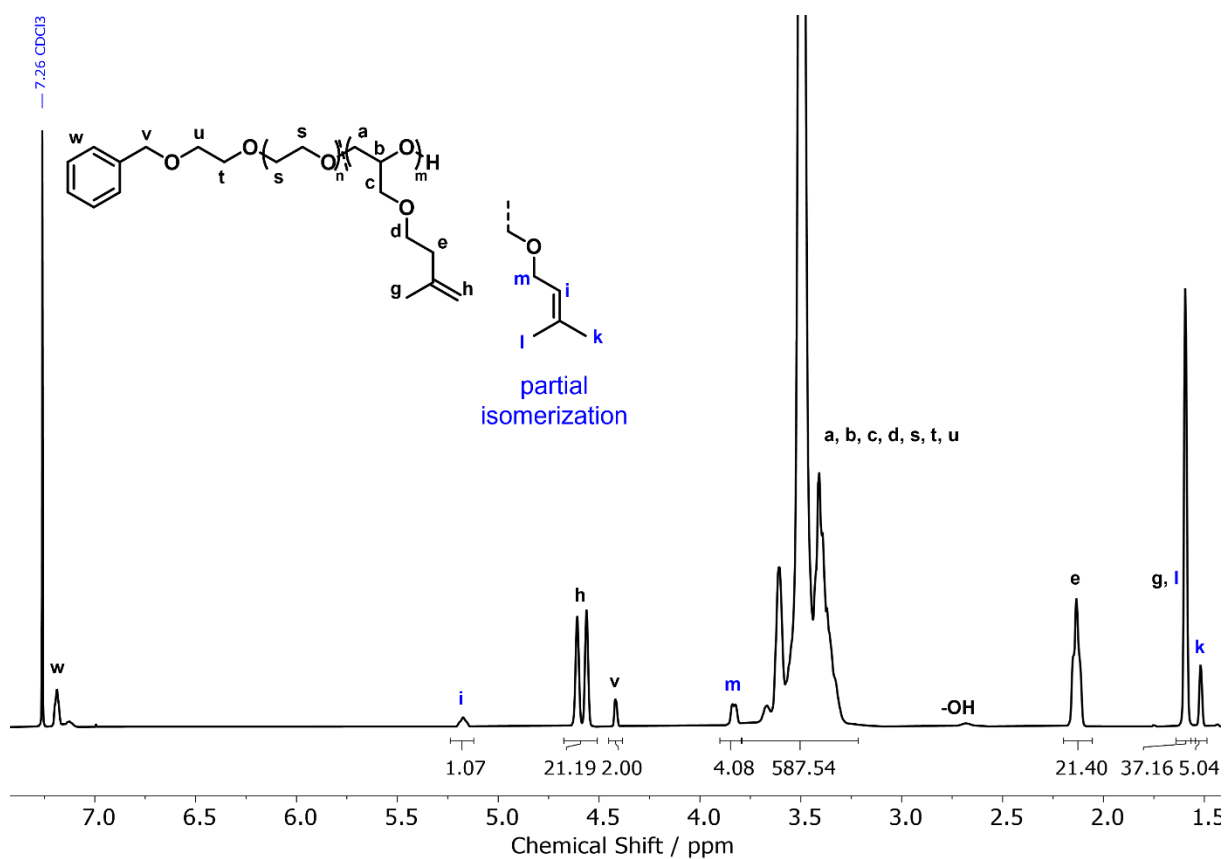
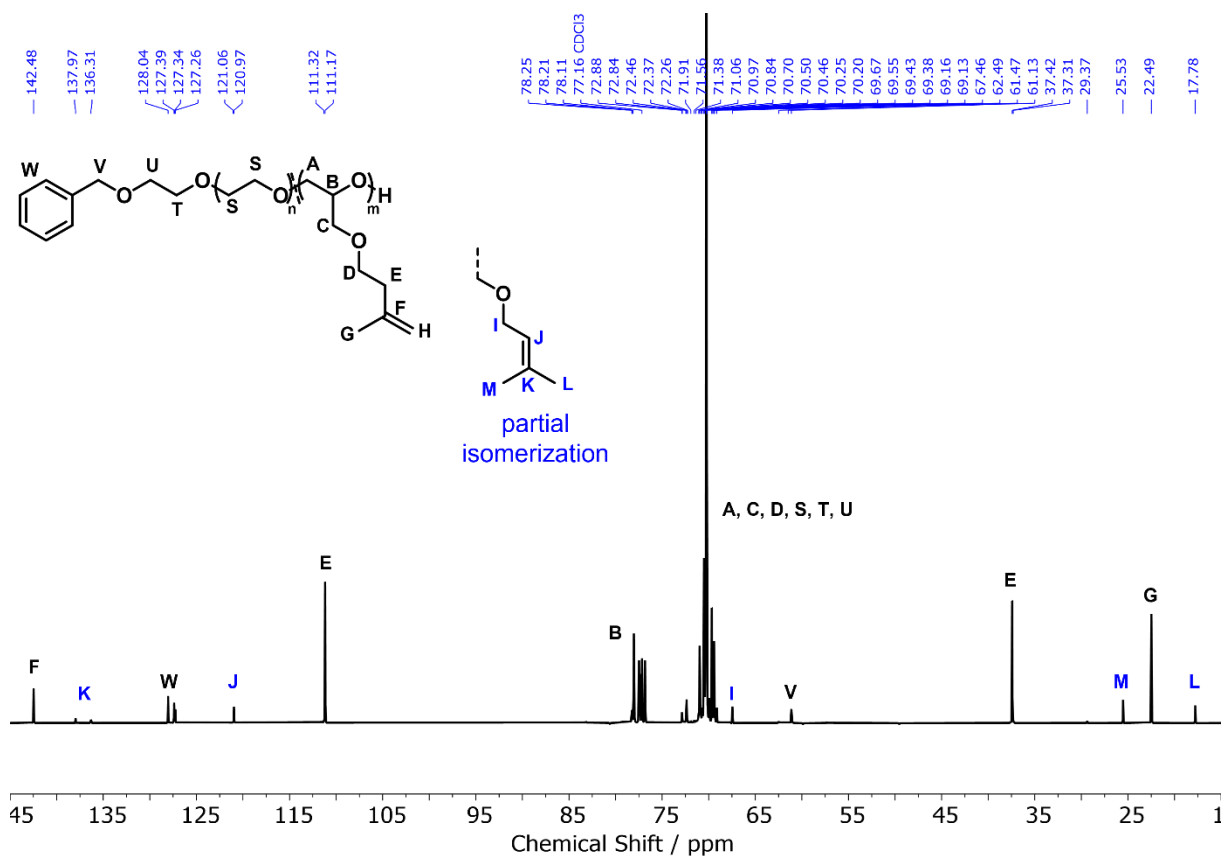
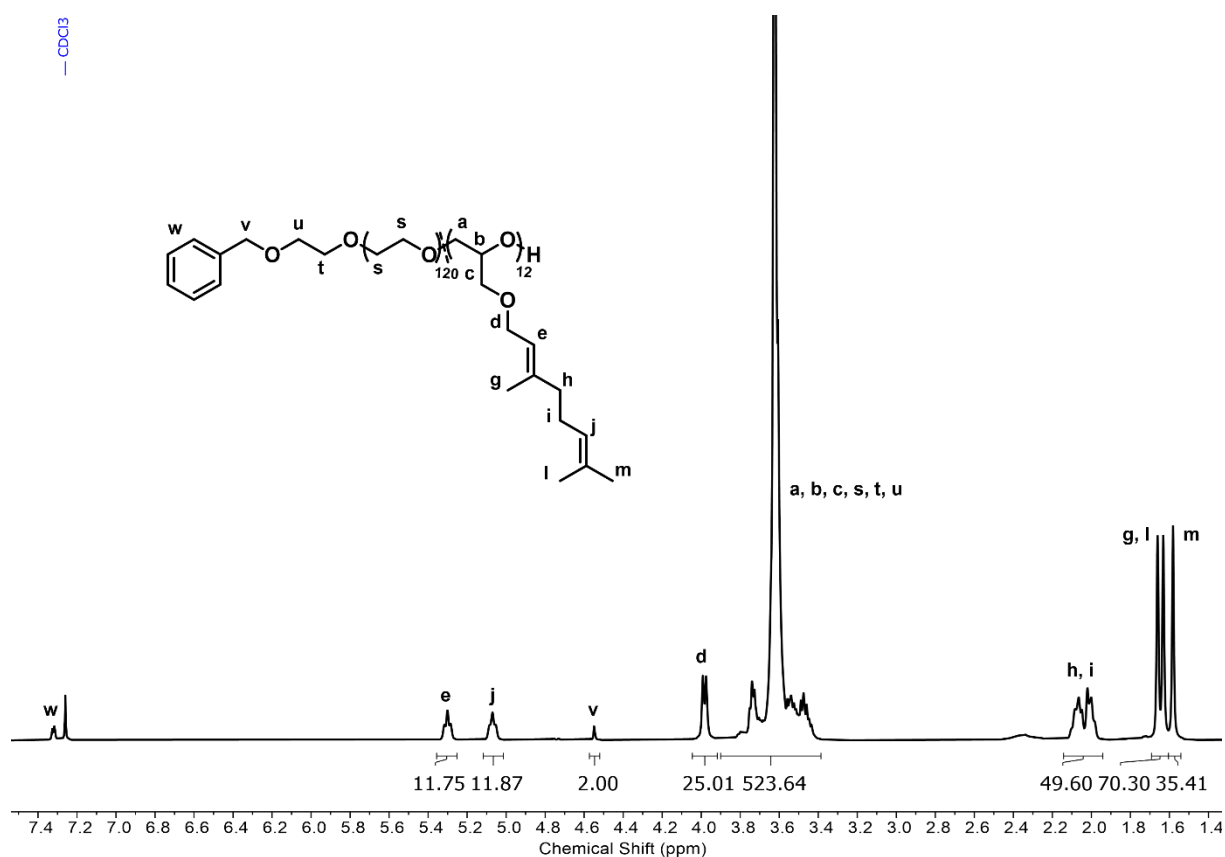
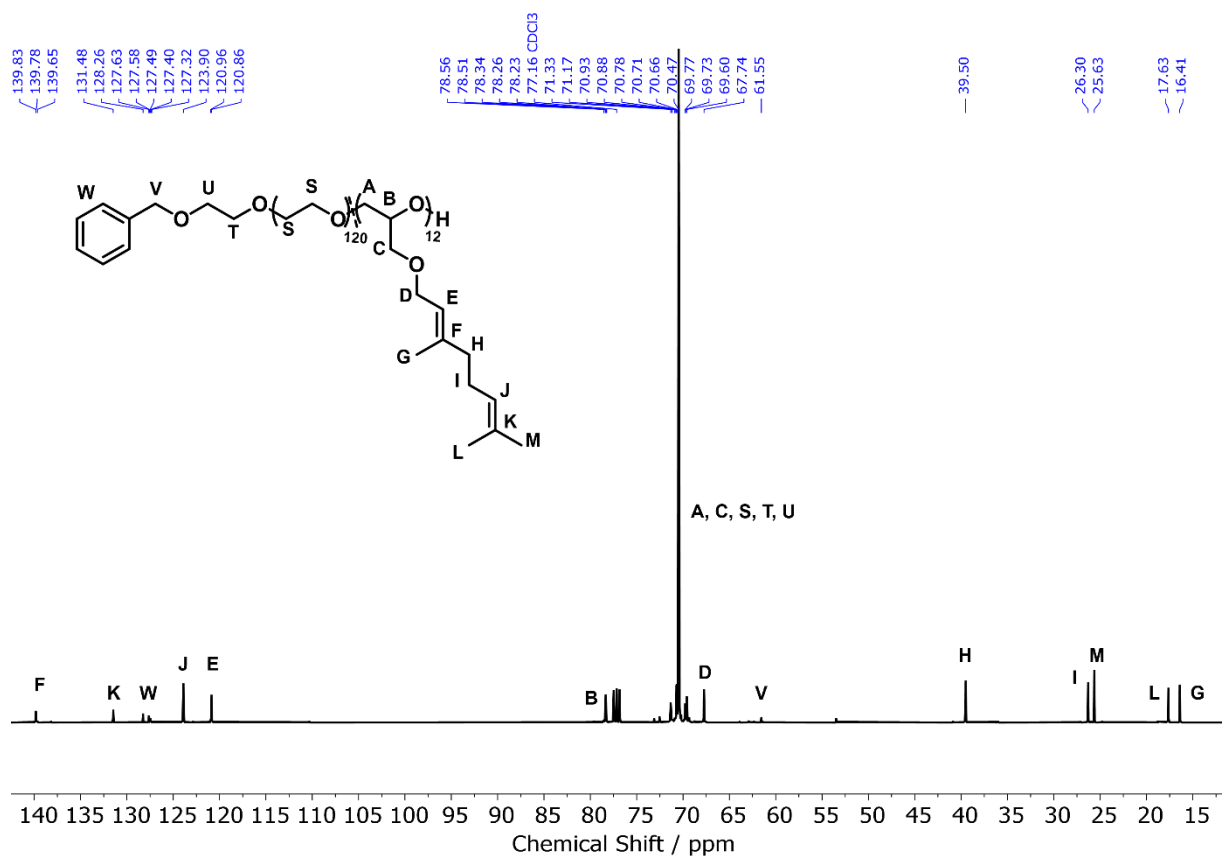
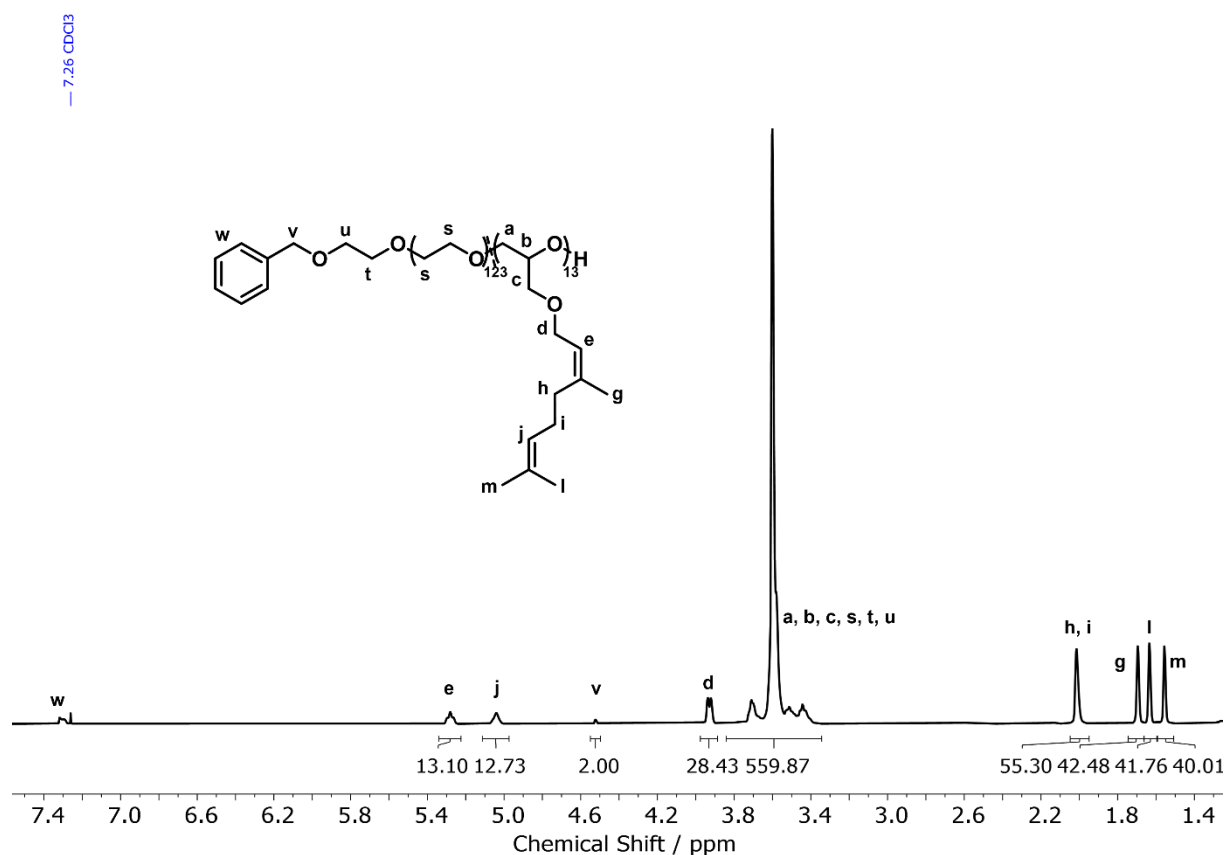
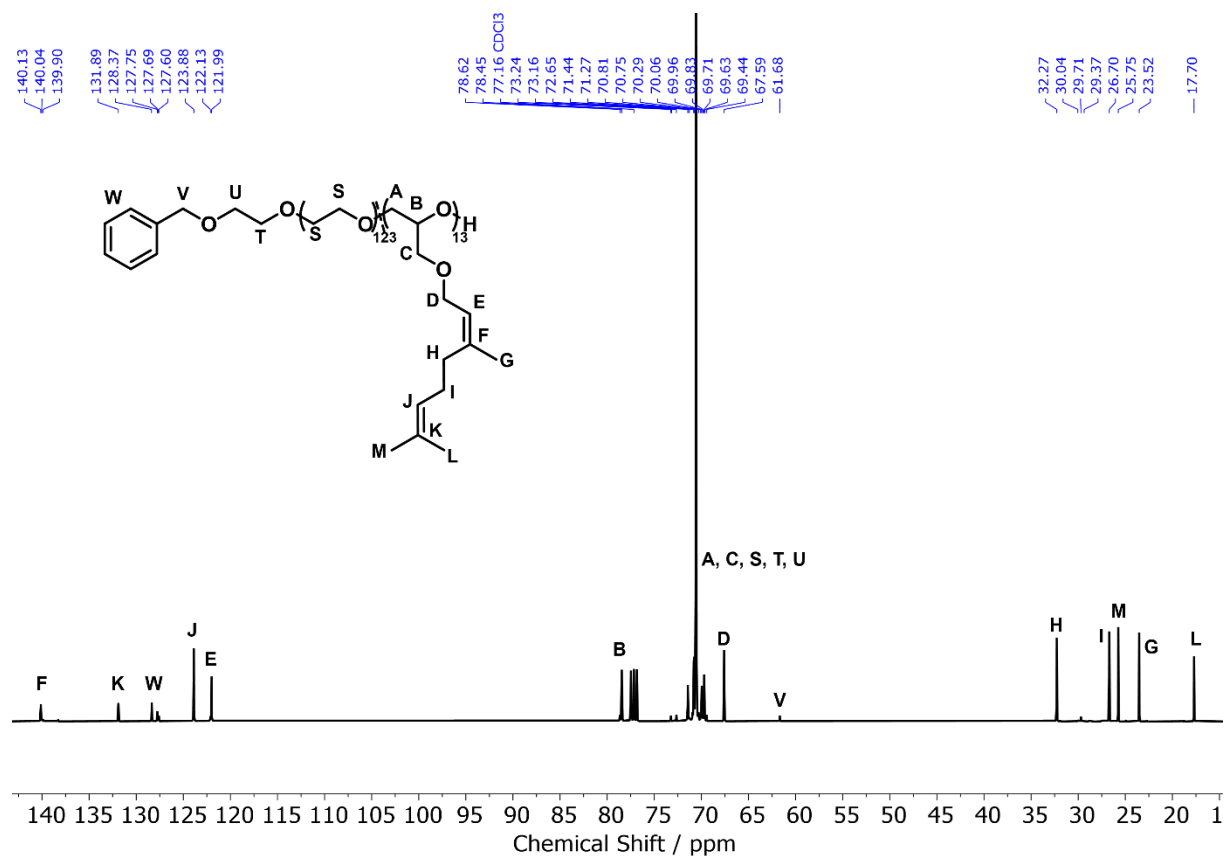


Figure S 18: SEC traces of $P(EG_n\text{-}co\text{-}NerGE_m)$ (RI detector, eluent: DMF, PEG calibration).

Figure S 19: ^1H NMR spectrum (400 MHz, CDCl_3) of $\text{P}(\text{EG}_{102}\text{-co-PreGE}_{10})$.Figure S 20: ^{13}C NMR spectrum (100 MHz, CDCl_3) of $\text{P}(\text{EG}_{102}\text{-co-PreGE}_{10})$.

Figure S 21: ¹H NMR spectrum (400 MHz, CDCl₃) of P(EG₁₂₆-co-IsoPreGE₁₂).Figure S 22: ¹³C NMR spectrum (100 MHz, CDCl₃) of P(EG₁₂₆-co-IsoPreGE₁₂).

Figure S 23: ¹H NMR spectrum (400 MHz, CDCl₃) of P(EG₁₂₀-co-GeraGE₁₂).Figure S 24: ¹³C NMR spectrum (100 MHz, CDCl₃) of P(EG₁₂₀-co-GeraGE₁₂).

Figure S 25: ¹H NMR spectrum (400 MHz, CDCl₃) of P(EG₁₂₃-co-NerGE₁₃).Figure S 26: ¹³C NMR spectrum (100 MHz, CDCl₃) of P(EG₁₂₃-co-NerGE₁₃).

***In situ* ^1H NMR Copolymerization Kinetics of TGEs with EO**

Non-terminal, ideal copolymerization model and Jaacks fit.

The evaluation of the reactivity ratios is based on the non-terminal, ideal copolymerization model, which was introduced by Wall in 1941.¹⁰ Assuming first order polymerizations, the following polymerization rates apply for a binary copolymerization system:

$$\frac{d[\text{M}_1]}{dt} = -k_1[\text{M}_1][\text{P}] \quad (1)$$

$$\frac{d[\text{M}_2]}{dt} = -k_2[\text{M}_2][\text{P}] \quad (2)$$

[P] refers to the active chain end. Eliminating t from the equations by dividing rate (1) by rate (2), followed by rearrangement, the time-independent differential equation (4) is obtained:

$$\frac{d[\text{M}_1]}{d[\text{M}_2]} = \frac{k_1 [\text{M}_1]}{k_2 [\text{M}_2]} \quad (3)$$

$$\frac{d[\text{M}_1]}{[\text{M}_1]} = r_1 \frac{d[\text{M}_2]}{[\text{M}_2]} \quad \text{with } r_1 = \frac{k_1}{k_2} \quad (4)$$

Wall was the first to use relative rates to describe copolymerizations and the resulting reactivity ratios r_1 and r_2 represent the compositional drift due to different comonomer reactivities.¹¹ The model assumes a copolymerization behavior that is not dependent on the identity of the growing chain end, but solely on the comonomer reactivities.

The integration of the rearranged Wall's equation (4) leads to the Jaacks equation (5)⁶:

$$\log \frac{[\text{M}_1, t=x]}{[\text{M}_1, t=0]} = r_1 \log \frac{[\text{M}_2, t=x]}{[\text{M}_2, t=0]} \quad (5)$$

The Jaacks equation allows for the determination of the reactivity ratios at any comonomer ratio when ideal copolymerization conditions are applicable ($r_1 \cdot r_2 = 1$).⁶

In line with the Ockhams razor, the non-terminal model represents the most basic model for the determination of the reactivity ratios and poses the model of choice to avoid overfitting.^{12,13} Experimental data suggest its suitability for the copolymerization of EO and monosubstituted epoxides, which tend to obey ideal copolymerization behavior.¹¹

Jaacks fit for the copolymerization of TGEs with EO

The signal scattering noticeably increases at high copolymerization conversions while the signal-to-noise ratio decreases. Hence, all reactivity ratios were calculated for a TGE monomer conversion of approximately 90%. The results are summarized in Table 2.

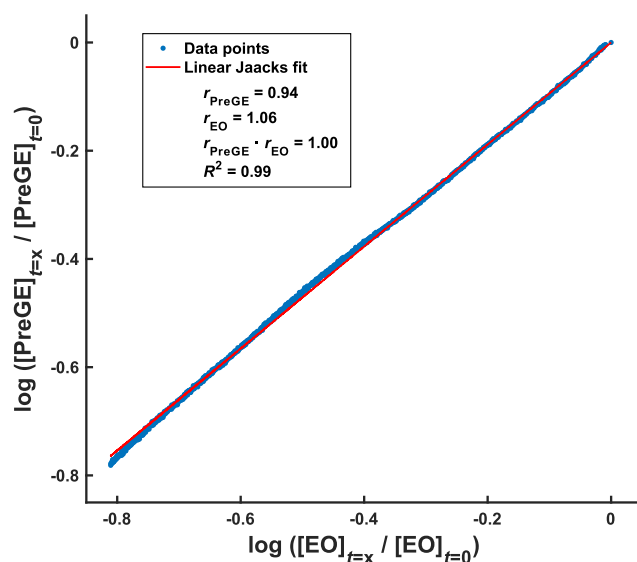


Figure S 27: Jaacks fit of the *in situ* ^1H NMR copolymerization kinetics of PreGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

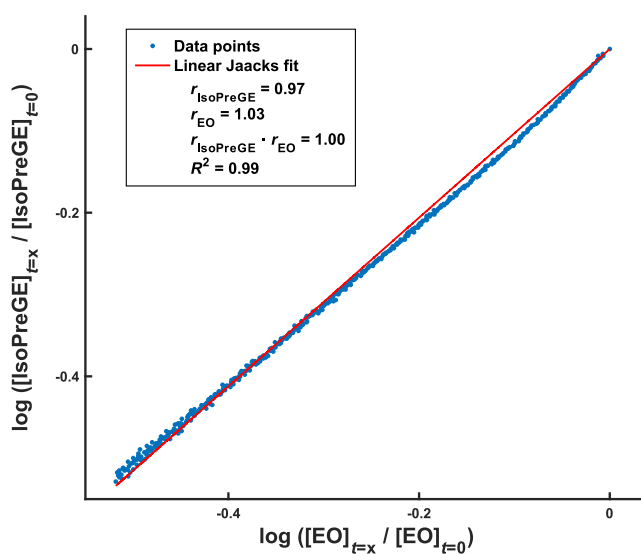


Figure S 28: Jaacks fit of the *in situ* ^1H NMR copolymerization kinetics of IsoPreGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

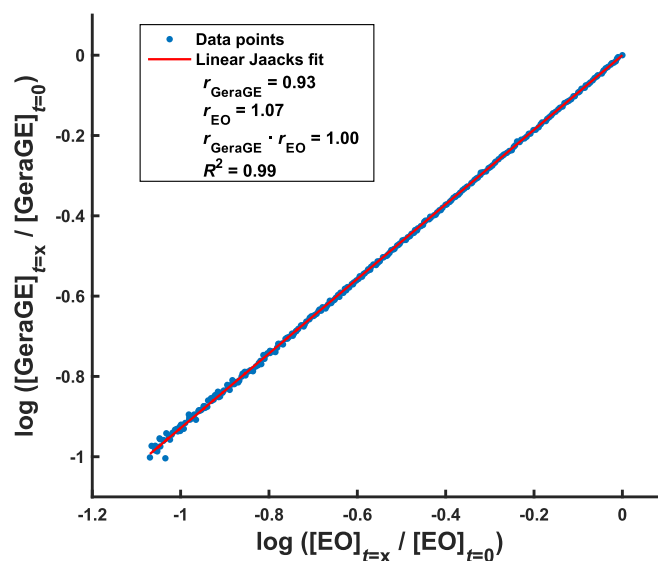


Figure S 29: Jaacks fit of the *in situ* ^1H NMR copolymerization kinetics of GeraGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

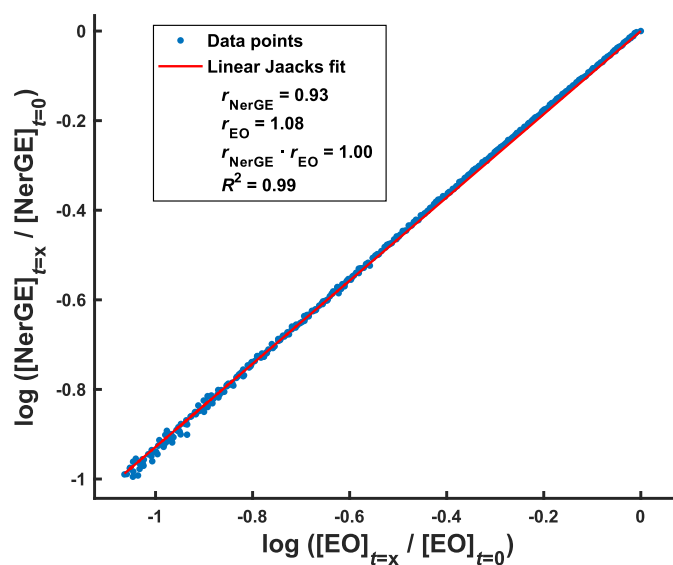


Figure S 30: Jaacks fit of the *in situ* ^1H NMR copolymerization kinetics of NerGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

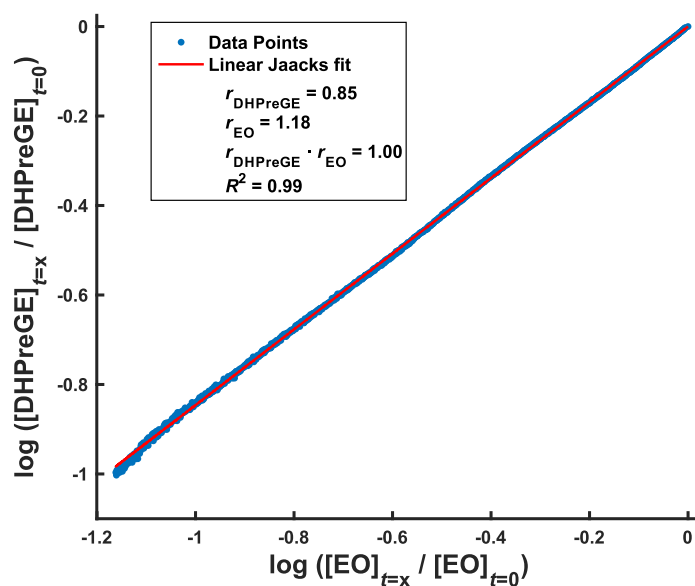


Figure S 31: Jaacks fit of the *in situ* ^1H NMR copolymerization kinetics of DHPreGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

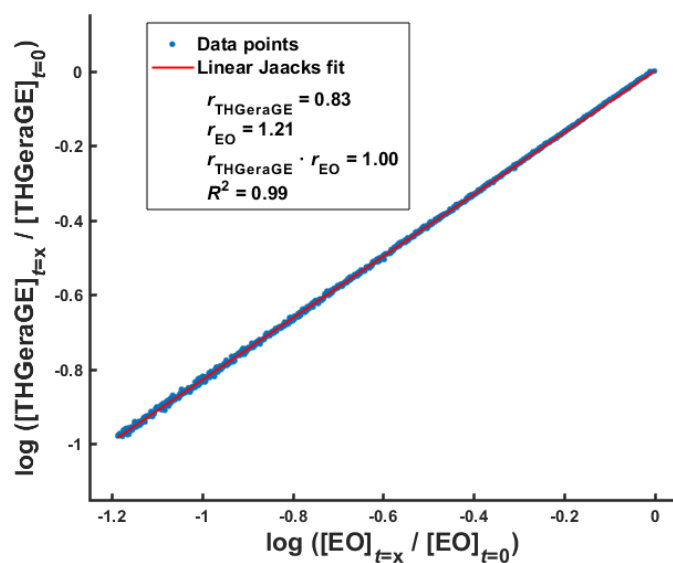


Figure S 32: Jaacks fit of the *in situ* ^1H NMR copolymerization kinetics of THGeraGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

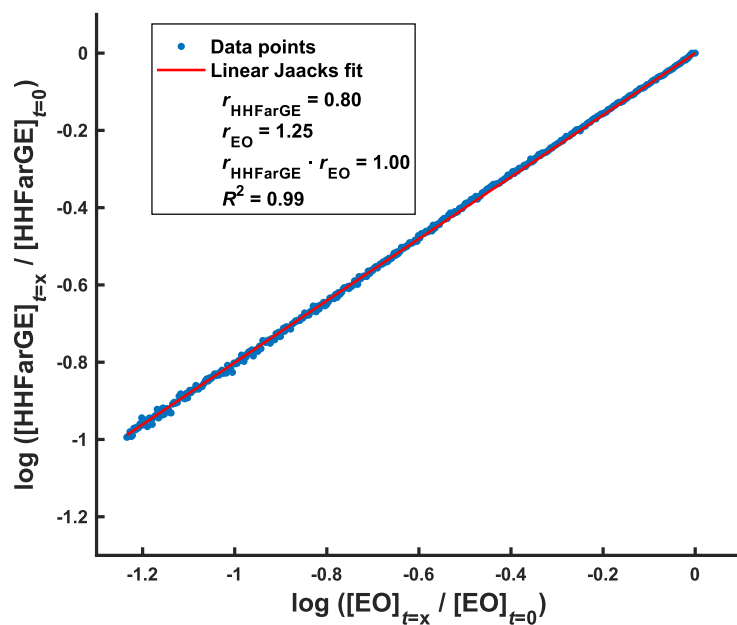
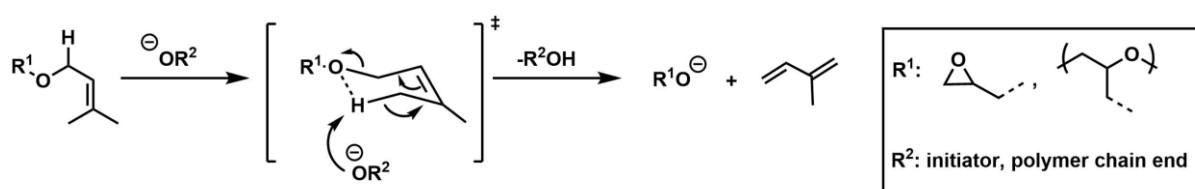


Figure S 33: Jaacks fit of the *in situ* ^1H NMR copolymerization kinetics of HHFarGE with EO in a mixture of THF- d_8 and DMSO- d_6 (5:1) at 40 °C.

Investigation of side reaction during *in situ* copolymerization kinetics of PreGE with EO

Note that we unexpectedly observed the appearance of new signals between 4.9 – 6.6 ppm during the *in situ* copolymerization kinetics (Figure 3 + Figure S 34). Chain transfer to the monomer due to proton abstraction of the α -methylene proton is a literature-known side reaction of the AROP, prevailing proton signals in a similar down-field region.¹⁴ To reliably determine the reactivity ratios, we sought to further investigate this phenomenon as proton abstraction would falsely simulate an increased PreGE consumption. On account of previous reports applying the prenyl functionality as an OH protective group, we hypothesized that a base-catalyzed elimination by the alkoxide chain end leads to the formation of isoprene.^{15,16} Scheme S 2 suggests a six-membered transition state prior to elimination, which tentatively explains the elimination predominantly occurring for the short TGEs.



Scheme S 2: Proposed base-catalyzed elimination of isoprene during the copolymerization of PreGE with EO.

In a second *in situ* kinetic experiment, all volatile components were cryo-transferred (THF- d_8 , DMSO- d_6 , isoprene) into a Young NMR tube. Subsequent NMR and GC analyses corroborate the hypothesis of isoprene forming during the copolymerization (Figures S 35 - S 37). In summary, monomer consumption is solely caused by monomer incorporation into the polymer chain, legitimizing the determined reactivity ratios and the related copolymer microstructure. Figure S 38 additionally reveals the partial base-catalyzed prenyl-to-isoprenyl isomerization of the side chain under basic conditions (and vice versa for IsoPreGE).^{17,18}

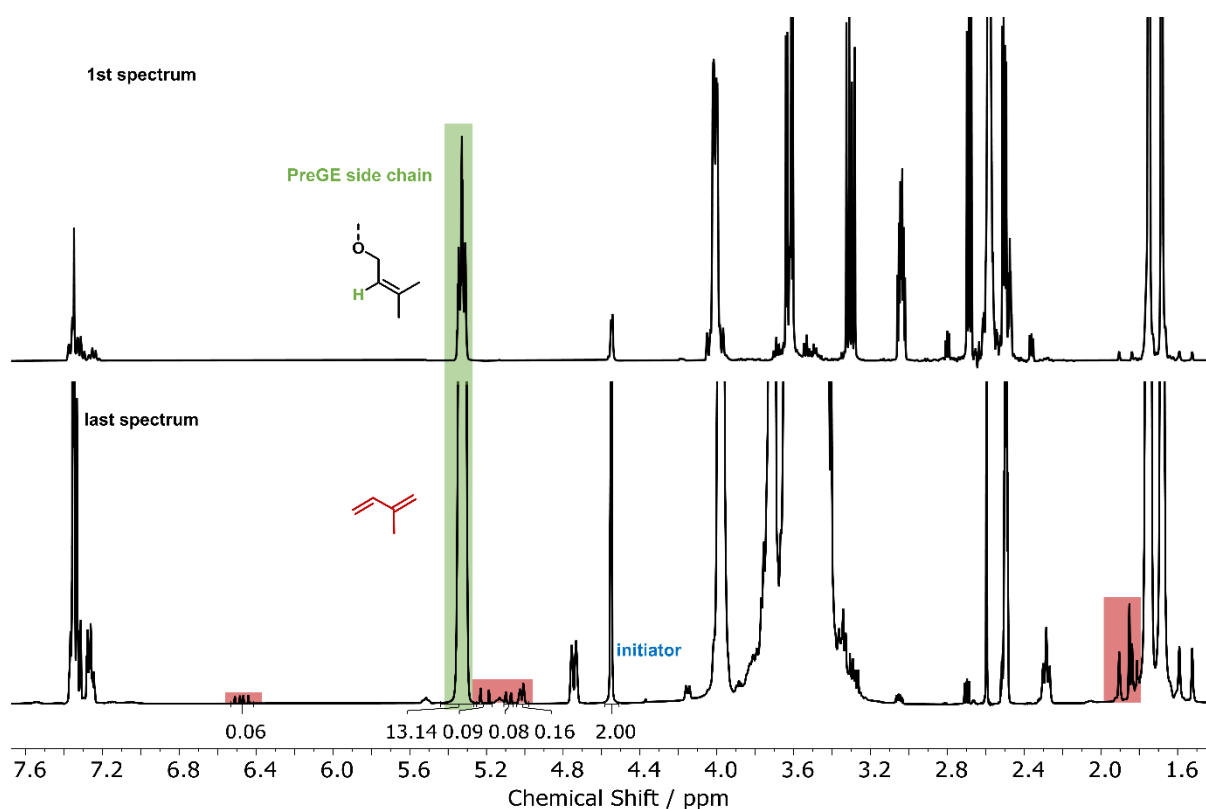


Figure S 34: Overlay of the first and last ^1H NMR spectrum (400 MHz, $\text{THF-}d_8$) of the *in situ* kinetics, proving the elimination of isoprene in small quantities during copolymerization. The monomer amount undergoing elimination is below 0.5%.

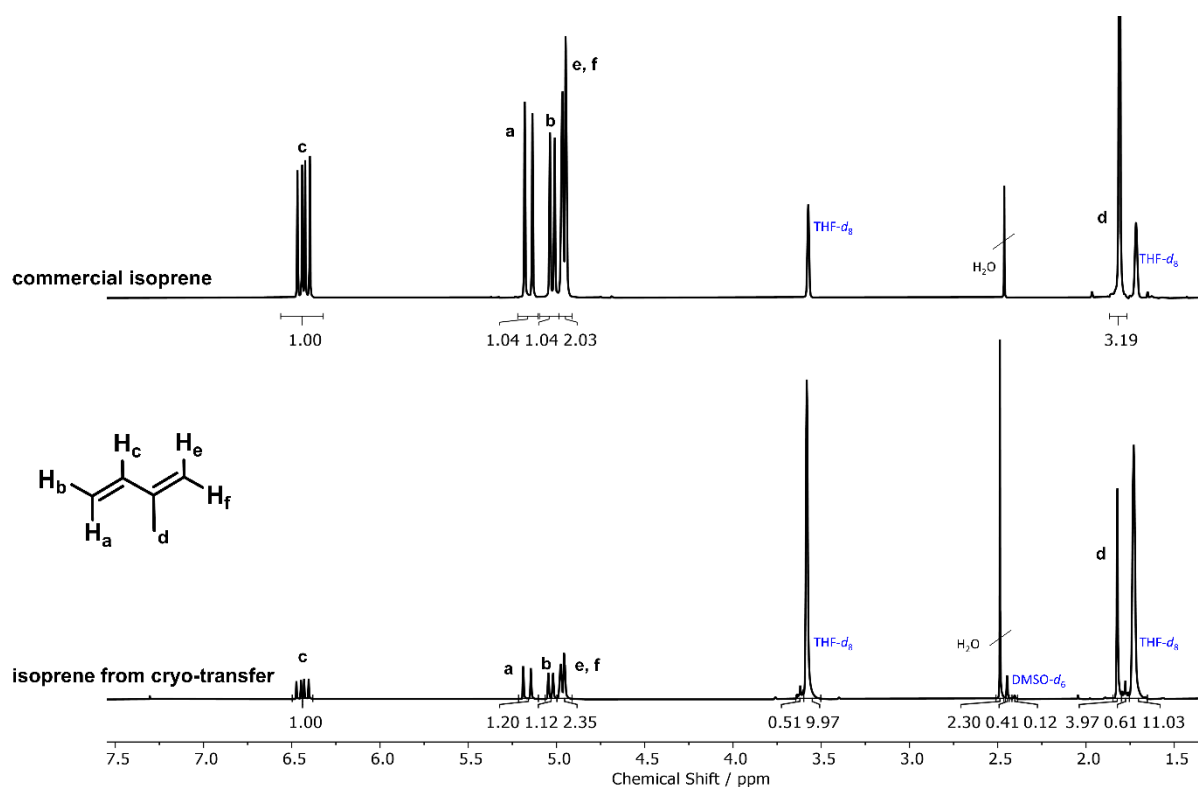


Figure S 35: Overlay of ^1H NMR spectra (400 MHz, $\text{THF-}d_8$) of the commercial isoprene and cryo-transferred isoprene.

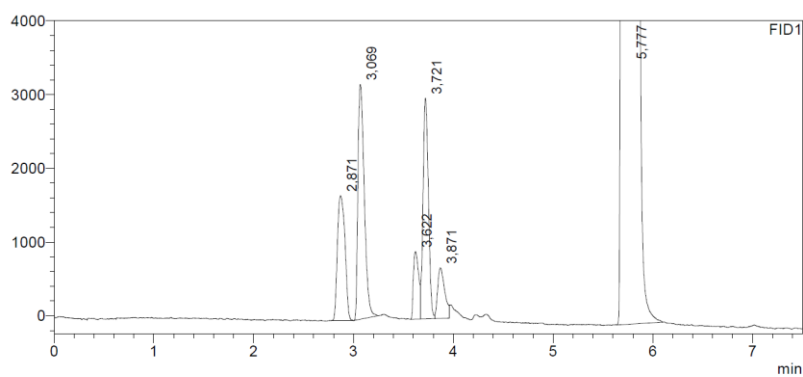


Figure S 36: GC analysis of isoprene eliminated during the copolymerization with a $t_{\text{retention, isoprene}} = 3.721$ (area 98.8%). Isoprene and THF- d_8 were isolated via cryo-transfer from the NMR tube and the major peak can be ascribed to THF- d_8 with a $t_{\text{retention, THF}} = 5.777$. All other signals are impurities in DMSO, which was used to prepare the GC sample.

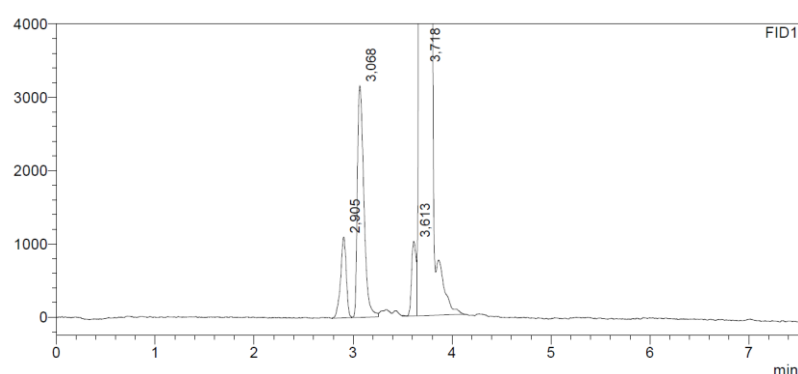


Figure S 37: GC analysis of commercial isoprene with a $t_{\text{retention, isoprene}} = 3.718$ (area 98.8%). All other signals are impurities in DMSO, which was used to prepare the GC sample.

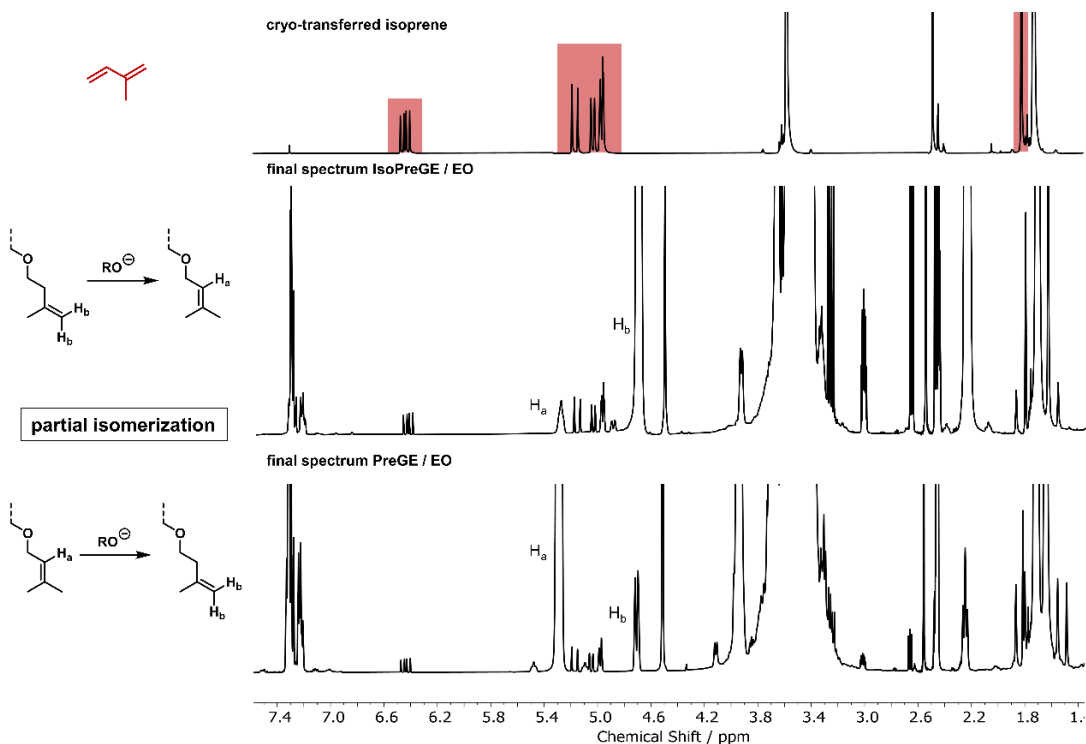


Figure S 38: Overlay of ^1H NMR spectra (400 MHz, CDCl_3) of the spectrum of the cryo-transferred isoprene (top) and the final spectra of the in situ kinetic measurements of IsoPreGE (middle) with EO and PreGE with EO (bottom). *In situ* NMR kinetics mirror the formation of isoprene in trace amounts. The overlay also demonstrates a slight isomerization of the prenyl and isoprenyl side chain to the respective isomer (H_a and H_b).

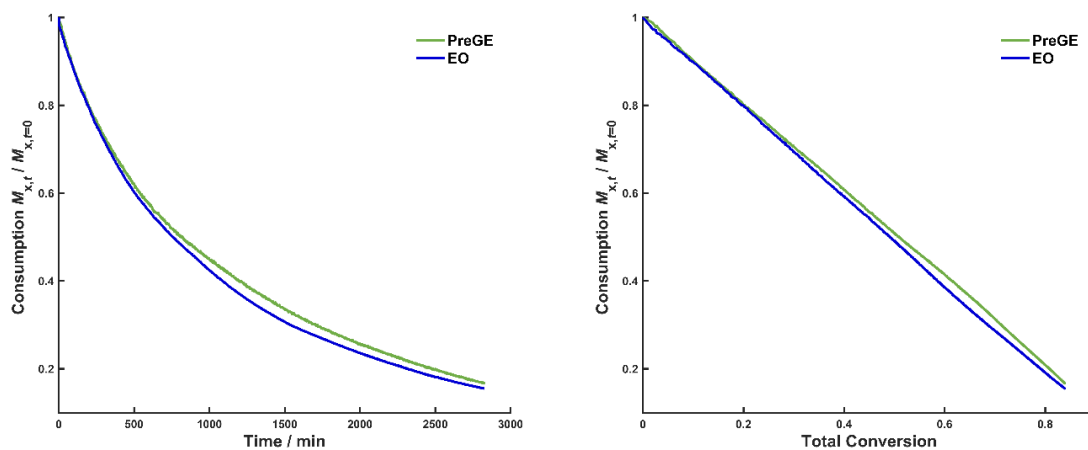
Kinetic data of the copolymerization of PreGE with EO.

Figure S 39: Time-conversion plot of the anionic copolymerization of IsoPreGE and with EO, determined via *in situ* ^1H NMR kinetics (left). Individual monomer conversion versus total monomer conversion (right).

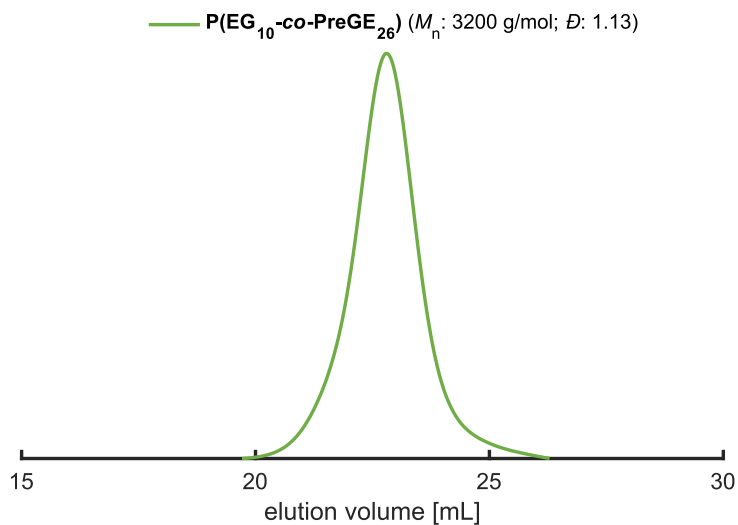


Figure S 40: SEC elugram (RI detector, eluent: DMF, PEG calibration) of the $\text{P(EG}_{10}\text{-co-PreGE}_{26})$ copolymer synthesized from the *in situ* ^1H NMR copolymerization kinetics. SEC analysis: $M_n = 3200 \text{ g}\cdot\text{mol}^{-1}$, $\bar{D} = 1.13$.

Kinetic data of the copolymerization of IsoPreGE with EO.

Note that the isoprene formation has additionally been observed during the copolymerization of IsoPreGE and EO. We conclude an elimination of isoprene (Scheme S 2) from the glycidyl side chain occurring, which is confirmed in analogy to the PreGE/EO comonomer pair in the previous section (Figure S 38).

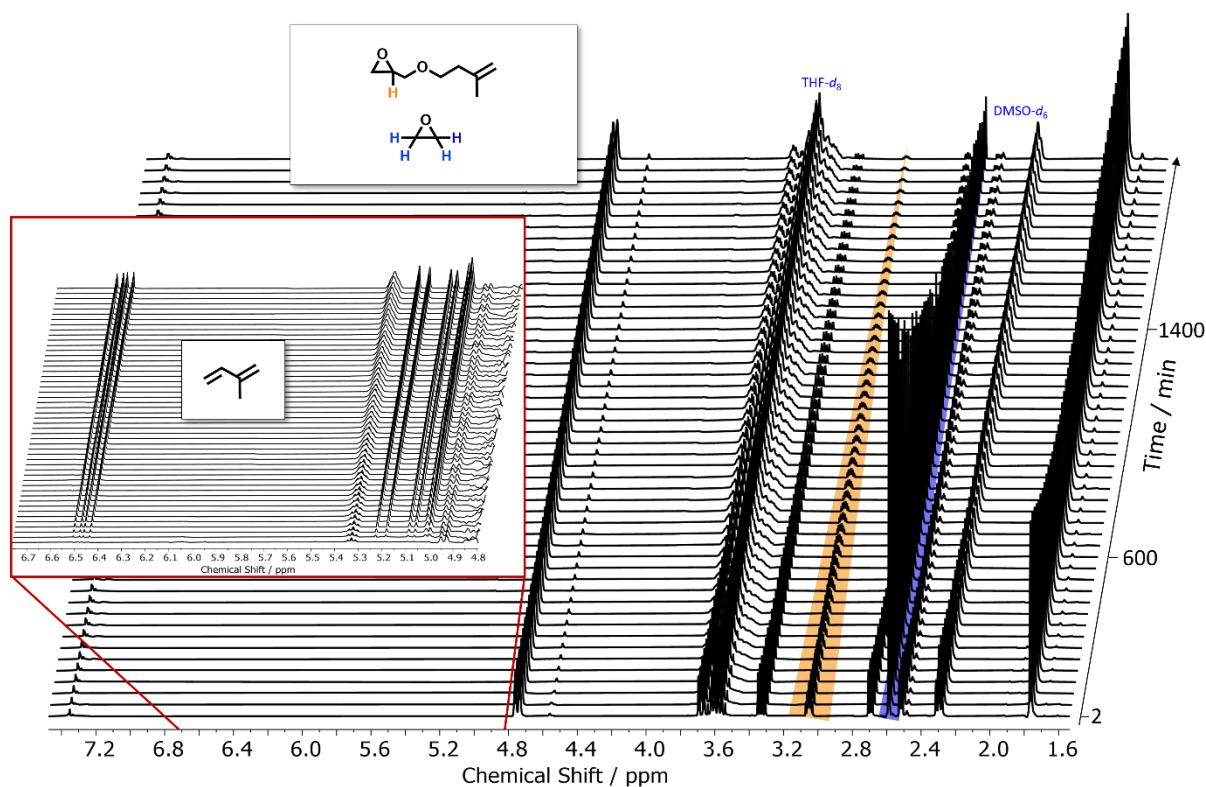


Figure S 41: Selection of ¹H NMR spectra (400 MHz, THF-d₈ : DMSO-d₆= 5:1) for the in situ NMR kinetics of the statistical copolymerization of IsoPreGE with EO at 40 °C. Relevant epoxide signals for evaluation are highlighted in green at 3.05 ppm (IsoPreGE) and blue at 2.59 ppm (EO). Since spectra were recorded at 2 min intervals over a period of 32.9 h, only every 20th spectrum is displayed. The zoom-in section displays the appearance of new signals, which is ascribed to the isoprene formation during the copolymerization.

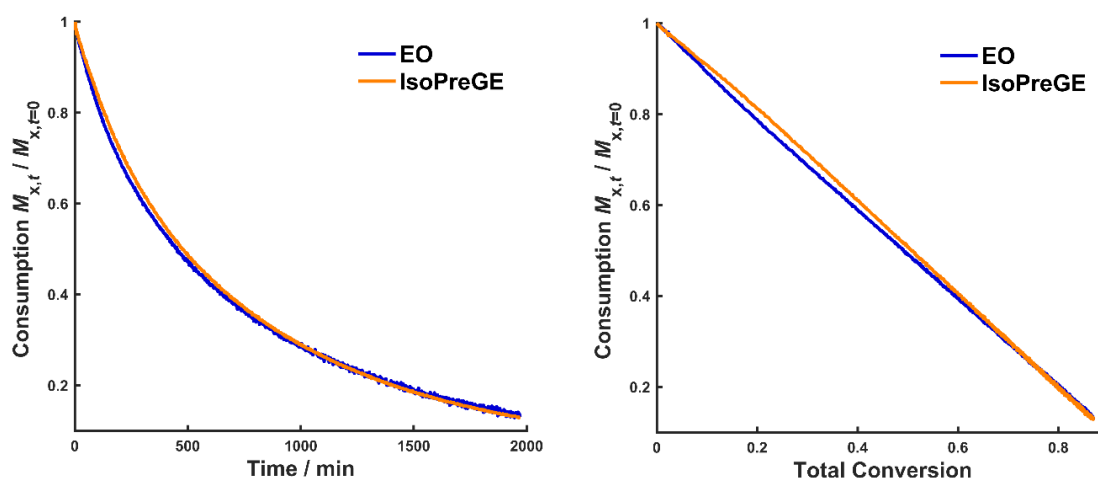


Figure S 42: Time-conversion plot of the anionic copolymerization of IsoPreGE and with EO, determined via *in situ* ¹H NMR kinetics (left). Individual monomer conversion versus total monomer conversion (right).

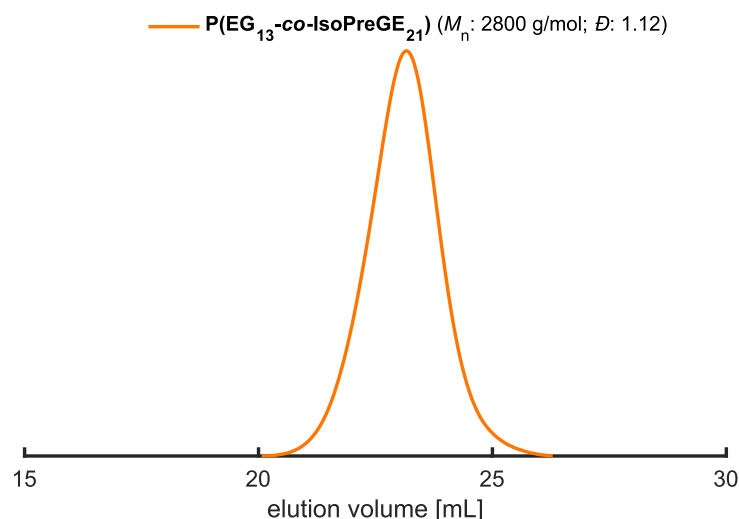


Figure S 43: SEC elugram (RI detector, eluent: DMF, PEG calibration) of the P(EG₁₃-co-IsoPreGE₂₁) copolymer synthesized from the *in situ* ¹H NMR copolymerization kinetics. SEC analysis: $M_n = 2800 \text{ g}\cdot\text{mol}^{-1}$, $\bar{D} = 1.12$.

Kinetic data of the copolymerization of GeraGE with EO.

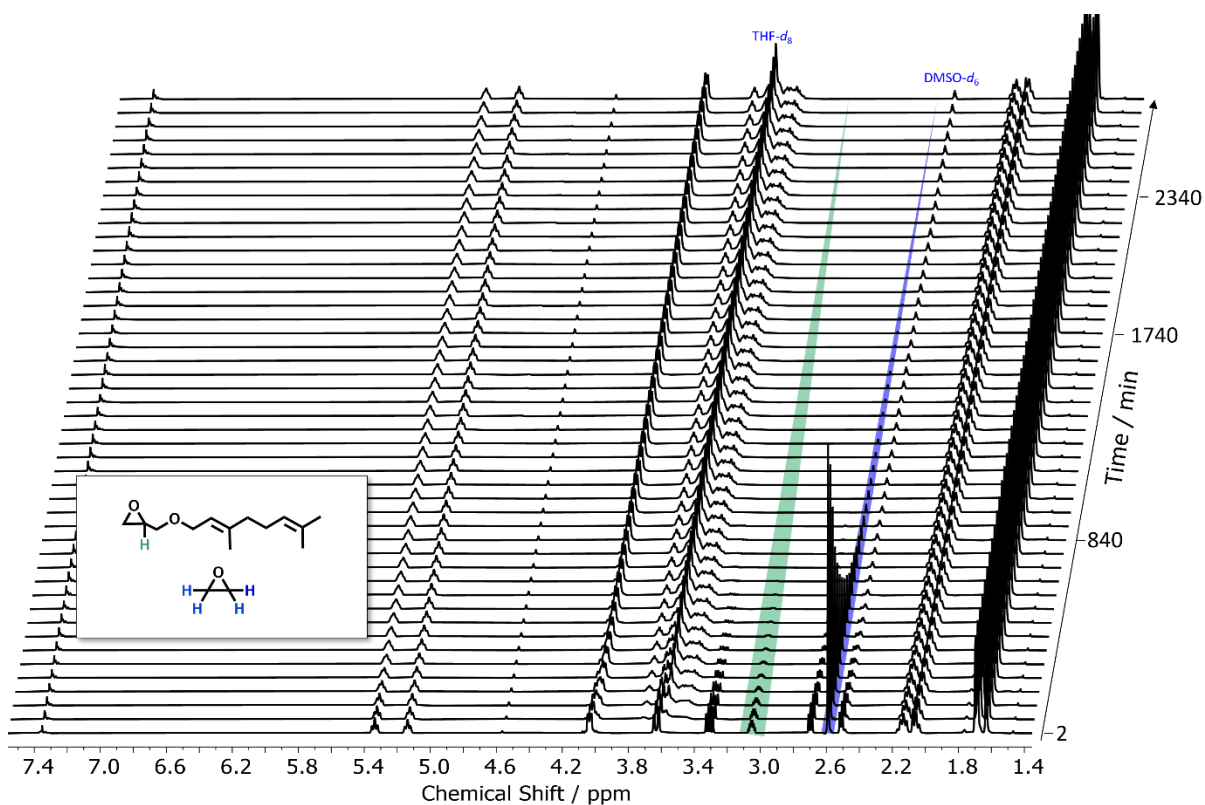


Figure S 44: Selection of ¹H NMR spectra (400 MHz, THF-d₈ : DMSO-d₆ = 5:1) for the *in situ* NMR kinetics of the statistical copolymerization of GeraGE with EO at 40 °C (top). Relevant epoxide signals for evaluation are highlighted in green at 3.05 ppm (GeraGE) and blue at 2.59 ppm (EO). Since spectra were recorded at 2 min intervals over a period of 46.0 h, only every 30th spectrum is displayed.

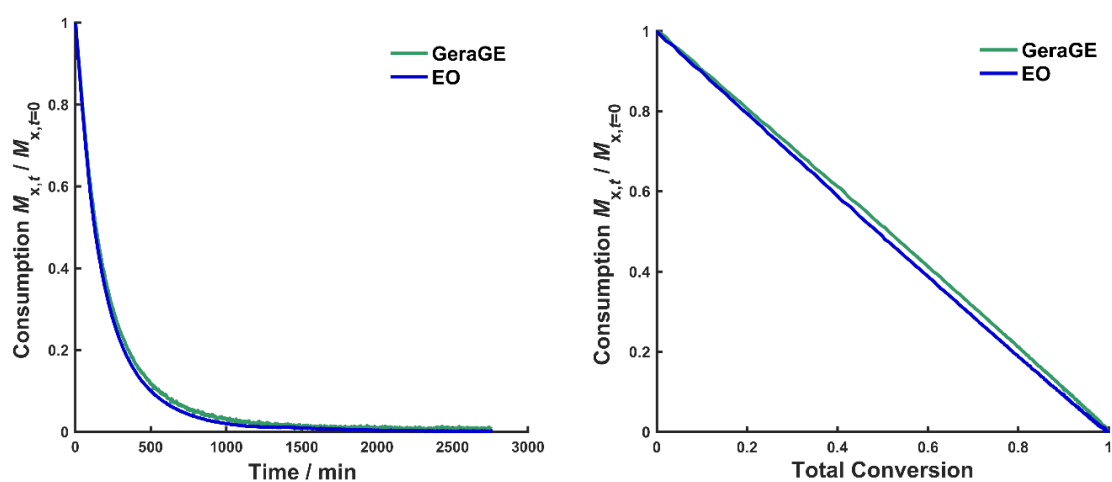


Figure S 45: Time-conversion plot of the anionic copolymerization of GeraGE and with EO, determined via *in situ* ^1H NMR kinetics (left). Individual monomer conversion versus total monomer conversion (right).

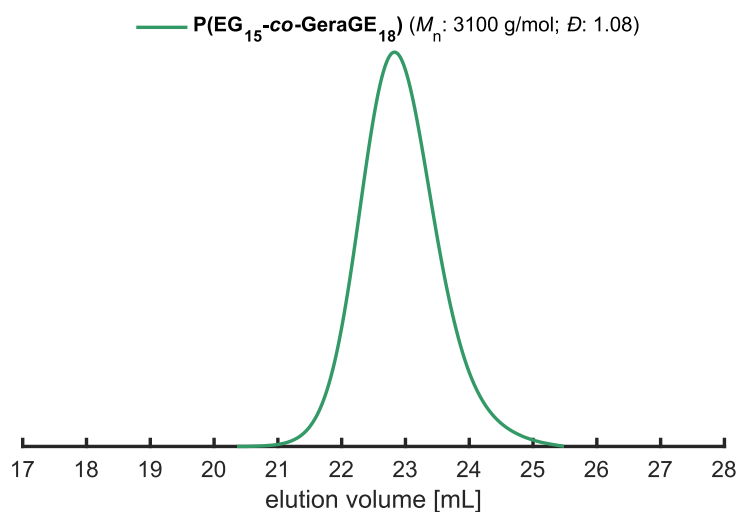


Figure S 46: SEC elugram (RI detector, eluent: DMF, PEG calibration) of the P(EG₁₅-co-GeraGE₁₈) copolymer synthesized from the *in situ* ^1H NMR copolymerization kinetics. SEC analysis: $M_n = 3100 \text{ g}\cdot\text{mol}^{-1}$, $D = 1.08$.

Kinetic data of the copolymerization of NerGE with EO.

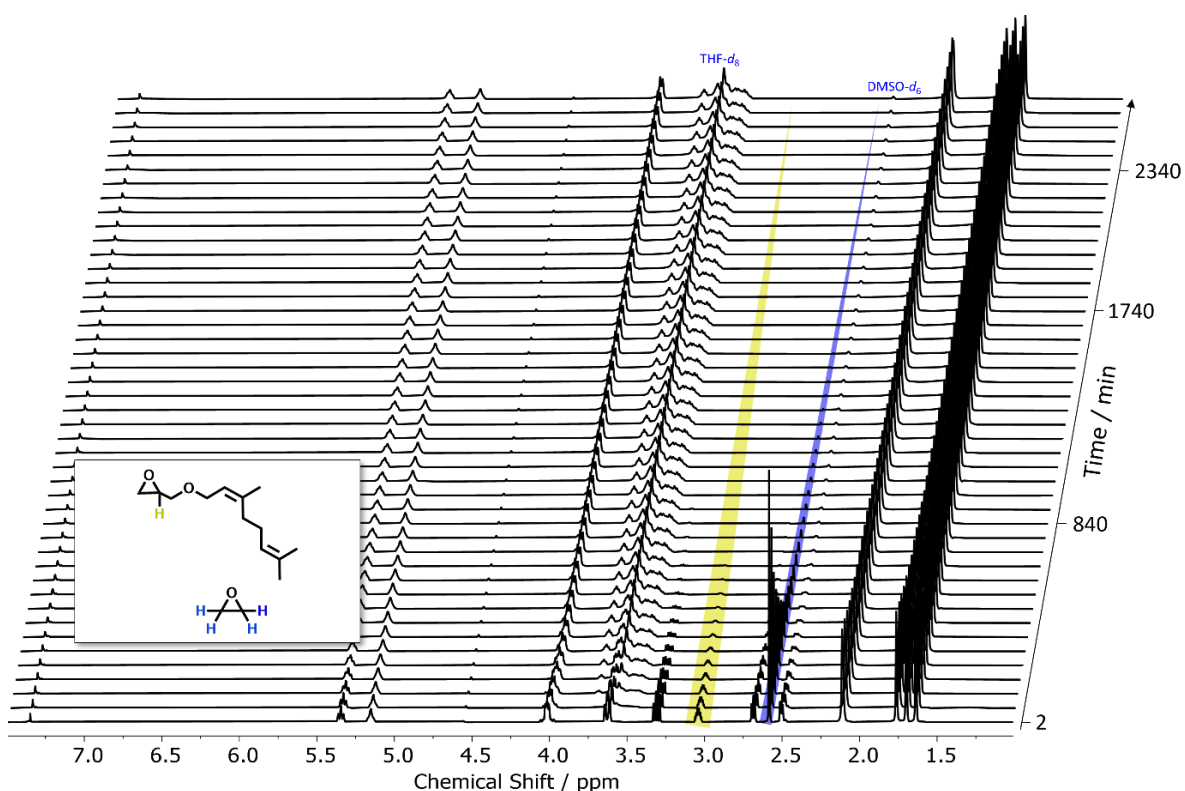


Figure S 47: Selection of ^1H NMR spectra (400 MHz, THF- d_8 : DMSO- d_6 = 5:1) for the in situ NMR kinetics of the statistical copolymerization of NerGE with EO at 40 °C. Relevant epoxide signals for evaluation are highlighted in yellow at 3.04 ppm (NerGE) and blue at 2.59 ppm (EO). Since spectra were recorded at 2 min intervals over a period of 44.6 h, only every 30th spectrum is displayed.

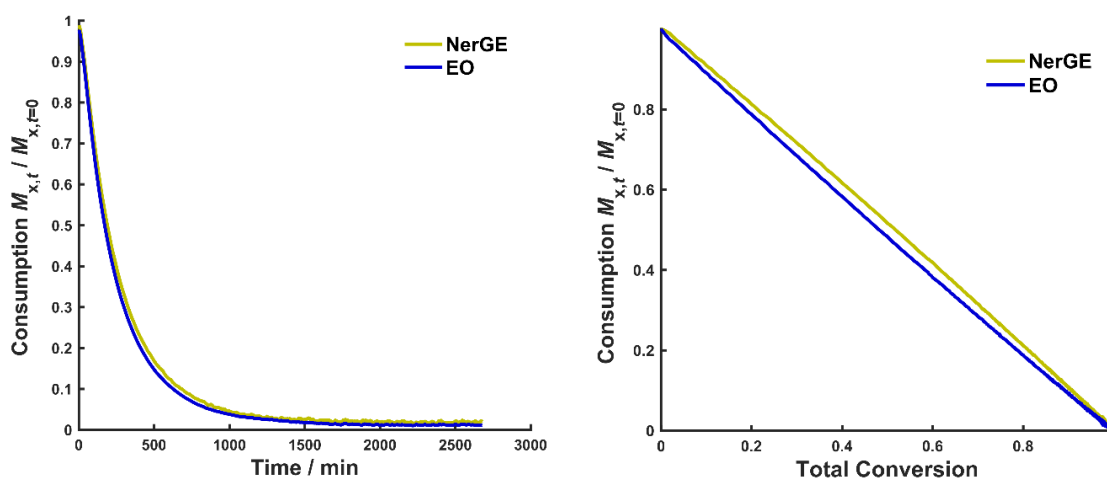


Figure S 48: Time-conversion plot of the anionic copolymerization of NerGE and with EO, determined via in situ ^1H NMR kinetics (left). Individual monomer conversion versus total monomer conversion (right).

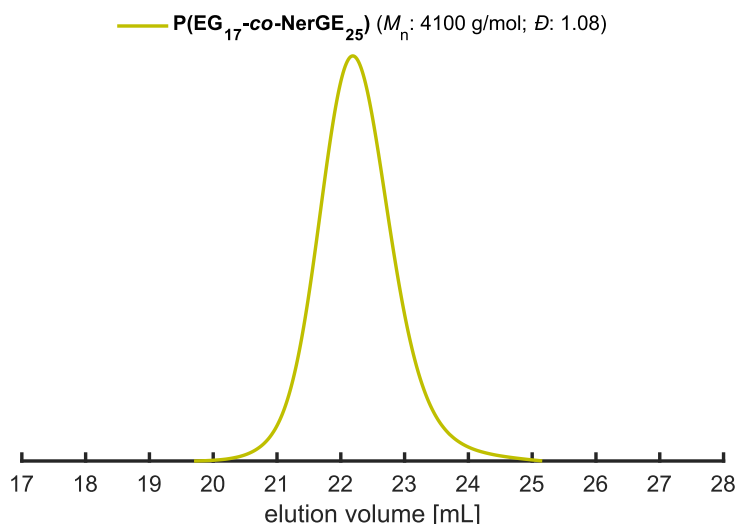


Figure S 49: SEC elugram (RI detector, eluent: DMF, PEG calibration) of the P(EG₁₇-co-NerGE₂₅) copolymer synthesized from the *in situ* ¹H NMR copolymerization kinetics. SEC analysis: $M_n = 4100 \text{ g}\cdot\text{mol}^{-1}$, $\bar{D} = 1.08$.

Kinetic data of the copolymerization of DHPreGE with EO.

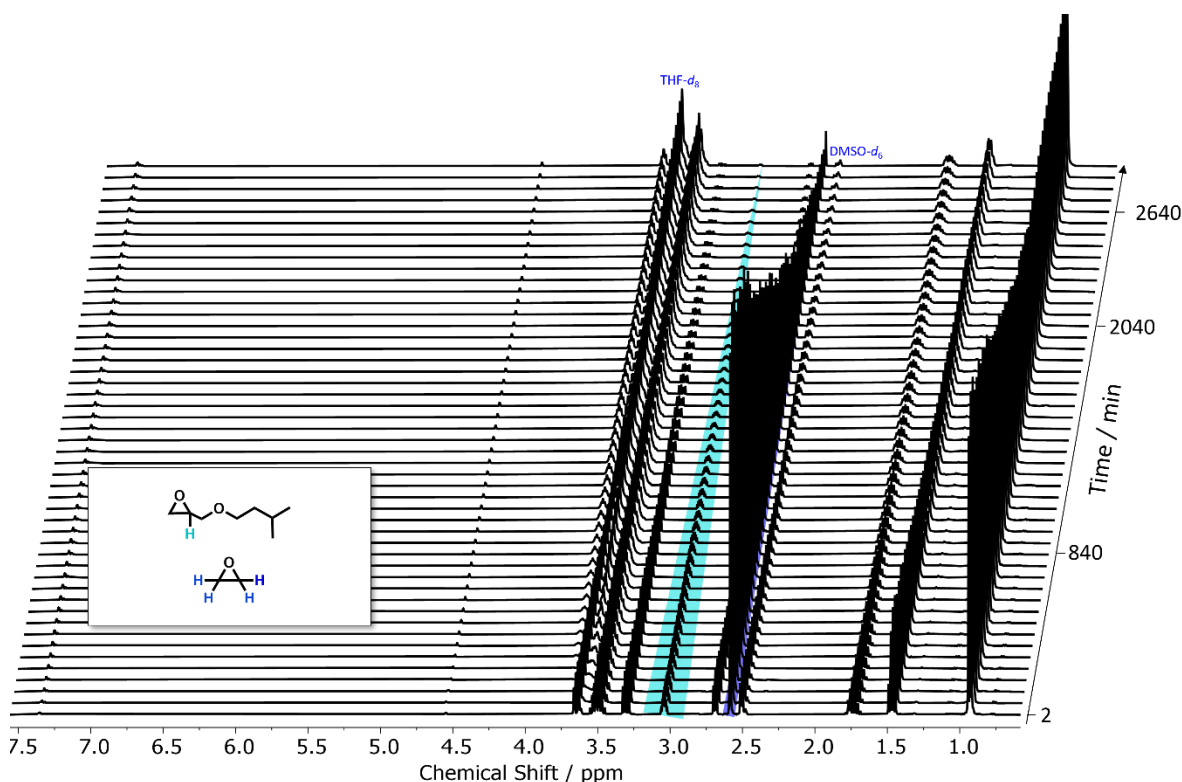


Figure S 50: Selection of ¹H NMR spectra (400 MHz, THF-*d*₈ : DMSO-*d*₆ = 5:1) for the *in situ* NMR kinetics of the statistical copolymerization of DHPreGE with EO at 40 °C. Relevant epoxide signals for evaluation are highlighted in cyan at 3.04 ppm (DHPreGE) and blue at 2.59 ppm (EO). Since spectra were recorded at 2 min intervals over a period of 48.4 h, only every 30th spectrum is displayed.

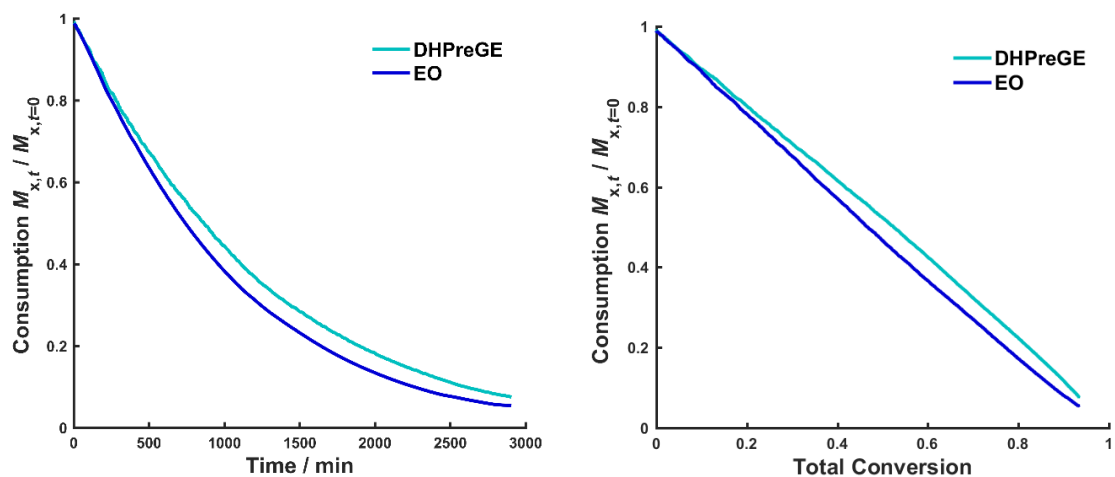


Figure S 51: Time-conversion plot of the anionic copolymerization of DHPreGE and with EO, determined via *in situ* ^1H NMR kinetics (left). Individual monomer conversion versus total monomer (right).

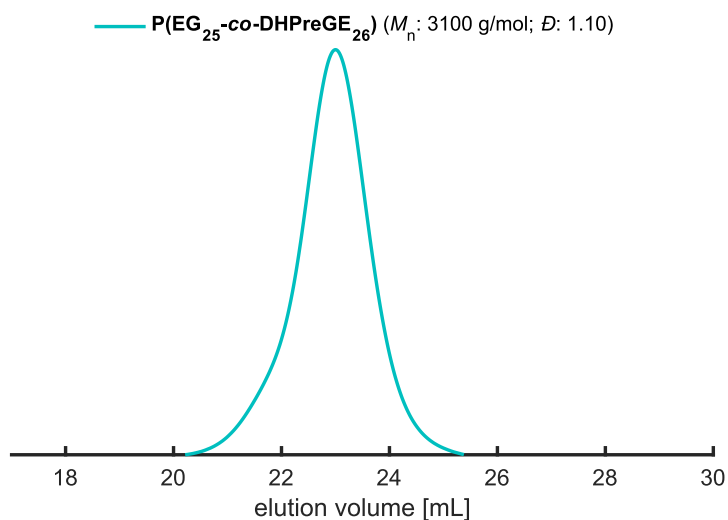


Figure S 52: SEC elugram (RI detector, eluent: DMF, PEG calibration) of the P(EG₂₅-co-DHPreGE₂₆) copolymer synthesized from the *in situ* ^1H NMR copolymerization kinetics. SEC analysis: $M_n = 3100 \text{ g}\cdot\text{mol}^{-1}$, $\bar{D} = 1.10$.

Kinetic data of the copolymerization of THGeraGE with EO.

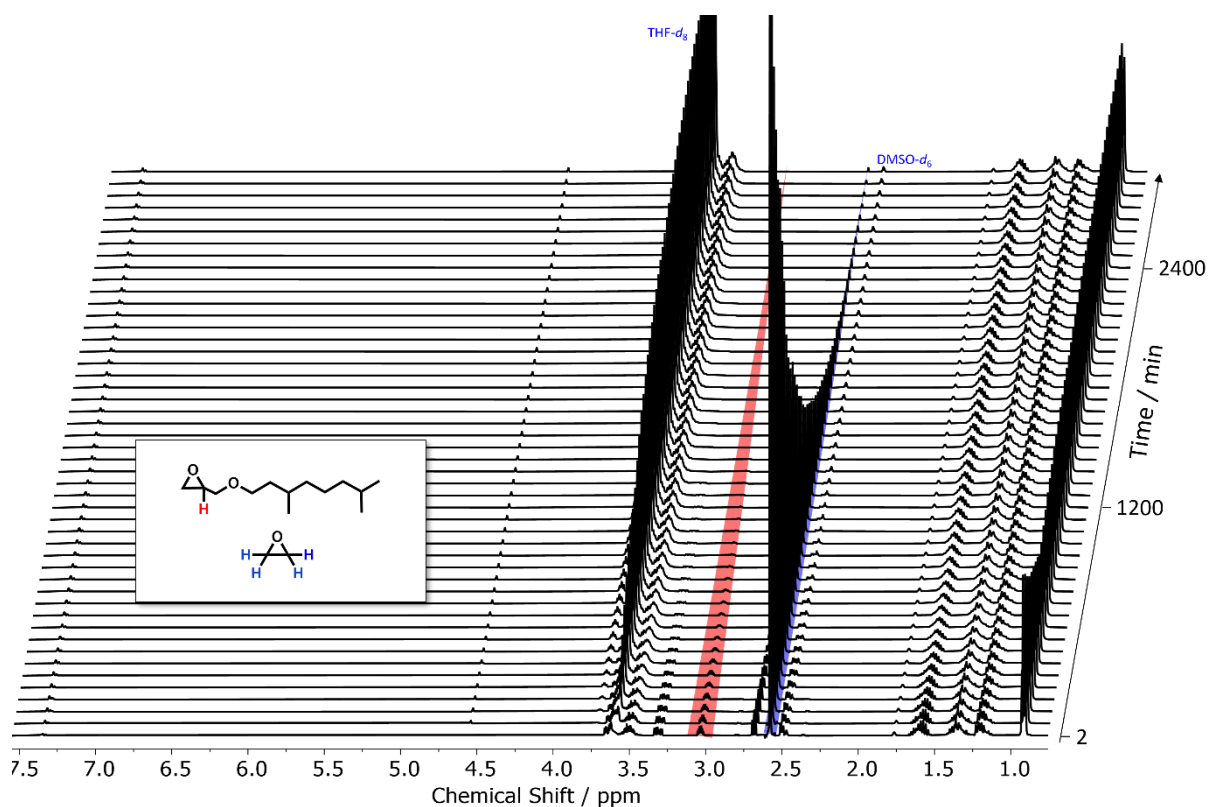


Figure S 53: Selection of ^1H NMR spectra (400 MHz, THF-d_8 : DMSO-d_6 = 5:1) for the in situ NMR kinetics of the statistical copolymerization of THGeraGE with EO at 40 °C. Relevant epoxide signals for evaluation are highlighted in red at 3.03 ppm (THGeraGE) and blue at 2.59 ppm (EO). Since spectra were recorded at 2 min intervals over a period of 48 h, only every 30th spectrum is displayed.

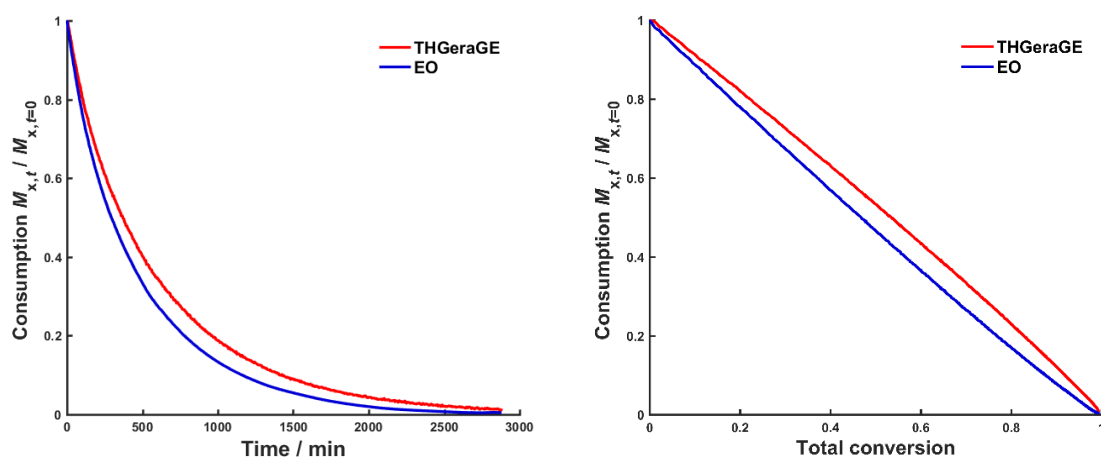


Figure S 54: Time-conversion plot of the anionic copolymerization of THGeraGE and with EO, determined via in situ ^1H NMR kinetics (left). Individual monomer conversion versus total monomer conversion (right).

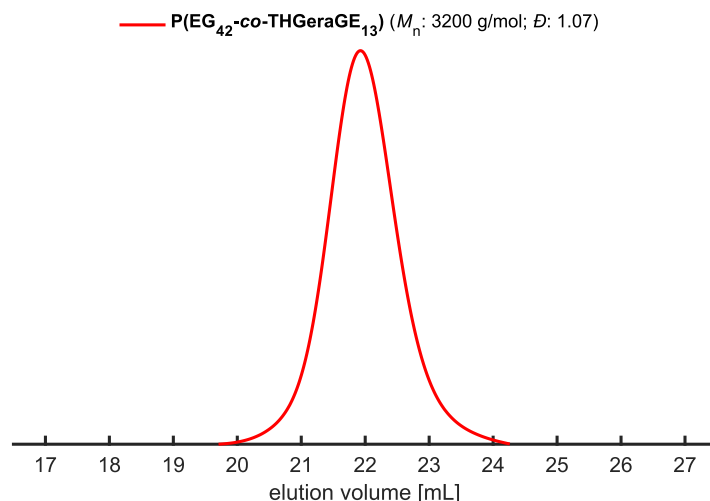


Figure S 55: SEC elugram (RI detector, eluent: DMF, PEG calibration) of the P(EG₄₂-co-THGeraGE₁₃) copolymer synthesized from the *in situ* ¹H NMR copolymerization kinetics. SEC analysis: M_n = 3200 g·mol⁻¹, $\bar{D}$ = 1.07.

Kinetic data of the copolymerization of HHFarGE with EO.

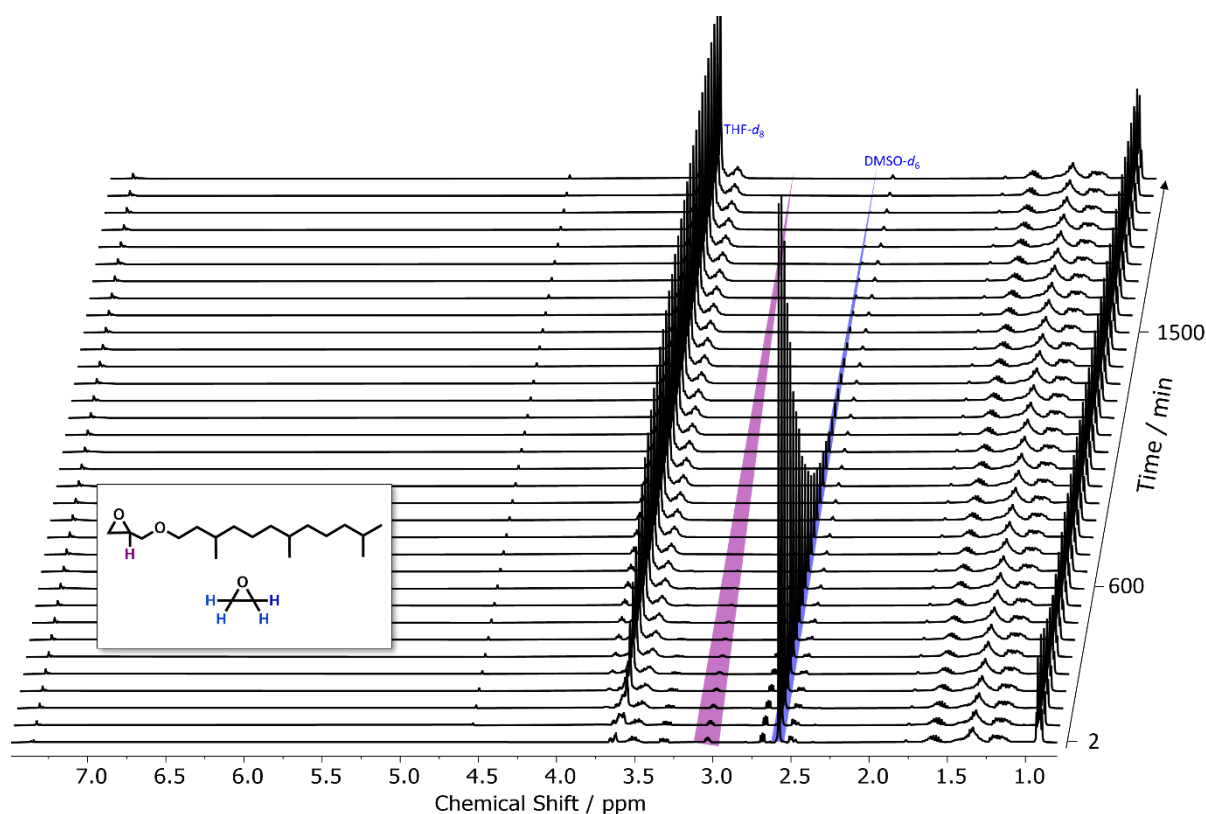


Figure S 56: Selection of ¹H NMR spectra (400 MHz, THF-*d*₈ : DMSO-*d*₆ = 5:1) for the *in situ* kinetics of the statistical copolymerization of HHFarGE with EO at 40 °C. Relevant epoxide signals for evaluation are highlighted in purple (HHFarGE) at 3.05 ppm and blue (EO) at 2.59 ppm. Since spectra were recorded every 2 min over a period of 34.0 h, only every 30th spectrum is displayed.

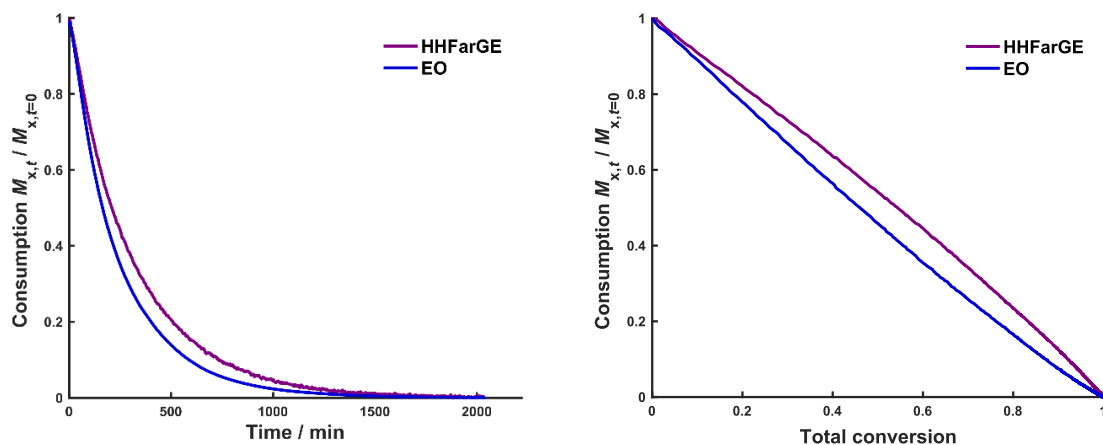


Figure S 57: Time-conversion plot of the anionic copolymerization of HHFarGE and with EO, determined via in situ ^1H NMR kinetics (left). Individual monomer conversion versus total monomer conversion (right).

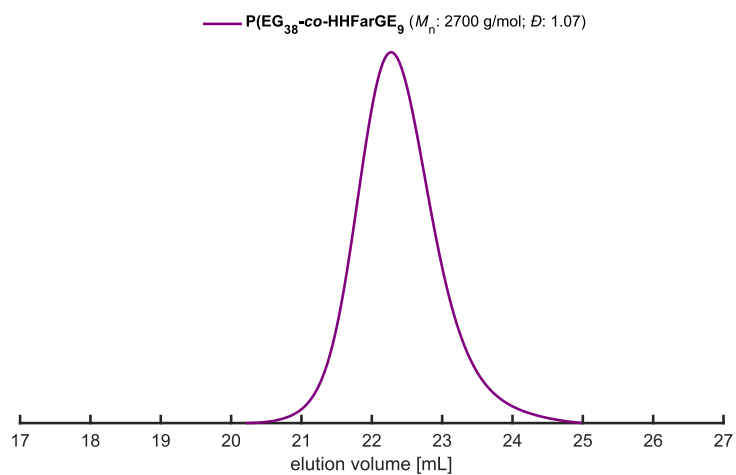


Figure S 58: SEC elugram (RI detector, eluent: DMF, PEG calibration) of the P(EG₃₈-co-HHFarGE₉) copolymer synthesized from the in situ ^1H NMR copolymerization kinetics. SEC analysis: $M_n = 2700 \text{ g}\cdot\text{mol}^{-1}$, $\bar{D} = 1.07$.

Post-polymerization Functionalizations

Thiol-Ene Click

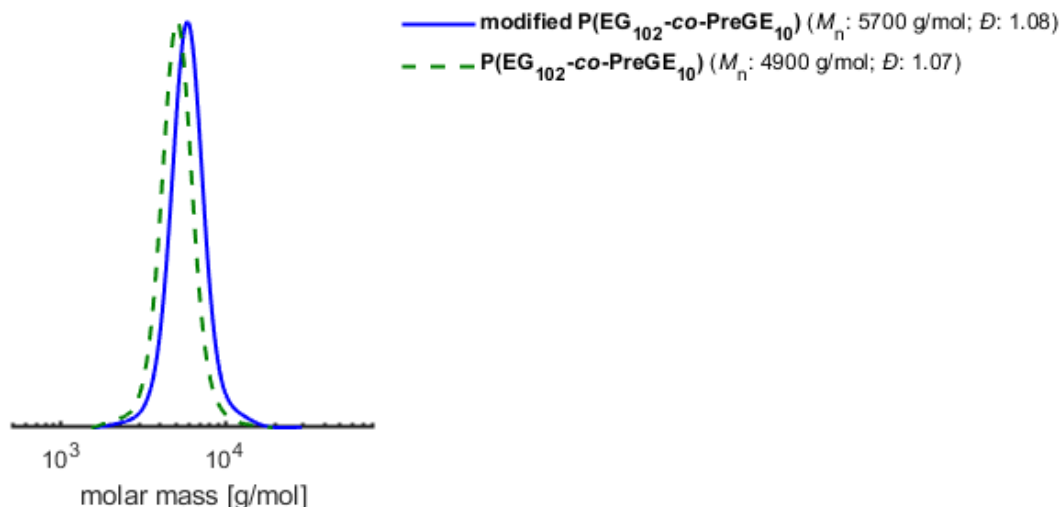


Figure S 59: SEC traces of modified P(EG₁₀₂-co-PreGE₁₀) (blue) and its respective precursor polymer (green, dotted line). (Eluent: DMF, RI-Detector, PEG calibration).

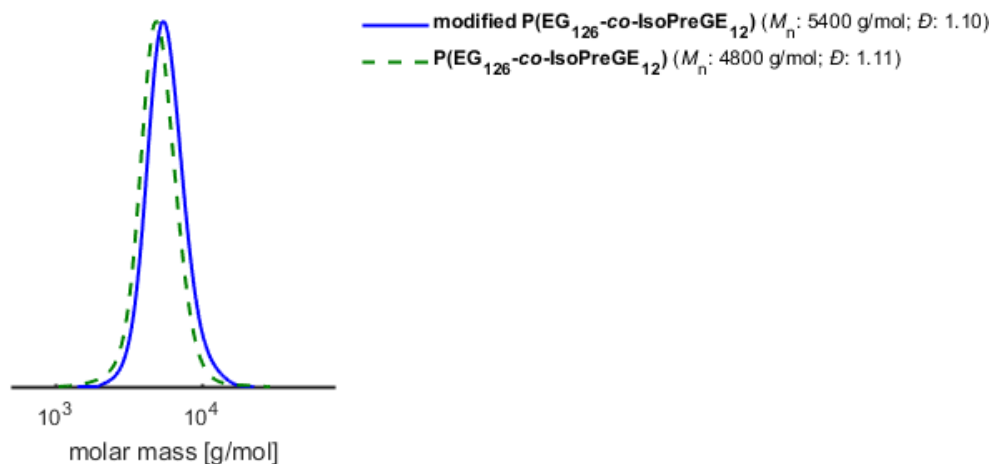


Figure S 60: SEC traces of modified P(EG₁₂₆-co-IsoPreGE₁₂) (blue) and its respective precursor polymer (green, dotted line). (Eluent: DMF, RI-Detector, PEG calibration).

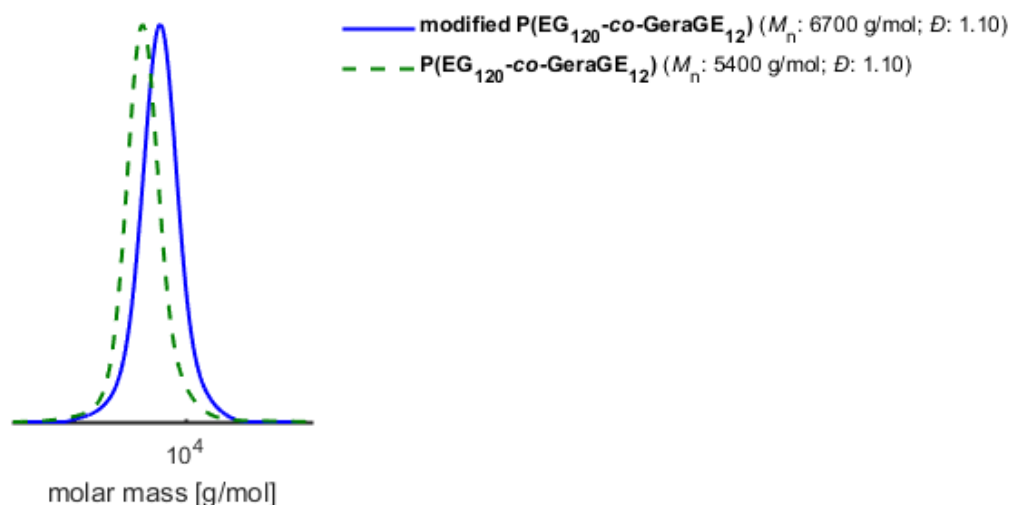


Figure S 61: SEC traces of modified P(EG₁₂₀-co-GeraGE₁₂) (blue) and its respective precursor polymer (green, dotted line). (Eluent: DMF, RI-Detector, PEG calibration).

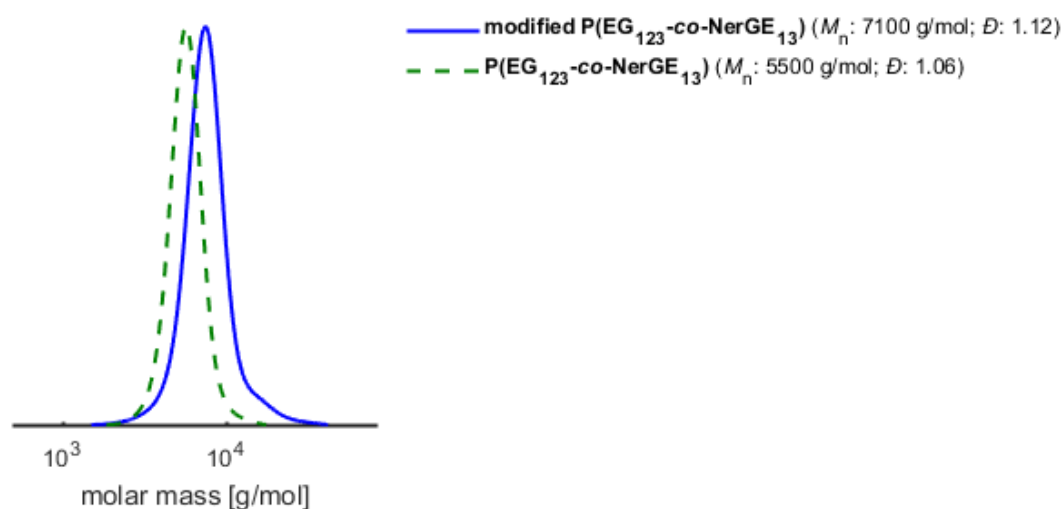


Figure S 62: SEC traces of modified P(EG₁₂₃-co-NerGE₁₃) (blue) and its respective precursor polymer (green, dotted line) (Eluent: DMF, RI-Detector, PEG calibration).

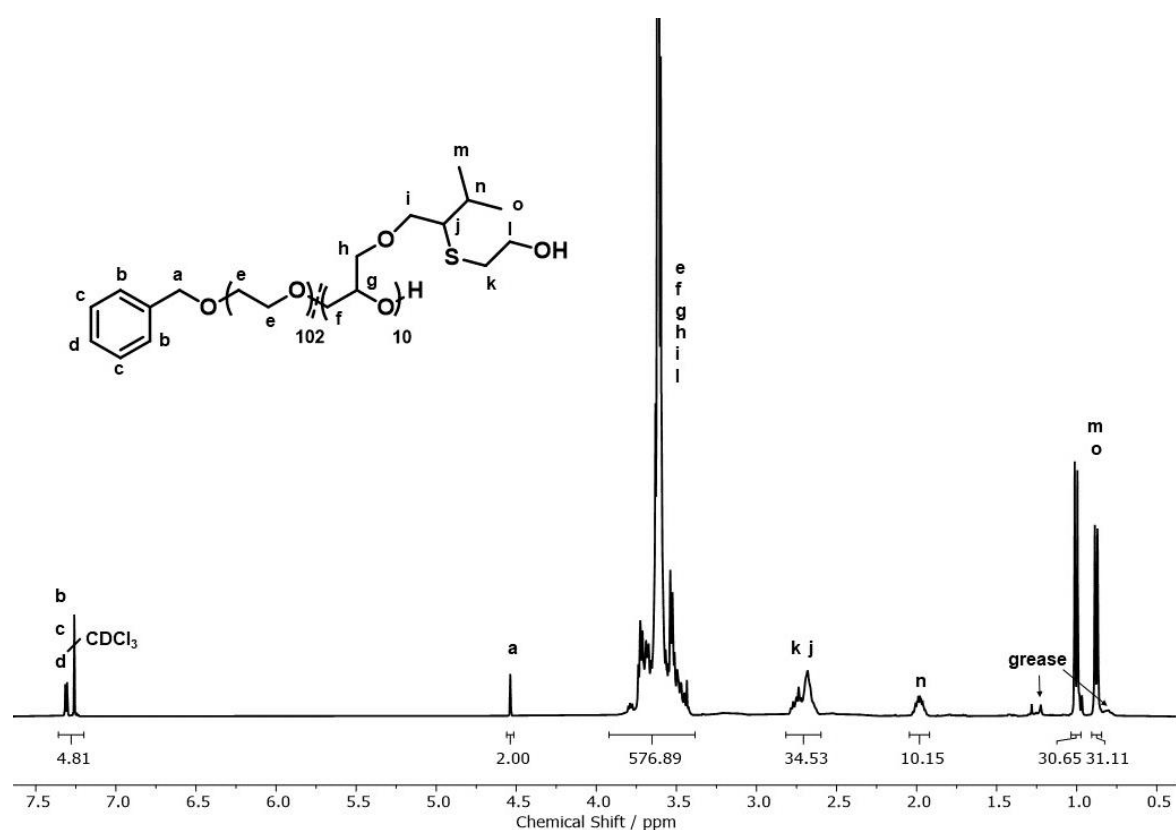


Figure S 63: ¹H NMR spectrum of P(EG₁₀₂-co-PreGE₁₀) functionalized with 2-mercaptoethanol via Thiol-ene click reaction (400 MHz, CDCl₃).

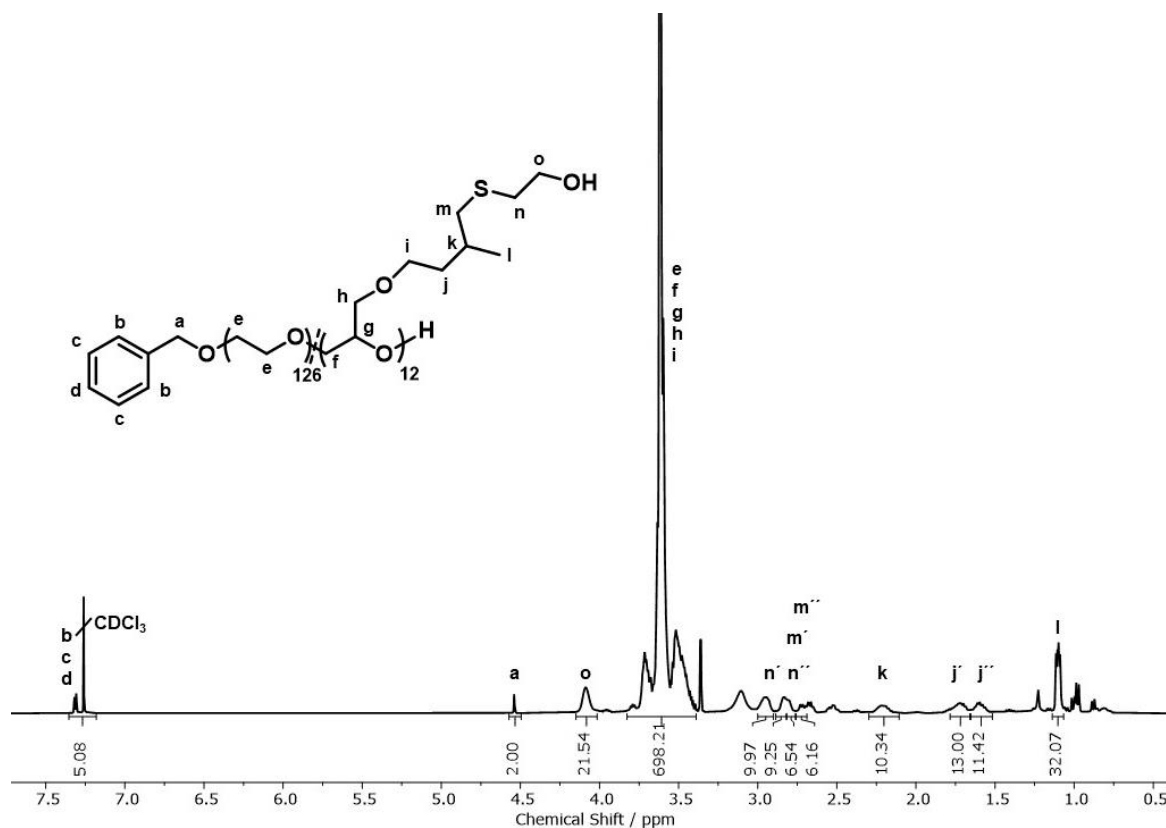


Figure S 64: ¹H NMR spectrum of P(EG₁₂₆-co-IsoPreGE₁₂) functionalized with 2-mercaptoethanol via Thiol-ene click reaction (400 MHz, CDCl₃). Isoprenyl glycidyl ether partially isomerized to prenyl glycidyl ether during polymerization and was also functionalized. Signals are omitted for clarity.

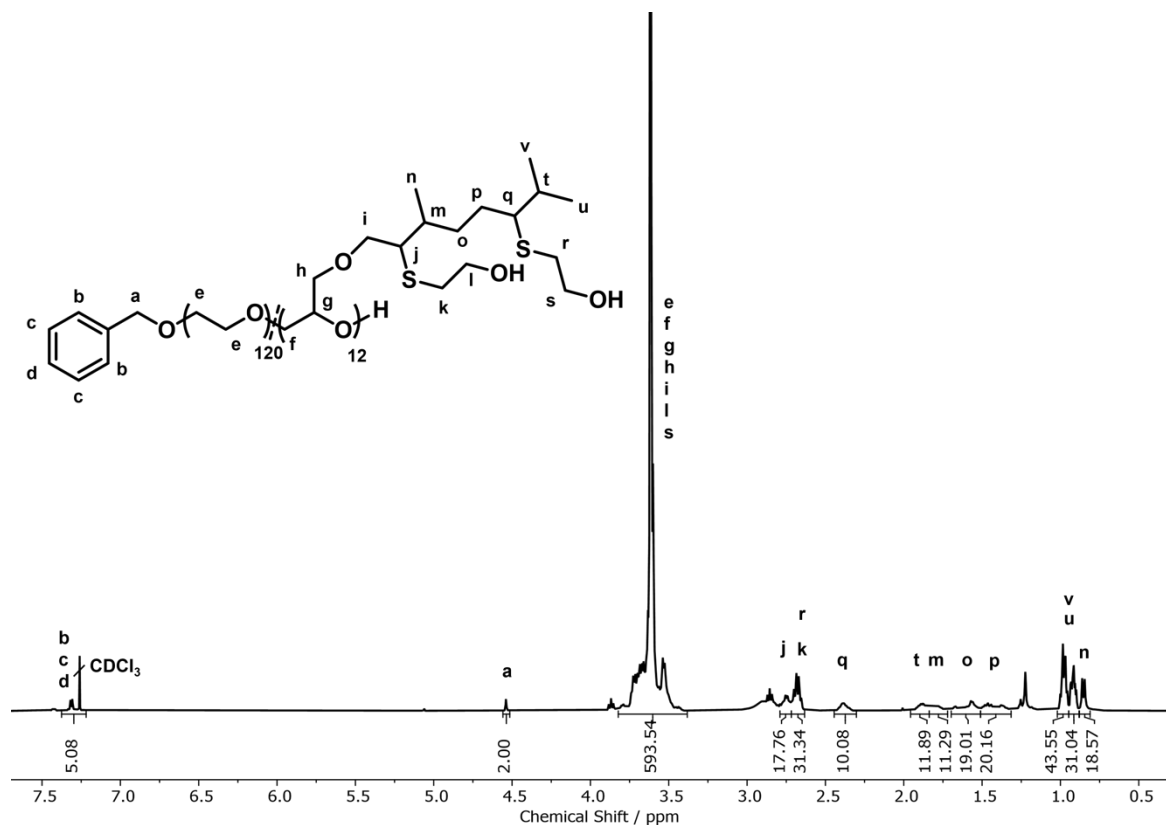


Figure S 65: ¹H NMR spectrum of P(EG₁₂₀-co-GeraGE₁₂) functionalized with 2-mercaptoethanol via thiol-ene click reaction (400 MHz, CDCl₃).

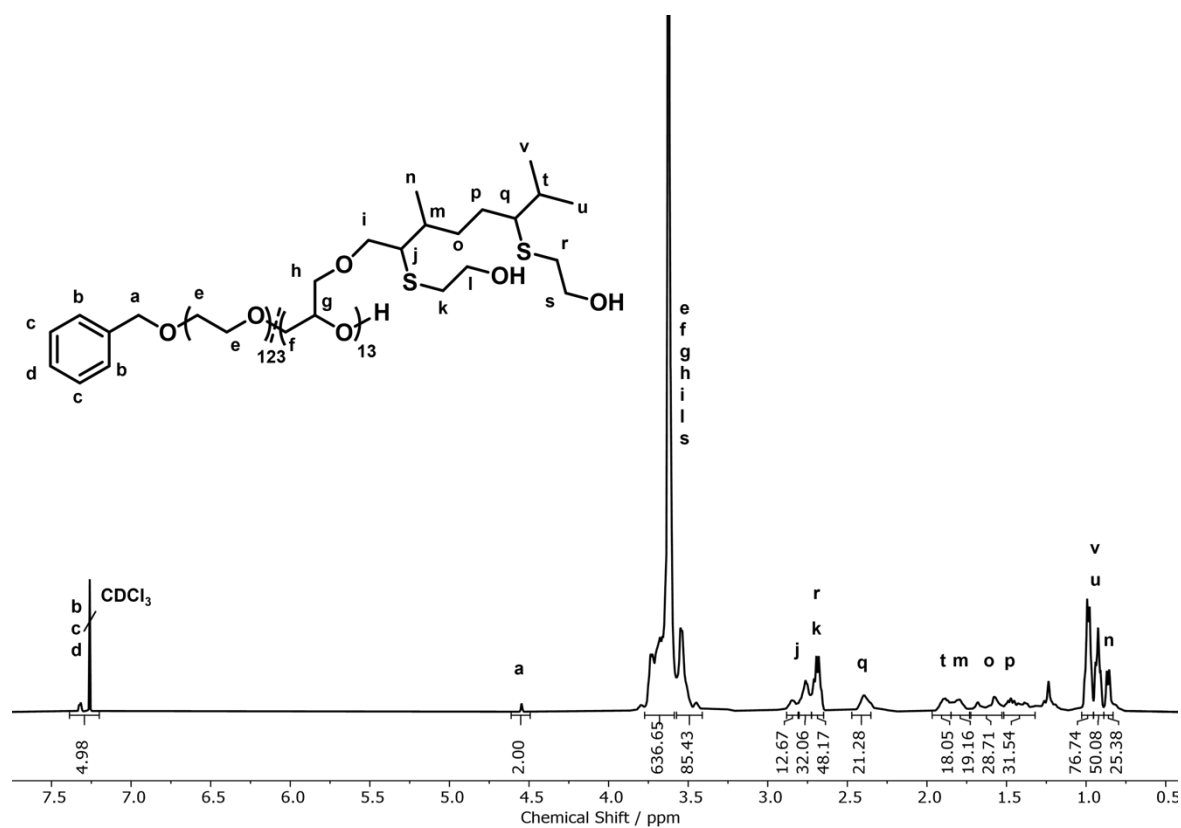


Figure S 66: ^1H NMR spectrum of $\text{P}(\text{EG}_{123}\text{-co-NerGE}_{13})$ functionalized with 2-mercaptoethanol via thiol-ene click reaction (400 MHz, CDCl_3).

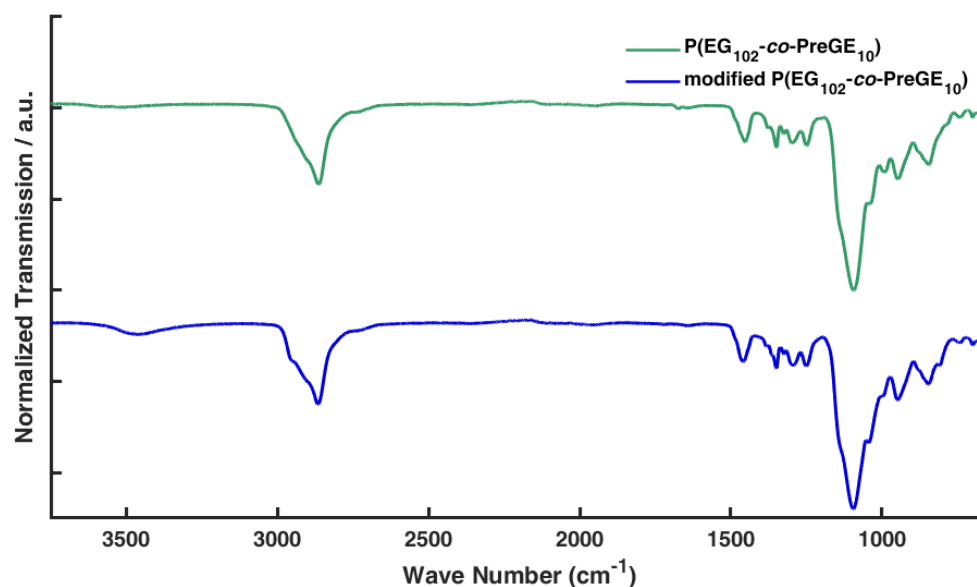


Figure S 67: IR spectrum of $\text{P}(\text{EG}_{102}\text{-co-PreGE}_{10})$ functionalized with 2-mercaptoethanol via thiol-ene click reaction.

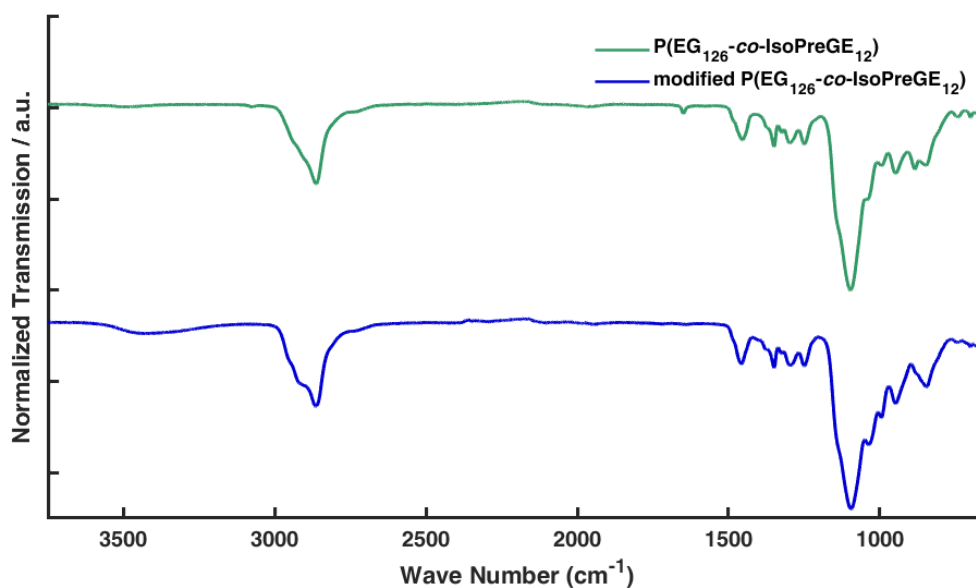


Figure S 68: IR spectrum of P(EG₁₂₆-co-IsoPreGE₁₂) functionalized with 2-mercaptoethanol via thiol-ene click reaction.

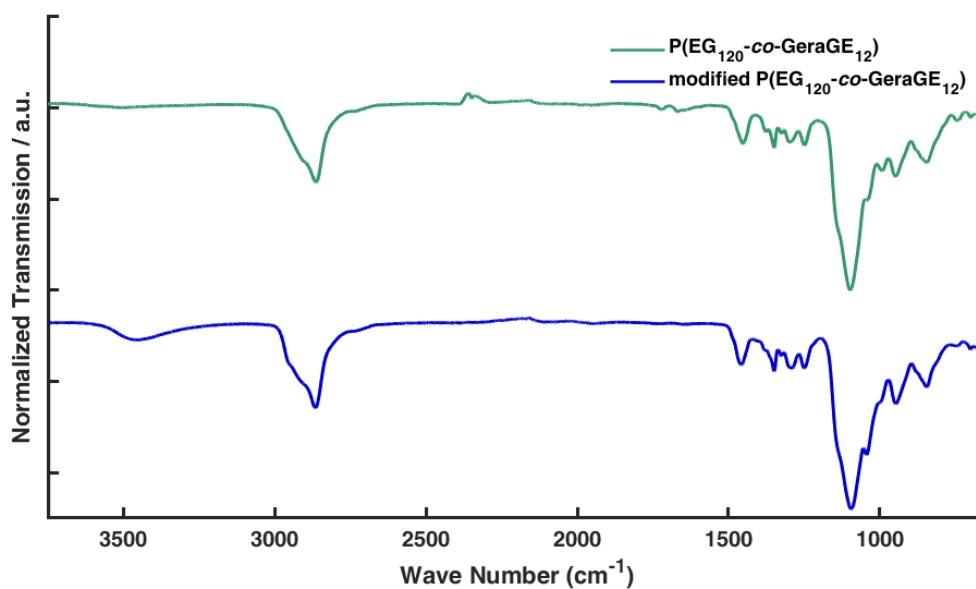


Figure S 69: IR spectrum of P(EG₁₂₀-co-GeraGE₁₂) functionalized with 2-mercaptoethanol via thiol-ene click reaction.

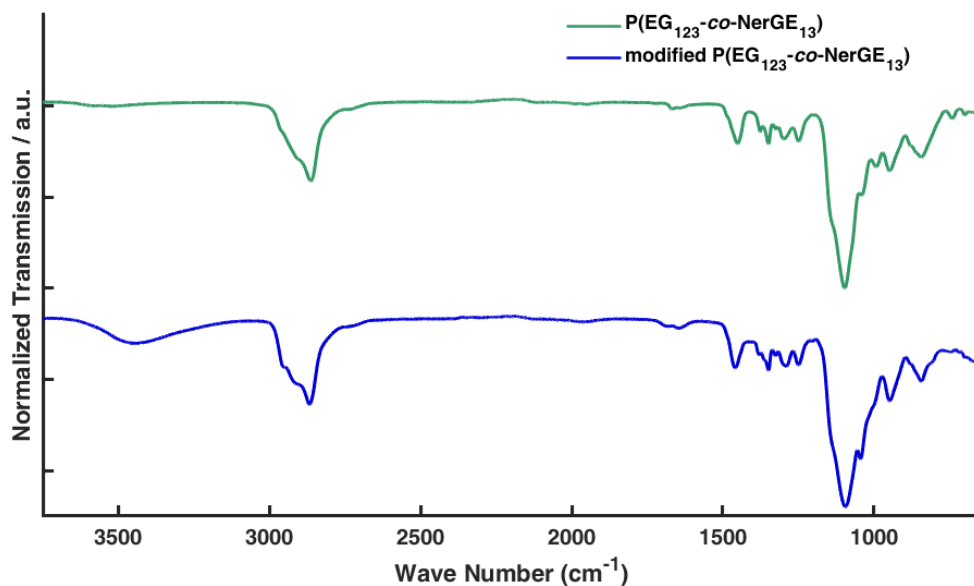


Figure S 70: IR spectrum of P(EG₁₂₃-co-NerGE₁₃) functionalized with 2-mercaptoethanol via Thiol-ene click reaction.

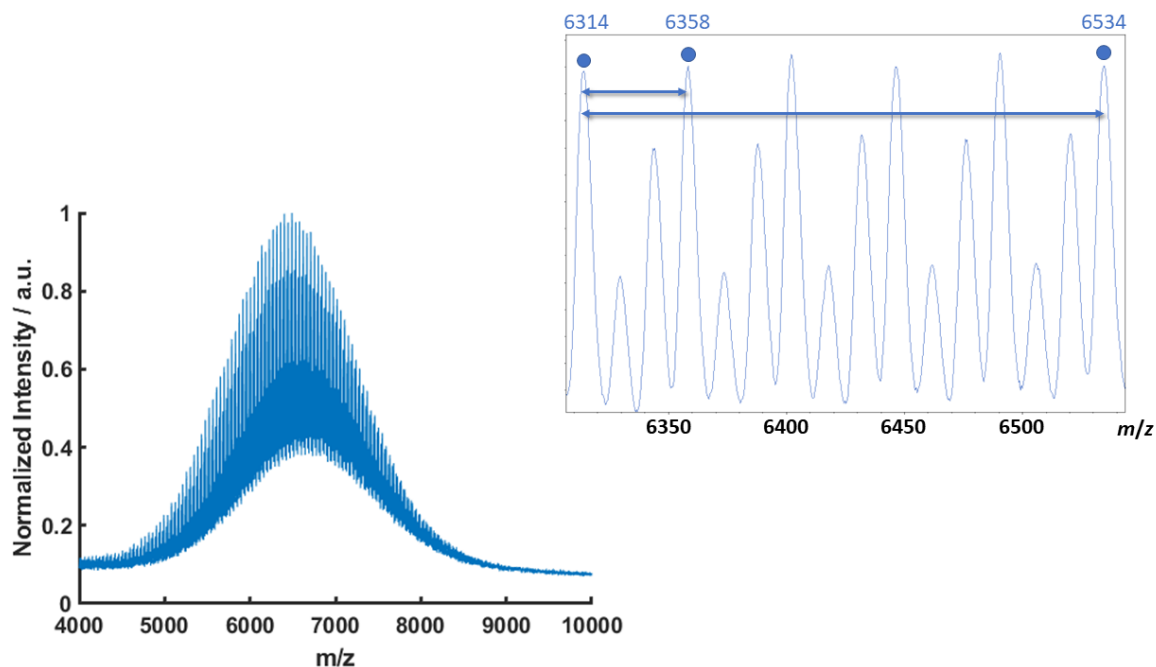


Figure S 71: MALDI-ToF of P(EG₁₀₂-co-PreGE₁₀) functionalized with 2-mercaptoethanol via Thiol-ene click reaction. Small arrow denotes the mass difference of one EO unit with 44 g/mol. Large arrow denotes the mass difference of the functionalized PreGE unit with a mass difference of 220 g/mol. To be exact, 220 g/mol could also be a multiple of 44 g/mol.

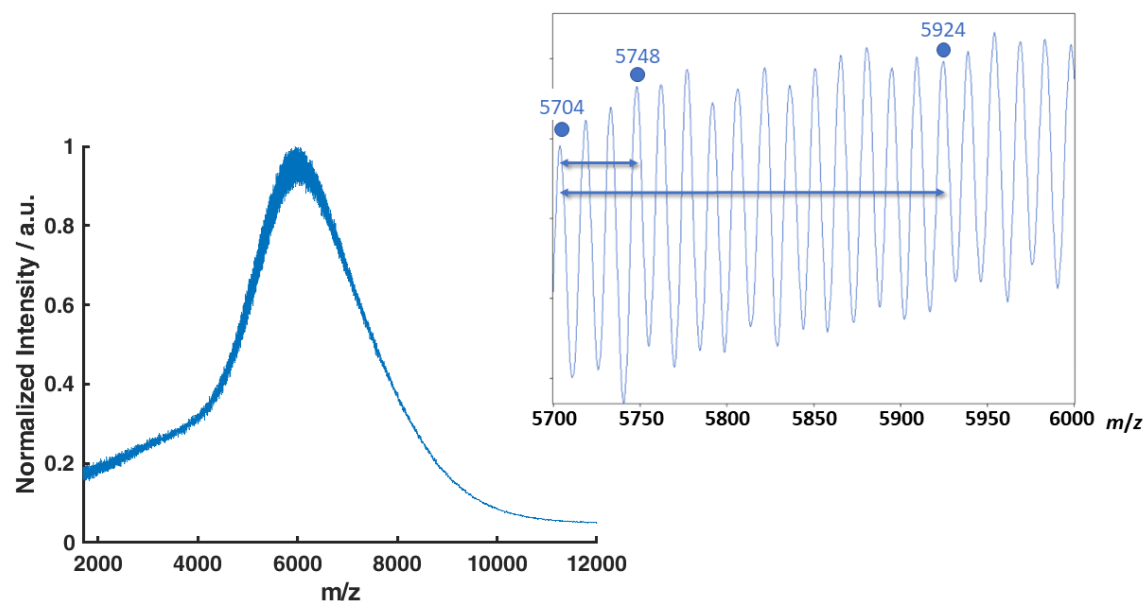


Figure S 72: MALDI-ToF of P(EG₁₂₆-co-IsoPreGE₁₂) functionalized with 2-mercaptoethanol via Thiol-ene click reaction. Small arrow denotes the mass difference of one EO unit with 44 g/mol. Large arrow denotes the mass difference of the functionalized IsoPreGE unit with a mass difference of 220 g/mol. To be exact, 220 g/mol could also be a multiple of 44 g/mol.

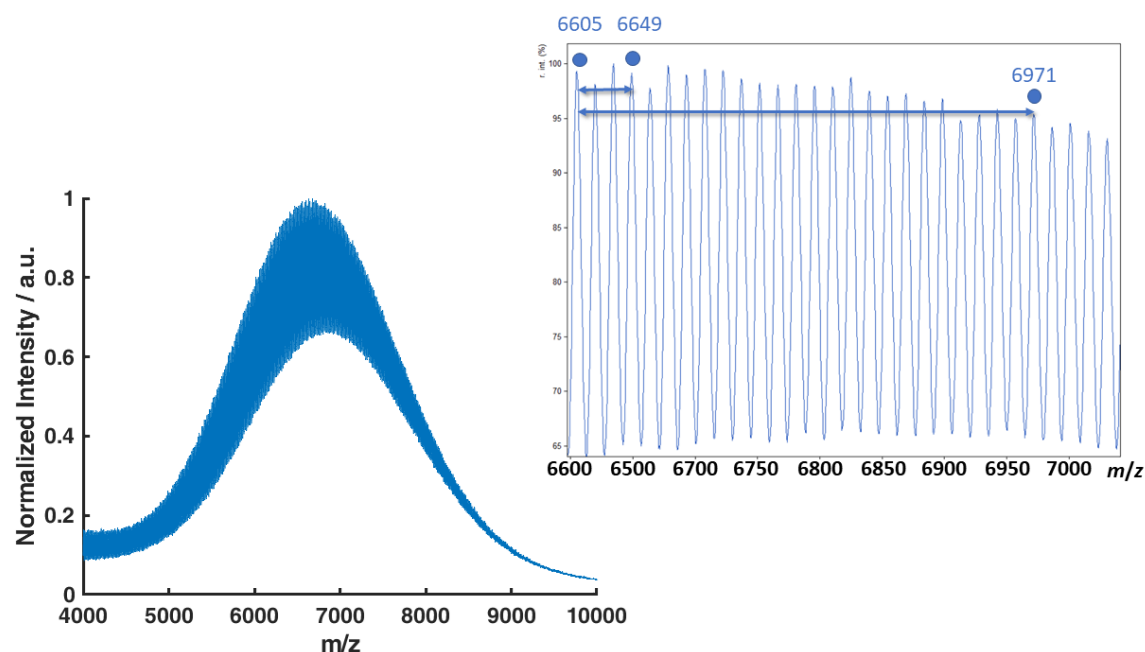


Figure S 73: MALDI-ToF of P(EG₁₂₀-co-GeraGE₁₂) functionalized with 2-mercaptoethanol via Thiol-ene click reaction. Small arrow denotes the mass difference of one EO unit with 44 g/mol. Large arrow denotes the mass difference of the double functionalized GeraGE unit with a mass difference of 366 g/mol.

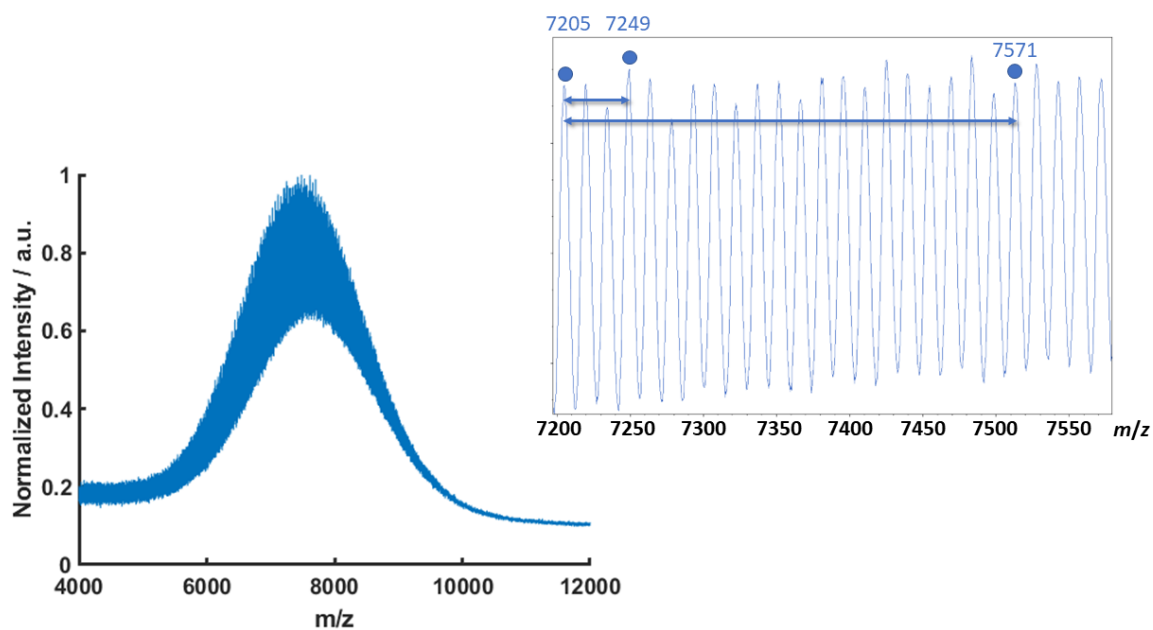


Figure S 74: MALDI-ToF of P(EG₁₂₃-co-NerGE₁₃) functionalized with 2-mercaptoethanol via Thiol-ene click reaction. Small arrow denotes the mass difference of one EO unit with 44 g/mol. Large arrow denotes the mass difference of the double functionalized NerGE unit with a mass difference of 366 g/mol.

Hydrogenation

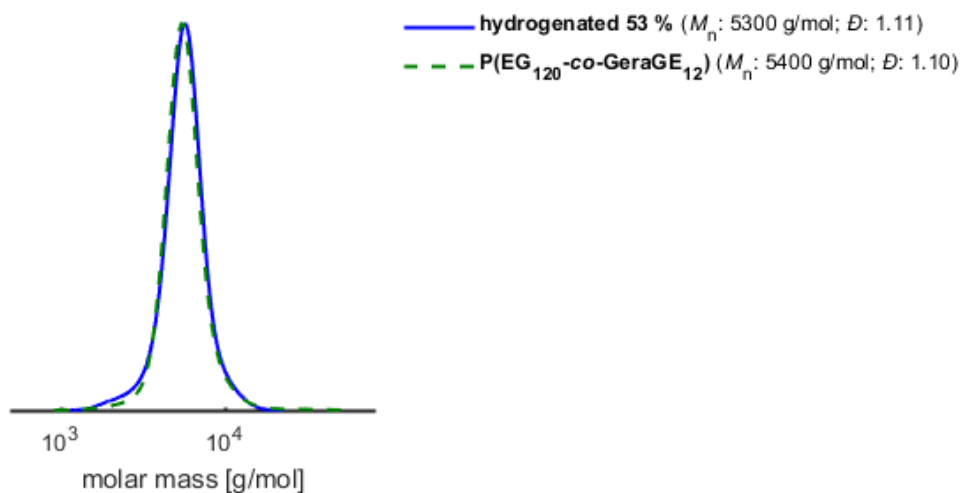


Figure S 75: SEC traces of P(EG₁₂₀-co-GeraGE₁₂) with a degree of hydrogenation of 53%. (Eluent: DMF, RI-Detector, PEG calibration).

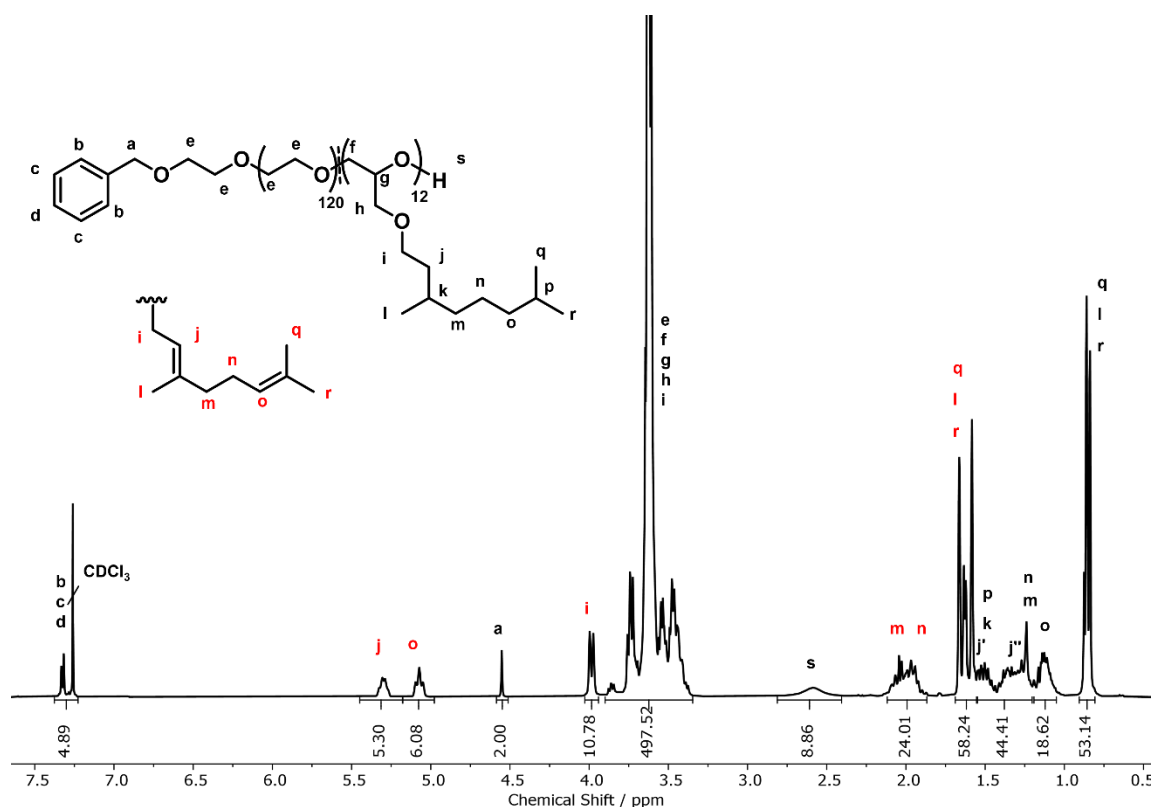


Figure S 76: ^1H NMR spectrum of $\text{P}(\text{EG}_{120}\text{-co-GeraGE}_{12})$ hydrogenated with PADA (300 MHz, CDCl_3). The degree of hydrogenation is 53%. Note that the electron-poor double bond is hydrogenated preferentially. Red letters denote atoms of residual not hydrogenated precursor polymer.

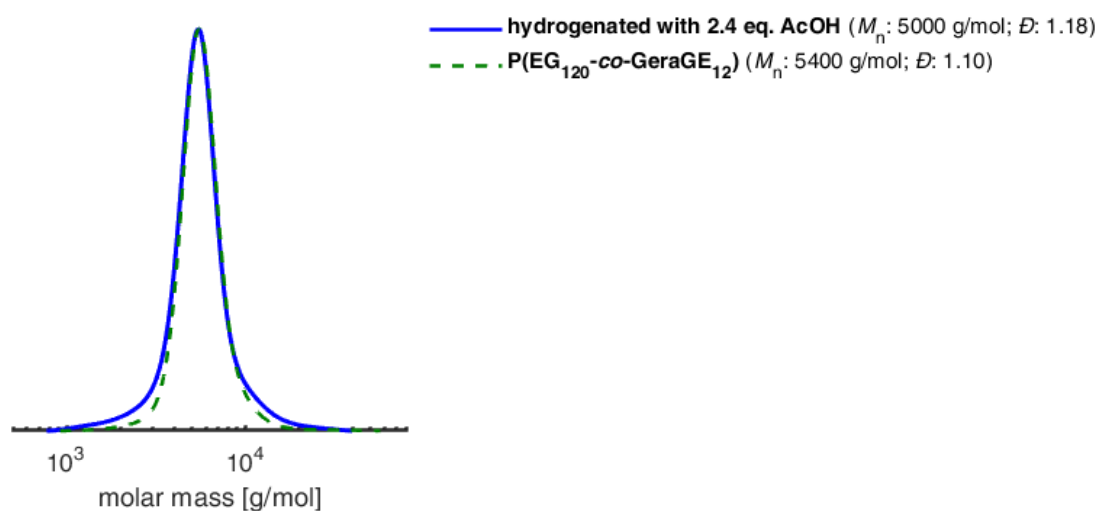


Figure S 77: SEC traces of $\text{P}(\text{EG}_{120}\text{-co-GeraGE}_{12})$ before and after hydrogenation utilizing 2.4 eq. of acetic acid (standard: 2 eq., compare Figure S 75). Higher amounts of acid result in an increase in dispersity and a small lower molecular weight shoulder.

Thermal Characterization of Polymers

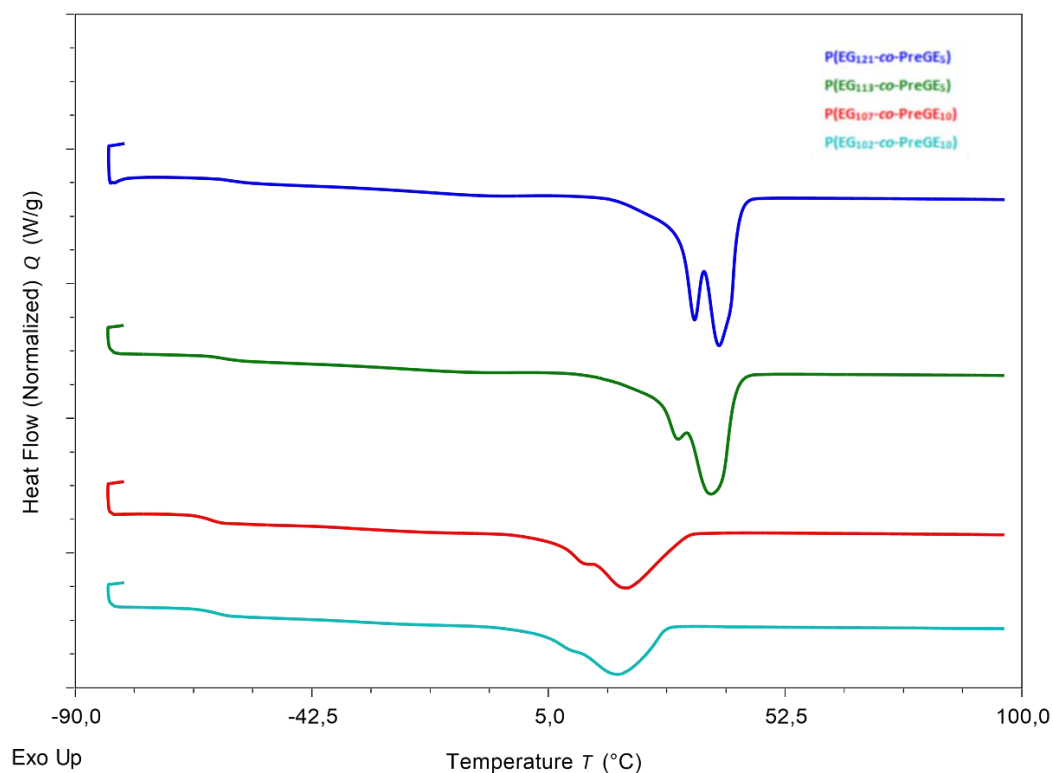


Figure S 78: DSC thermograms of $P(EG_n\text{-co-PreGE}_m)$ copolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

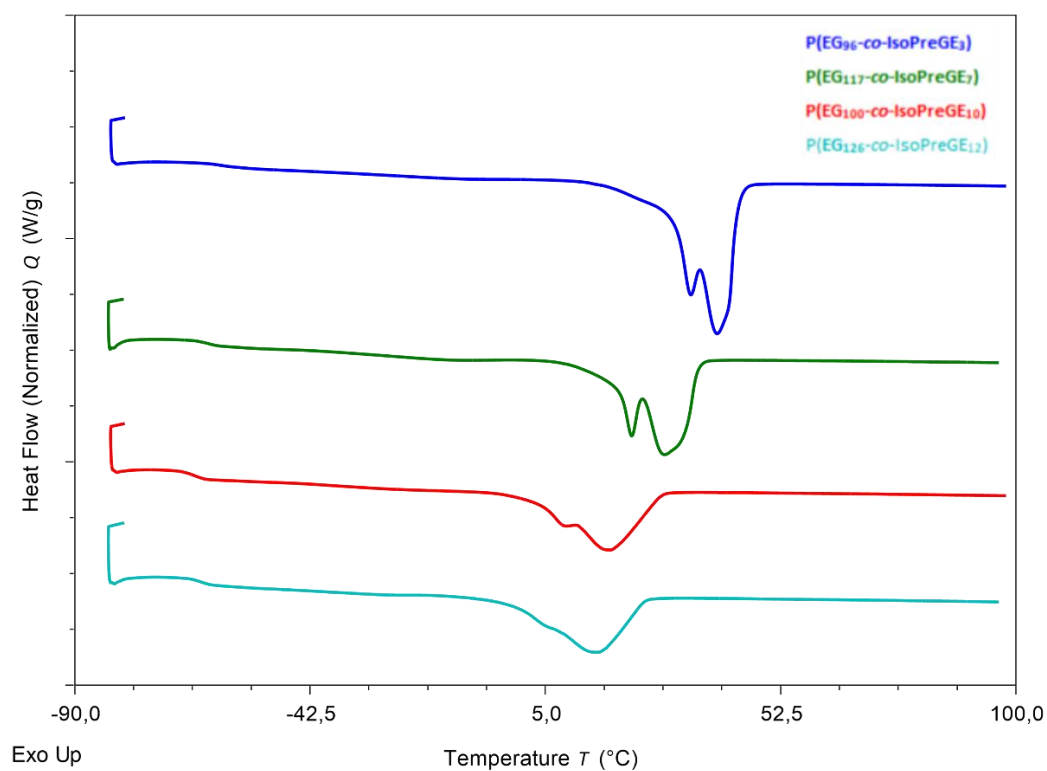


Figure S 79: DSC thermograms of $P(EG_n\text{-co-IsoPreGE}_m)$ copolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

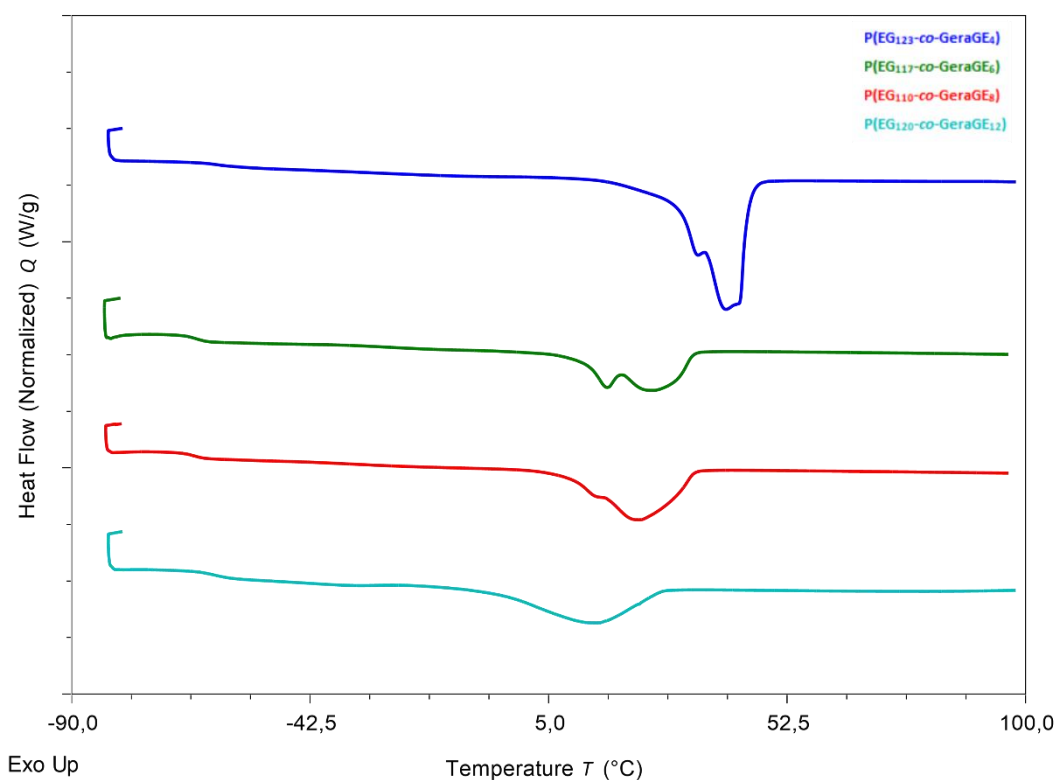


Figure S 80: DSC thermograms of P(EG_n-co-GeraGE_m) copolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

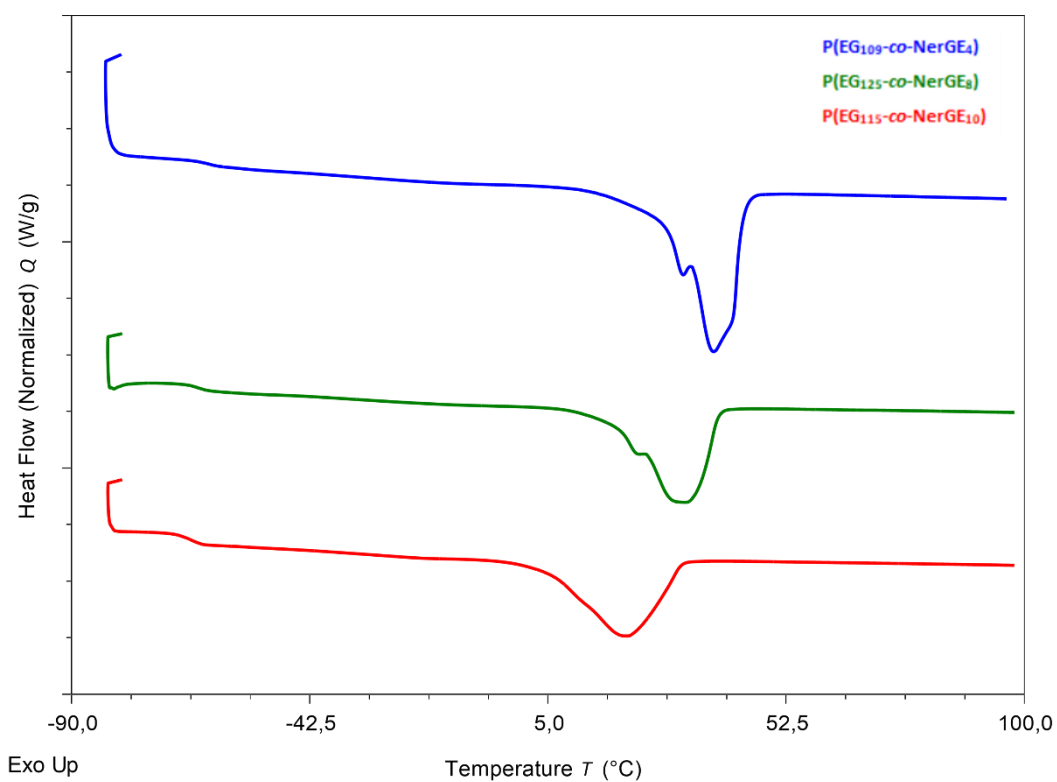


Figure S 81: DSC thermograms of P(EG_n-co-NerGE_m) copolymers (second heating cycle, from -90 to 100 °C, 10 °C·min⁻¹).

References

- (1) Mouzin, G.; Cousse, H.; Rieu, J.-P.; Duflos, A. A Convenient One-Step Synthesis of Glycidyl Ethers. *Synthesis* **1983**, 117–119.
- (2) Schüttner, S.; Krappel, M.; Koziol, M.; Marquart, L.; Schneider, I.; Sottmann, T.; Frey, H. Anionic Ring Opening Copolymerisation of Terpenoid-derived Farnesyl Glycidyl Ether: A Facile Approach to Amphiphilic Polyethers. *submitted to Macromolecules* **2023**.
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Chapter 3

Bio-based Thermoplastic Elastomers

3 Bio-based Thermoplastic Elastomers derived from Citronellyl Glycidyl Ether, CO₂ and Polylactide

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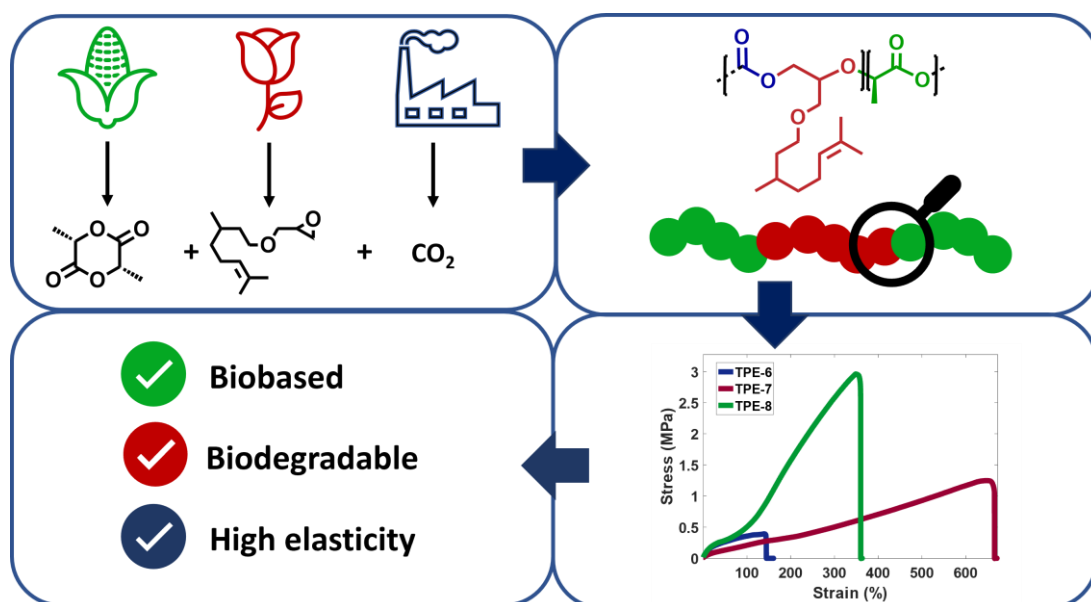
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Abstract

An important rationale for potentially sustainable materials are biodegradability and biobased feedstocks. This work presents the synthesis of PLLA-*b*-PCitroGEC di- and triblock copolymers (PCitroGEC: poly(citronellyl glycidyl ether carbonate) as degradable thermoplastic elastomers (TPEs), sourced from bio-renewable feedstocks. The cyclic ester L,L-Lactide (LLA) is produced by fermentation of corn or sugar on a large scale, whilst citronellol can be extracted from rose or lemon grass. A key feature of the current TPE application is the low glass temperature (T_g) of the polycarbonate midblock (the soft mid-block), based on PCitroGEC. PCitroGEC was synthesized by catalytic copolymerization of CO₂ and citronellyl glycidyl ether, using (*R,R*)-(salcy)-Co(III)Cl (CoSalenCl) and bis-(triphenylphosphine)iminium chloride ([PPN]Cl) as a catalyst system. The resulting PCitroGEC macroinitiators (11 000 to 26 000 g·mol⁻¹, DMF) were used in a DBU-catalyzed ring opening polymerization of LLA, resulting in a series of PLLA-*b*-PCitroGEC block copolymer structures. NMR and IR spectroscopy, along with SEC analysis, support the successful synthesis of the novel triblock copolymer system. Molar masses range between 18 000 and 41 000 g·mol⁻¹, with a molar fraction of the “soft” PCitroGEC block varied between 22 and 60 mol%. The low (PCitroGEC) and high (PLLA) glass temperatures in the block copolymers were studied with a combination of temperature-modulated differential scanning calorimetry and dielectric spectroscopy techniques. Small angle X-ray scattering confirmed nanophase separation for all synthesized TPEs. It was further employed to construct the PLLA-*b*-PCitroGEC phase diagram. It comprises classical phases (spheres, cylinders, and lamellae). Tensile testing illustrated elastic properties for all TPEs with elongation at break up to 600% and almost no plastic deformation, for copolymers with a PCitroGEC content higher than 31 mol%. Cyclic tensile tests confirmed the elastic recovery properties of the TPEs. Furthermore, the materials exhibited low *E*-moduli of 0.15-1.0 MPa, rendering the PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers suitable for potential use in soft tissue engineering.

Introduction

Thermoplastic elastomers (TPEs) are biphasic polymer materials of high industrial and academic interest. They exhibit the processability of thermoplastics and the elasticity of vulcanized rubber.¹⁻⁴ Common TPEs are based on an ABA triblock copolymer structure, which combines a nanophase separated elastomeric middle B-block with “hard” outer A-blocks.^{1,3,4} The hard blocks exhibit a high glass temperature (T_g) and create a physically crosslinked, three-dimensional nanodomain network within the low T_g rubbery matrix. The resulting dimensional stability provides creep resistance, whereas the soft segments lead to elasticity without the need for chemical vulcanization. The mechanical properties derived from the covalent linkage between the immiscible blocks can be compared to vulcanized rubber while maintaining thermally reversible crosslinking. Hence, TPEs are excellent materials for industrial thermoplastic processing such as melt extrusion and injection molding.^{1,3-6}

Nevertheless, commercial TPEs like SIS (S for styrene, I for isoprene) or SBS (B for butadiene) are produced from fossil resources and also lack degradability.⁶⁻⁹ To reduce the overall environmental footprint, a transition to a more sustainable approach for polymer synthesis is important. The identification and assessment of feedstock-based monomer precursors provides considerable potential for the manufacture of sustainable materials and products.^{5,10-14} Additionally, utilizing and fixating greenhouse gases such as carbon dioxide (CO₂) in polymer materials provides a promising opportunity. CO₂ represents a cheap, renewable carbon source and a clean C1 building block in polycarbonate synthesis. Additionally, it is readily available, non-toxic, and the resulting polycarbonates are biocompatible as well as biodegradable.¹²⁻¹⁸

In 1969, Inoue et al. discovered the synthesis of aliphatic polycarbonates based on CO₂, however, interest in polycarbonate-based TPEs has only emerged in recent years.¹⁹ Jia et al. published an all-polycarbonate TPE based on poly(cyclohexene carbonate) (PCHC) as outer hard blocks and poly(octene carbonate) (POC) as flexible midblock, showing elastomeric behavior.²⁰ Although polycarbonates allow for T_g modulation over a wide temperature range, all-carbonate triblock copolymer TPEs only show nanophase separation for high molar masses.²⁰ Consequently, very high molar masses or deployment of invariable blocks are required to facilitate phase separation. Furthermore, Yang et al. developed a TPE via post-polymerization modification of a PCHC-*b*-PAGEC-*b*-PCHC triblock copolymer, generating a hydroxyl-functional midblock. The reaction of the hydroxyl groups with boronic esters results in a physically crosslinked network, leading to a phase separated, elastic polymer.²¹

Terpenes and terpenoids are attracting growing attention as polymeric building blocks. Their structural diversity renders them suitable for various polymerization techniques, ranging from catalytic, radical to carbanionic and oxyanionic polymerization.^{5,10,13,22,23} Cyclic terpenoids featuring a *p*-menthane scaffold, such as limonene oxide (LO) and menthene oxide (MEO), present a bioderived alternative for cyclohexene oxide and are well-established in polycarbonate synthesis with CO₂.^{22,24–27} Limonene is abundant in orange peels with the corresponding LO already commercially available.^{10,24} The resulting aliphatic polycarbonates exhibit high T_g (over 120 °C), and high stiffness, thus, can be employed as the glassy outer blocks in TPEs.^{28,29} Polycarbonates with a low T_g (e.g. below -40 °C) may be suitable as a soft middle block. Zhang et al. recently provided a fully bioderived polycarbonate based on fatty acid with a low T_g of -44 °C.³⁰ Alternatively, Allais and coworkers produced a cellulose-derived polycarbonate from a levoglucosenone-derived triol monomer (triol-citro) via polycondensation. This fully bioderived polycarbonate is characterized by a low T_g of -76 °C with a citronellol side chain as a photocrosslinkable moiety.³¹

More recently, the synthesis of polycarbonate-*b*-polyester block copolymers has garnered increased interest. Their chemical dissimilarity promotes phase-separation and therefore leads to improved thermomechanical properties for polycarbonate-based block copolymers.³² Synthetic approaches involve sequential or one-pot ring opening copolymerization (ROCOPs) of CO₂ with epoxides and anhydrides, resulting in polycarbonate and polyester blocks, respectively.^{28,32–34} An alternative approach employs cyclic esters such as lactide and ϵ -decalactone in a ring opening polymerization (ROP) to produce the polyester block.^{35–37}

In 2020, Williams and coworkers employed a switchable catalyst, leading to PCHC-*b*-PDL-*b*-PCHC triblock copolymers (PDL = polydecalactone) in a one-pot reaction. These new materials feature good thermal stability ($T_{d,5} \sim 280$ °C), high toughness (112 MJm⁻³) and very high elongation at break (> 900%).³⁷ Within the same year, the authors also presented a biobased alternative using LO instead of CHO for the outer blocks, leading to polymers with high elasticity (elongation at break = 400%).²⁶ In this context, Agarwal and coworkers further introduced a double degradable diblock copolymer consisting of poly-L,L-lactide acid (PLLA) and a poly limonene oxide carbonate (PLimOC).²⁸ Furthermore, they formed a TPE using a hexyl substituted lactide (diHLA) and limonene oxide, resulting in a PLimOC-*b*-P(diHLA)-*b*-PLimOC triblock copolymer.²⁷ Another relevant work for potentially fully degradable TPEs by Zhang et al. combines poly(1,3-trimethylene carbonate) (PTMC) as a soft middle block

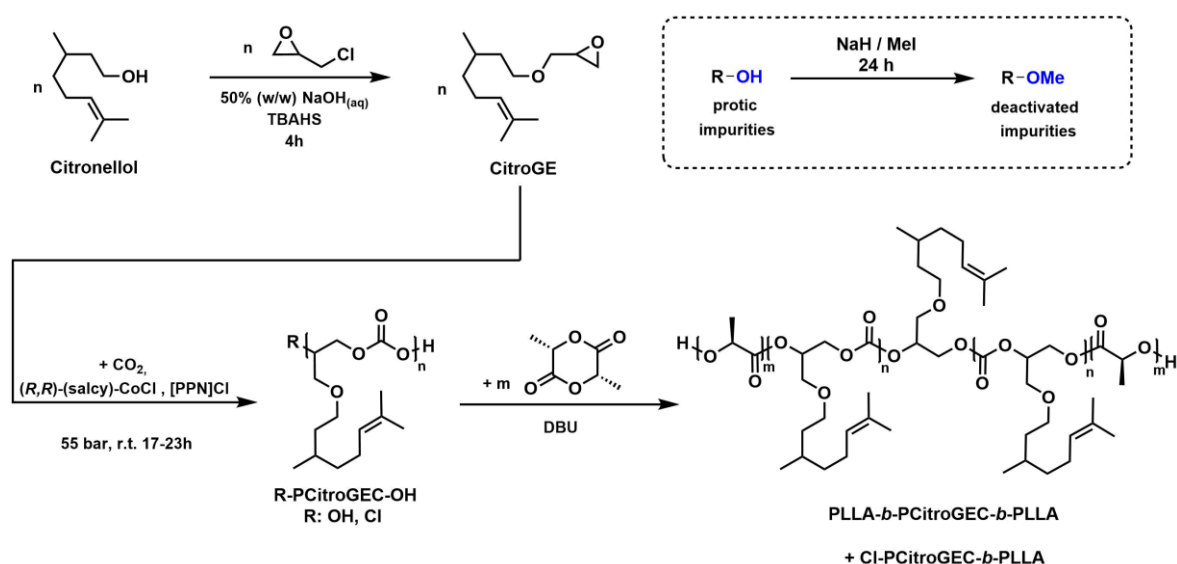
and various semicrystalline polylactides (PDLA, PLLA) as outer blocks.³⁸ Williams and coworkers also explored PTMC as a TPE soft block in combination with Zn²⁺-ionomer polyesters, enhancing mechanical strength of the TPE.³⁹

Motivated by the lack of low T_g polycarbonates, in the current work we introduce poly(citronellyl glycidyl ether carbonate) (PCitroGEC) as a bio-derived alternative for the soft block in poly(ester-*b*-carbonate-*b*-ester) copolymer TPEs. Sequential catalytic synthesis is explored to obtain a central PCitroGEC block, which is flanked by glassy PLLA end blocks. An investigation of the thermal, dielectric, and mechanical properties of the di- and triblock copolymers combined with SAXS is employed to study, respectively, the local polymer dynamics associated with the liquid-to-glass temperature of the low- and high- T_g components, the degree of nanophase separation, the pertinent phase diagram and its relation to the elastic recovery.

Results and Discussion

Synthesis of the PCitroGEC Macroinitiator

The soft middle block PCitroGEC was synthesized using CitroGE and CO₂ as monomers in a catalytic ring opening copolymerization with (*R,R*)-(salcy)-Co(III)Cl (CosalenCl) and bis(triphenylphosphine)-iminium chloride ([PPN]Cl) as a catalyst system. The glycidyl ether CitroGE was prepared in a phase transfer reaction of epichlorohydrin with citronellol (Scheme 1 top, Figure S 1).⁴⁵ Citronellol itself is abundant in lemongrass and roses and is a biobased monoterpene.²³ The long alkyl side chain possesses an alkene (“ene”) moiety, which enables further post-polymerization modification to tailor the polymer properties.²³



Scheme 1: Synthesis sequence used for the PLLA-*b*-PCitroGEC di- and triblock copolymers. CitroGE was synthesized via phase transfer catalysis, followed by the methylation of protic impurities as a relevant purification step (top, right).

Successful polymerization showing quantitative conversion of CitroGE was confirmed via NMR, SEC, and IR analysis (Table 1, Figures S 2 – S 9). The formation of thermodynamically favored cyclic carbonates was suppressed by employing room temperature (r.t.) and reaction times of 20 h. IR spectroscopy still reveals small quantities of cyclic carbonates in the crude product, which were removed by multiple precipitations in ice-cold methanol (Figure S 9). The amount of the cyclic carbonates was quantified using ¹H NMR analysis of the crude products (Figure S 10). High amounts of catalyst result in an increase of the cyclic carbonates as a by-product (Table 1). The integrals of the ¹H NMR spectrum verify the absence of any potential metathesis or radical reaction of the double bonds caused by the catalyst (Figure S 2). Moreover, the ¹³C NMR spectrum reveals the formation of a carbonate structure, and the signal at 155.40 ppm is ascribed to the carbonyl carbon (Figure S 3). Since CoSalen catalyst systems are known for the

alternative incorporation of CO₂ and epoxides, no further ether signals (except for the monomer ether signals at 3.63 and 3.49 ppm) were identified by ¹H NMR spectroscopy (Figure S 2). To overcome molar mass limitations caused by monomer impurities, CitroGE was treated with methyl iodide and sodium hydride before use in the copolymerization reaction (Scheme 1, top right).²⁴ In a series of experiments, the molar mass could be increased with this treatment from 6 000 to 19 000 g·mol⁻¹ using the same amount of the catalyst (Figure S 11). CO₂ was dried over molecular sieves (technical CO₂ gas contains water impurities)⁴⁶ to obtain higher molar masses and reduce water initiation. The pre-treatment of the monomers led to molar masses between 11 000 to 26 000 g·mol⁻¹, using DMF as eluent and PEG as standard (Figure S 7). Since no end group analysis is possible for these polymers, SEC analysis was used to estimate the molar mass. The PCitroGEC homopolymers were also measured by THF-SEC with PS as a standard, resulting in molar masses of up to 54 000 g·mol⁻¹ (Figure S 8, Table S 1). Based on a comparison of the results of SEC in THF and DMF, the absolute molar mass of the PCitroGEC macroinitiators for the triblock copolymer synthesis were estimated by multiplying DMF-SEC values by 1.5. Despite careful drying of CO₂, bimodal SEC traces confirm water initiation (Figures S 7 and S 8). We further sought to determine absolute molar masses of the PCitroGEC via SEC-MALS (Figure S 24).⁴⁷ The absolute weight molar mass (*M_w*) of PCitroGEC_{11K} is in accordance with relative molar masses of SEC measurements in THF (polystyrene standard). Nevertheless, as molar masses of the PCitroGEC increase, a significant deviation between relative and absolute molar masses is observed. We ascribe this effect to the structural difference of the PCitroGEC and polystyrene standard used in the relative SEC measurements, which ultimately translates into a cumulative underestimation of the synthesized PCitroGEC macroinitiators. Figure S 24 further shows that crosslinking of the citronellyl side chains occurred when not stored at low temperatures, impeding the determination of absolute molar masses for PCitroGEC_{24K} and PCitroGEC_{26K}. Hence, a potential overestimation of the absolute molar mass may contribute to the deviation of relative and absolute molar masses (an explanation to MALS-SEC analysis and choice of integration limits can be found in the SI).

To vary molar masses for the macroinitiator, we used different amounts (mol%) of the catalyst system (0.15 - 0.4 mol%). High catalyst amounts present during the polymerization led to lower molar masses due to the presence of chloride ions in the cocatalyst acting as an initiating species (Table 1). The lowest amount of catalyst required to start the polymerization is 0.15 mol%, resulting in the highest molar masses. However, water impurities in CO₂ gas and the resulting fluctuation in water initiation

significantly influence the achievable molar masses, ranging from 20 to 26 kg·mol⁻¹ for 0.15 mol% (Table 1). Based on the DMF-SEC traces (DMF, PEG, Figure S 7), it can be estimated that in the case of PCitroGEC_{11K}, 40% of the PCitroGEC chains are initiated by water and 60% by chloride. Although both water and the chloride ions in the cocatalyst can initiate the polycarbonate polymerization, respectively, we tentatively propose that the type of initiation does not have a major impact on the resulting triblock copolymers. MALDI-ToF analyses show that hydroxyl end groups are predominately formed after workup with 5 vol% HCl in methanol (Figure S12 and S13), resulting in telechelic polycarbonate macroinitiators. The acidic termination leads to catalyst deactivation and a substitution reaction of the chloride by a hydroxide ion. Remaining amounts of chloride-initiated, monofunctional PCitroGEC result in PCitroGEC-*b*-PLLA diblock copolymer formation during PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymer synthesis, however, the impact on mechanical properties is negligible. For styrene and isoprene based TPEs, Steube et al. demonstrated high elongation at break (700 ± 55%), even with a blend of 40 wt% diblock in a hexablock copolymer, whereas the pure hexablock copolymer exhibited an elongation at break of 800 ± 96%.⁴

Table 1: Overview of the PCitroGEC homopolymers.

Entry	Sample ^b	Catalyst (mol%)	Conv. ^a (%)	CC ^b (%)	M_n^c (kg·mol ⁻¹)	$\bar{D}^c$	M_n^d (kg·mol ⁻¹)	$\bar{D}^d$	M_w^e (kg·mol ⁻¹)	T_g^f (K)
1	PCitroGEC _{11K}	0.4	98	22	11	1.24	28	1.17	28	202
2	PCitroGEC _{20K}	0.15	98	2	20	1.23	42	1.30	-	211
3	PCitroGEC _{24K}	0.21	99	1	24	1.27	45	1.41	64	215
4	PCitroGEC _{26K}	0.2	99	3	26	1.23	54	1.28	77	217

^aConversion. ^bCalculated using ¹H NMR spectroscopy. ^cDetermined via SEC using DMF as eluent and PEG as standard.

^dDetermined via SEC using THF as eluent and PS as standard. CC illustrates the cyclic carbonates content. ^eAveraged weight molar mass (M_w) was determined via SEC light scattering detector, using THF as eluent. Values are averaged using three data sets of measurements. ^fDetermined by DSC with a heating rate of 10 K/min.

Synthesis of Triblock Copolymers

The difunctional PCitroGEC macroinitiators were employed in the ROP of LLA, using 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) as a catalyst.⁴⁴ Although Sn(Oct)₂ is an industrially relevant catalyst for the synthesis of PLLA, DBU provides notable advantages as an organocatalyst. With regard to potential transesterification reactions and the degradability of PCitroGEC, mild reaction conditions (r.t., short reactions times),

low cost and excellent polymerization control make DBU a superior choice in comparison to established Sn-based catalyst systems.⁴⁹

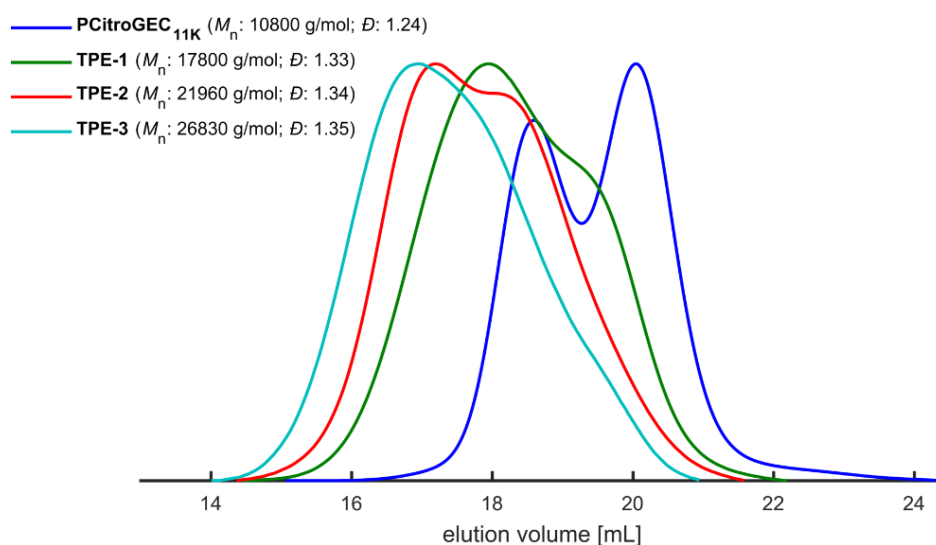


Figure 1: SEC elution traces of PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers TPE-1, TPE-2 and TPE-3 (eluent DMF, standard: PEG) derived from PCitroGEC_{11K}.

Molar masses were determined via SEC and range between 18 kg·mol⁻¹ and 41 kg·mol⁻¹, exhibiting dispersities ($\bar{D}$) of 1.25 to 1.38 (Figure 1 and Figures S 21 – S 23). The triblock copolymers are presented together with their PCitroGEC macroinitiator. The shift of triblock copolymer traces toward smaller elution volumes indicates an increase in molar mass and therefore proves successful polymerization. Moreover, molar compositions were determined via ¹H NMR spectroscopy (Table 2) and range between 22 and 60 mol% of PCitroGEC. Successful polymerisation can be confirmed, as the distinct quartet of the PLLA methine group signal is visible at 5.15 ppm. The characteristic peak for the PLLA methyl group is overlapping with methyl signals of the citronellyl side chain (1.62 – 1.45 ppm) (Figure S 14). Additionally, the polycarbonate-polyester structure features two different carbonyl groups, which are distinguished in ¹³C NMR spectroscopy as a peak at 169.73 ppm (PLLA) and 154.33 ppm (PCitroGEC) (Figure S 15). No other carbonyl peaks are observed, which precludes the occurrence of side reactions, like backbiting, during the second polymerization step (Figures S 15 and S 19).³⁸ SEC analysis and DOSY spectroscopy validate block copolymer formation rather than blending of the two homopolymers of PCitroGEC and PLLA (Figure S 20).

Thermal Characterization

The thermal behavior was investigated by differential calorimetry (DSC). PCitroGEC macroinitiators showed T_g s between 202 K and 217 K (Table 1), which is in the range of soft rubbery blocks of commercial TPEs.³

Table 2: Overview of the synthesized PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers.

Sample	Composition ^a	$M_{n, \text{PCitroGEC}}^b$ ($\text{kg}\cdot\text{mol}^{-1}$)	$M_{n, \text{total}}^b$ ($\text{kg}\cdot\text{mol}^{-1}$)	$\bar{D}^b$	Morphology ^c	$T_{g,1}^d$ (K)	$T_{g,2}^d$ (K)
TPE-1	PLLA _{0.29} - <i>b</i> -PCitroGEC _{0.42} - <i>b</i> -PLLA _{0.29} -18K	11	18	1.33	LAM	227	313
TPE-2	PLLA _{0.35} - <i>b</i> -PCitroGEC _{0.31} - <i>b</i> -PLLA _{0.35} -22K	11	22	1.34	CYL	223	319
TPE-3	PLLA _{0.39} - <i>b</i> -PCitroGEC _{0.22} - <i>b</i> -PLLA _{0.39} -27K	11	27	1.35	Spheres	232	321
TPE-4	PLLA _{0.20} - <i>b</i> -PCitroGEC _{0.60} - <i>b</i> -PLLA _{0.20} -25K	20	25	1.28	CYL	226	314
TPE-5	PLLA _{0.31} - <i>b</i> -PCitroGEC _{0.38} - <i>b</i> -PLLA _{0.31} -28K	20	28	1.38	CYL	225	317
TPE-6	PLLA _{0.24} - <i>b</i> -PCitroGEC _{0.53} - <i>b</i> -PLLA _{0.24} -33K	24	33	1.35	LAM/CYL	229	314
TPE-7	PLLA _{0.29} - <i>b</i> -PCitroGEC _{0.42} - <i>b</i> -PLLA _{0.29} -40K	24	40	1.30	LAM	227	319
TPE-8	PLLA _{0.35} - <i>b</i> -PCitroGEC _{0.31} - <i>b</i> -PLLA _{0.35} -38K	24	38	1.32	CYL	227	322
TPE-9	PLLA _{0.30} - <i>b</i> -PCitroGEC _{0.41} - <i>b</i> -PLLA _{0.30} -39K	26	39	1.33	HPC	230	320
TPE-10	PLLA _{0.33} - <i>b</i> -PCitroGEC _{0.34} - <i>b</i> -PLLA _{0.33} -41K	26	41	1.33	HPC	231	322

^aThe indices show the molar fraction calculated *via* ¹H NMR spectroscopy. The numbers e.g. 19K demonstrate the molar mass examined by SEC. From characterization data, the presence from diblock copolymer impurities is likely. ^bDetermined via SEC using DMF as eluent and PEG as standard. ^cDetermined by SAXS. ^dDetermined by DSC with a heating rate of 10 K/min.

All triblock copolymers exhibit two T_g s, nearly independent of composition, indicating phase separation of the elastic PCitroGEC and glassy PLLA domains (Figures S 25 – S 28). The PLLA blocks exhibit a T_g in the range of 317 K to 324 K, which is slightly lower than the T_g of the PLLA homopolymer (328 K – 333 K).⁵⁰ In contrast, all T_g values for the PCitroGEC blocks are higher than those of the corresponding macroinitiator (Table 2). Definitive information on the level of phase separation can be obtained by SAXS below. Surprisingly, cold crystallization and melting (T_m) of PLLA was hardly observable in the first heating curve of some samples and disappears in subsequent heating runs (Figure S 29). Values of the enthalpy of melting during the first heating run are minute ($\Delta H_{m, \text{PLLA}} = 3.65 \text{ J}\cdot\text{g}^{-1}$, TPE-4, Table S 2), compared to literature values, ranging from 82-203 $\text{J}\cdot\text{g}^{-1}$. Our calculations suggest a rather low degree of crystallinity ($X_{c, \text{PLLA}} \sim 10\%$, Table S 2) of the PLLA domains in these TPEs.⁵¹⁻⁵³ In copolymers rich in PCitroGEC this

feature could associate with the effect of confinement on polymer crystallization.⁵⁴ Additionally, the second cooling curve of all TPEs shows no exothermic feature, indicating slow kinetic effects associated with the PLLA crystallization (Figures S 25 – S 28). Although PLLA is a semicrystalline polymer, it is known for its slow crystallization. Hence melt crystallization results in a higher degree of amorphous PLLA compared to cold recrystallization.⁵⁵

Furthermore, partial miscibility of the covalently bound polymer blocks can be ascribed to a plasticizing effect, which lowers the degree of crystallinity and results in amorphous PLLA. Nevertheless, Hillmyer and coworkers demonstrated that PLA crystallinity is not required for TPE applications, but rather the immiscibility of the hard and soft blocks plays a key role to achieve phase separation. They prepared phase-separated polylactide-*b*-polyisoprene-*b*-polylactide (PLA-*b*-PI-*b*-PLA) TPEs of varying composition and morphologies, featuring amorphous PLA blocks.³⁴ Although we detect two T_g s for the synthesized PLLA-*b*-PCitroGEC-*b*-PLLA TPEs, a profound understanding of the phase separation behavior requires structural investigation via small angle X-ray scattering (SAXS), which is discussed below in the morphology Section of this work.

Local dynamics

Precise information on the location of the two glass temperatures in the triblock copolymers can be obtained by TM-DSC in combination with dielectric spectroscopy (DS). Figure 2 provides the temperature dependence of the reversing heat capacity in TPE-3 for the different rate/period pairs used. Two steps, one corresponding to the glass temperature of PLLA and the other to PCitroGEC can be detected, depending on the actual rate/period. The first derivative of the reversing heat capacity with respect to temperature was used to locate the exact temperatures for the employed periods.

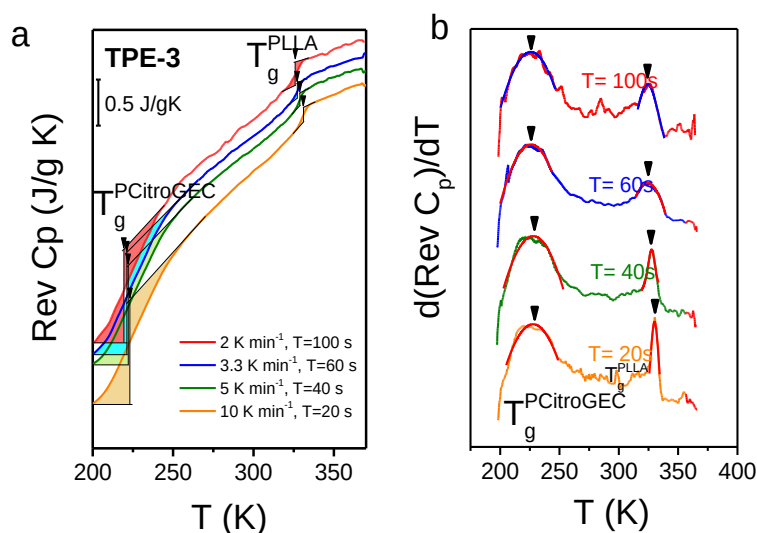


Figure 2: (a) Temperature dependence of the reversing heat capacity for TPE-3, obtained from TM-DSC at different periods of modulation as indicated. Data are shifted vertically for clarity. (b) Derivative of reversible heat capacity with respect to temperature plotted as a function of temperature for different periods of modulation. Arrows indicate the glass temperatures of PLLA and PCitroGEC.

Subsequently, the dipolar dynamics in the TPEs was investigated by DS. Dielectric loss curves of sample TPE-3 as a typical example of the materials are depicted as a function of temperature in Figure 3. The Figure indicates different processes within the temperature range from 248.15 K to 378.15 K. The dielectric loss curve at 288.15 K, shows the segmental process of PCitroGEC (α process) and a slower process (indicated as α^*) of reduced dielectric strength as compared to the α process. The curve at 358.15 K, shows the segmental process of PLLA and a conductivity contribution at lower frequencies. The dielectric loss curves were fitted with a summation of three HN functions to obtain the characteristic frequencies. The latter are plotted together with the TM-DSC results in Figure 4 as a function of inverse temperature. The two segmental processes conform to the Vogel-Fulcher-Tammann (VFT) dependence as:

$$f_{max} = f_0^{\#} \exp\left(-\frac{B}{T - T_0}\right) \quad (4)$$

Here, $f_0^{\#}$, is the limiting frequency at very high temperatures, B , is the activation parameter, and T_0 , is the "ideal" glass temperature located below the conventional T_g . The VFT parameters for the segmental processes of the four TPE investigated are summarized in Table 3. As expected, the T_g values (calculated at a segmental relaxation time of 100 s, *i.e.*, $\log(f_{max}/\text{Hz}) = -2.798$) are somewhat different from the ones shown in Table 2 (231 K, 223 K, 228 K, 224 K, and 228 K for the $T_g^{\text{PCitroGEC}}$ ($T_{g,1}$ in Table 2) in TPE-1, TPE-3, TPE-4, TPE-6, and TPE-9, respectively; and 323 K, 317 K, and 313 K for the T_g^{PLLA} ($T_{g,2}$ in Table 2) in TPE-3, TPE-6, and TPE-9, respectively). The liquid-to-glass temperature is a kinetic phenomenon (as such is not a "transition" in the thermodynamic sense). It depends largely on the cooling/heating rate. Hence T_g values reported through dynamic probes (as DS and TM-DSC, where the system is triggered by an external frequency) are always advantageous over single rate experiments (as, for example, in normal DSC).

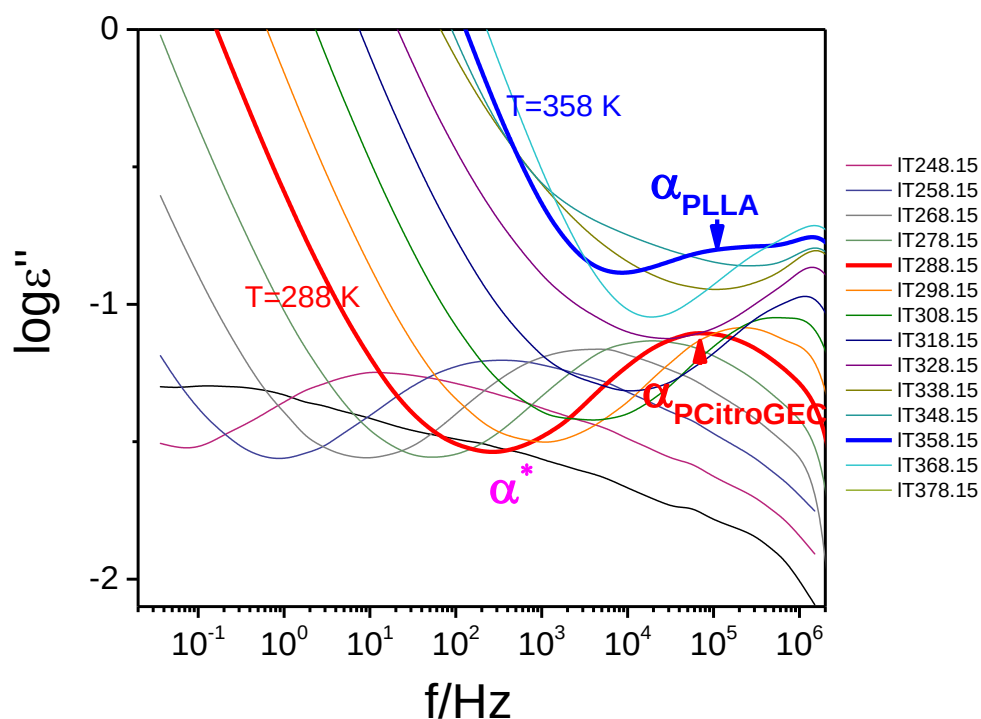


Figure 3: Dielectric loss curves of TPE-3 shown at different temperatures in the range from 248.15 K to 378.15 K. The curve at 288.15 K, shows the segmental process of PCitroGEC (α process) and a slower process (indicated as α^*). The curve at 358.15 K, shows the segmental process of PLLA.

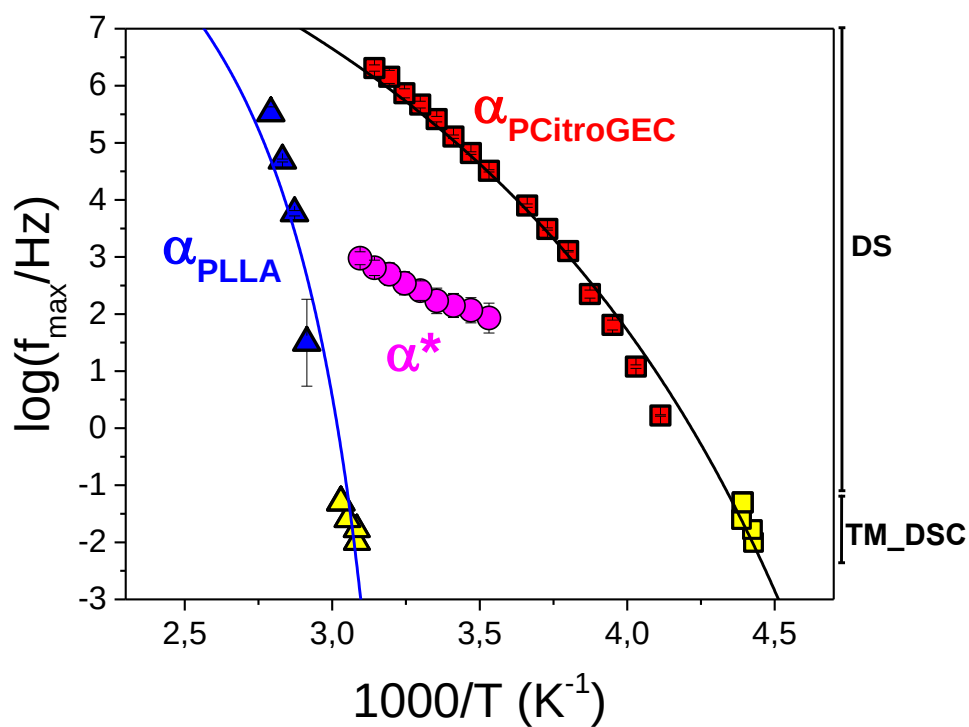


Figure 4: Activation plot of the relaxation times for the different processes in TPE-3. Starting from higher temperatures: (triangles): segmental process of PLLA, (squares): segmental process of PCitroGEC, (circles): α^* process of PCitroGEC. TM-DSC data are also shown (yellow symbols). The lines represent fits to the VFT equation (see text).

Table 3: VFT Parameters for the Segmental Dynamics of PCitroGEC and PLLA obtained from TM-DSC and DS.

Sample	Segmental Mode (PCitroGEC)			Segmental Mode (PLLA)		
	$\log(f_0^\# / \text{Hz})$	B (K)	T_0 (K)	$\log(f_0^\# / \text{Hz})$	B (K)	T_0 (K)
TPE-1	12*	1740 ± 58	180 ± 2	-	-	-
TPE-3	12*	2140 ± 50	160 ± 2	12*	1155 ± 147	289 ± 5
TPE-4	12*	1841 ± 24	174 ± 1	-	-	-
TPE-6	12*	2060 ± 64	164 ± 2	12*	1055 ± 60	286 ± 2
TPE-9	12*	1850 ± 60	174 ± 2	12*	3300 ± 230	216 ± 7

*fixed value

The slower α^* process with the low dielectric activity deserves some attention. It is probably related to a weak dipole moment contribution of PCitroGEC along the backbone. The process relaxes at longer times than the segmental process, it has a VFT temperature dependence and exhibits some molar mass dependence as expected for Rouse or reptating chains.⁵⁶ Nevertheless, a complete assignment of the process requires a detailed investigation of rather monodisperse PCitroGEC homopolymers as a function of molar mass. Efforts in this direction are currently ongoing in our laboratories.

Morphology

The phase state of the TPEs was investigated by SAXS by heating from 303 K to 423 K and cooling back to 303 K in 30 K steps. Exemplary SAXS curves are shown in Figure 5 for four TPEs with increasing PCitroGEC molar fraction. Additional SAXS results are provided in the Figures S 30 and S 31. The SAXS intensity profile of TPE-3 (PCitroGEC molar fraction of 0.22) exhibits some broad peaks consistent with the scattering from a dilute dispersion of spherical particles. The latter form factor develops minima at $qR = 4.484, 7.728, 10.87$ etc. From the position of the first minimum in Figure 5a, we obtain a particle radius of about 10.2 nm. In addition to the broad peaks, the scattering curve develops a maximum at lower q (arrow in Figure 5a) characteristic of the presence of interparticle interference. The structure factor, $S(q)$, that takes into account these interparticle correlations is related to the scattered intensity by $I(q) \sim KP(q)S(q)$, where K is a scaling factor, $P(q)$ is the particle form factor (spheres) and $S(q)$ is the structure factor.⁵⁷ Different from TPE-3, the intensity profile of TPE-10 exhibits Bragg reflections at positions with relative q values of $1:3^{1/2}:2:7^{1/2}:3:12^{1/2}$ suggestive of a hexagonally-packed cylindrical (HPC) structure. The periodicity (d_0) is 41.7 nm and the intercylinder

distance, d , is 48.1 nm ($d=d_0(4/3)^{1/2}$). Similarly, TPE-9 exhibits Bragg reflections with relative q values of $1:3^{1/2}:2:7^{1/2}$ suggestive of a hexagonally-packed cylindrical (HPC) structure. The periodicity, d_0 , is 37.9 nm and the intercylinder distance, d , is 43.8 nm. In the case of the more asymmetric TPE-4, Bragg reflection are broader and have relative q values of $1:3^{1/2}:7^{1/2}$ suggestive of a cylinders (CYL) in the absence of long-range order. Moreover, all SAXS patterns were found to be affected by annealing. Copolymer films cast from solution at ambient temperature suffer from incomplete nanophase separation. In particular, nanophase separation improves by annealing at higher temperatures, e.g. by crossing the PLLA T_g (Fig. 2 and Table 2 and Table 3) as evidenced in the SAXS patterns as a function of temperature (Figure S 32).

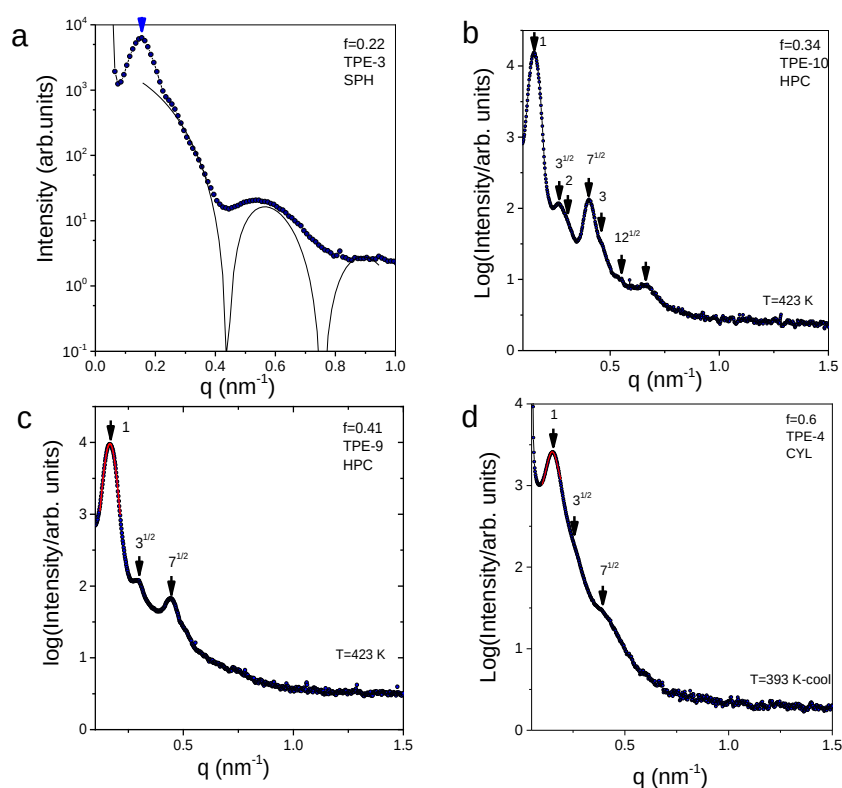


Figure 5: SAXS patterns of (a) TPE-3 (at 303 K), (b) TPE-10 (at 423 K), (c) TPE-9 (at 423 K) and (d) TPE-4 (at 393 K). Arrows in (b-d) indicate the positions of Bragg reflections corresponding to HPC and CYL morphologies. The solid curve in (a) gives the form factor of monodisperse dispersion of spheres.

These results for the TPE copolymers were employed in the construction of a phase diagram (Figure 6). Instead of the pertinent phase diagram (χN , vs volume fraction) and because of the unknown interaction parameter, χ , and density, we plot the ratio M_n/T as a function of the molar fraction of PCitroGEC. Despite the relatively small number of triblocks investigated (more than 40 compositions are required for a complete phase diagram⁵⁸) the different regions comprising classical nanophases can be distinguished with increasing molar fraction: from weakly ordered spheres (SPH), to cylinders

without long range order (CYL), to hexagonally-packed cylinders (HPC), and to lamellae (LAM). For a PCitroGEC molar fraction of ~ 0.42 the boundary is set at this composition because of the coexisting LAM and HPC phases. The same holds for the LAM/CYL boundary at a molar fraction of ~ 0.53 . The remaining boundaries are only an approximation. We note that the LAM morphology is somewhat asymmetric in composition, reflecting the asymmetric phase diagram of triblock copolymers⁵⁹, and, possibly, the conformational asymmetry of the two polymers.⁶⁰

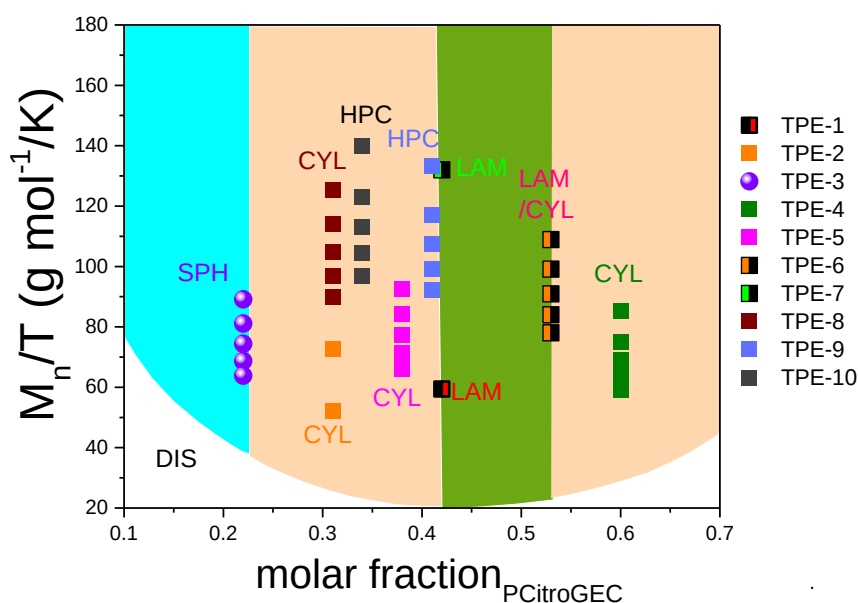


Figure 6: Experimental phase diagram of the triblock copolymers based on SAXS, indicating the presence of weakly ordered spheres (SPH), cylinders without long range order (CYL), hexagonally-packed cylinders (HPC), and lamellae (LAM). TPE-6 is located in the LAM/CYL boundary. The disordered phase (DIS) boundaries are only an approximation.

Mechanical Properties

Stress-strain measurements were conducted to analyze the mechanical properties of the polymers. In all cases 2-3 samples were characterized with respect to their stress-strain behavior. Comparing the polymers with PCitroGEC_{11K} as a middle block (Figure 7)), the following conclusions can be made: (i) Weakly ordered triblock copolymers display, in general, weak mechanical properties (TPE-1, TPE-2, TPE-4) with low elongation at break independent of the nanophase formed (Fig. 6); (ii) Ordered copolymers with the higher content in the high T_g component (PLLA) display the highest modulus (E) (TPE-3), toughness (TPE-3) and elongation at break (ϵ_{break}). In addition, with respect to the elongation at break, ordered copolymers with a PCitroGEC content of around 40% (TPE-7, TPE-9, TPE-5) display the maximum values. (iii) Alternatively, low toughness associates with weakly ordered copolymers (TPE-1, TPE-2) and with a

lower fraction of PLLA (TPE-4, TPE-6). Among the different copolymers, TPE-3 (PCitroGEC content of 22%; spherical nanodomains with weak interparticle correlations, Fig. 5a), exhibits the highest modulus and toughness and a high elongation at break.

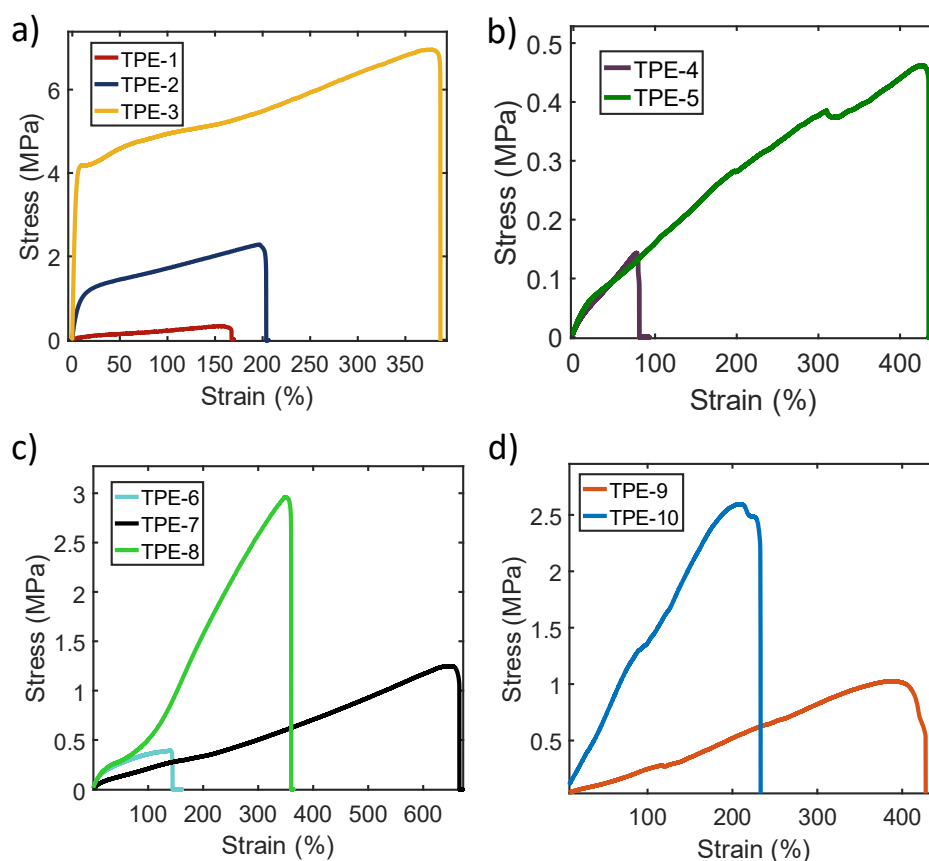


Figure 7: Stress-strain curves of the PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers. a) ABA triblock copolymers with PCitroGEC_{11K} as B middle block. b) ABA triblock copolymers with PCitroGEC_{20K} as B middle block. c) ABA triblock copolymers with PCitroGEC_{24K} as B middle block. d) ABA triblock copolymers with PCitroGEC_{26K} as B middle block.

Analytically, TPE-1 with the lowest molar mass exhibits (Table 4) the lowest elongation at break at around 164% and shows a weakly ordered lamellar structure. As TPE-2 and 3 feature higher molar masses, the corresponding microstructures correspond to cylinders and spheres of the flexible PCitroGEC domains, leading to stiffer materials due to the restricted mobility of the PCitroGEC chains.⁶¹ TPE-1 with the highest amount of PCitroGEC of 42 mol% shows elastic behavior (Figure 7, a)). However, the films were slightly elongated after break at maximum strain, indicating a small hysteresis (Figure S 33). No yield point is detectable. The triblock copolymers with lower PCitroGEC content of 31 and 22 mol% (TPE-2 and TPE-3) exhibit a yield point at around 7% elongation (Table 4). At the yield point, the elastic deformation changes to plastic deformation. Since the plastic deformation begins after 7% elongation, TPE-2 and TPE-3

can be considered as rather ductile materials (Figure 7, a), in which the flexible PCitroGEC form spherical or cylindrical domains, and hence stretching is limited.

Table 4: Overview of the mechanical properties of the PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers.

Sample	Composition ^a	E (MPa)	ϵ_{break} (%)	σ_{break} MPa	ϵ_{yield} (%)	σ_{yield} (MPa)	$W_{tensile}$ (MN/mm ²)
TPE-1	PLLA _{0.29} - <i>b</i> -PCitroGEC _{0.42} - <i>b</i> -PLLA _{0.29} 18K	0.41±0.07	164±15	0.37±0.05	-	-	0.37±0.08
TPE-2	PLLA _{0.35} - <i>b</i> -PCitroGEC _{0.31} - <i>b</i> -PLLA _{0.35} 22K	15±2	180±50	2.3±0.3	7.7±0.9	0.97±0.05	3±1
TPE-3	PLLA _{0.39} - <i>b</i> -PCitroGEC _{0.22} - <i>b</i> -PLLA _{0.39} 27K	100±10	352±46	7.5±0.5	6±2	4.4±0.6	22±3
TPE-4	PLLA _{0.20} - <i>b</i> -PCitroGEC _{0.60} - <i>b</i> -PLLA _{0.20} 25K	0.151±0.005	80±10	0.16±0.05	-	-	0.07±0.04
TPE-5	PLLA _{0.31} - <i>b</i> -PCitroGEC _{0.38} - <i>b</i> -PLLA _{0.31} 28K	0.20±0.06	420±20	0.6±0.2	-	-	1.7±0.5
TPE-6	PLLA _{0.24} - <i>b</i> -PCitroGEC _{0.53} - <i>b</i> -PLLA _{0.24} 33K	1.1±0.5	160±30	0.5±0.1	-	-	0.6±0.3
TPE-7	PLLA _{0.29} - <i>b</i> -PCitroGEC _{0.42} - <i>b</i> -PLLA _{0.29} 40K	0.188±0.004	650±20	1.26±0.08	-	-	4.1±0.1
TPE-8	PLLA _{0.35} - <i>b</i> -PCitroGEC _{0.31} - <i>b</i> -PLLA _{0.35} 38K	0.81±0.04	350±10	2.90±0.05	-	-	5.1±0.1
TPE-9	PLLA _{0.30} - <i>b</i> -PCitroGEC _{0.41} - <i>b</i> -PLLA _{0.30} 39K	0.24±0.01	316±80	0.8±0.2	-	-	1.6±0.8
TPE-10	PLLA _{0.33} - <i>b</i> -PCitroGEC _{0.34} - <i>b</i> -PLLA _{0.33} 41K	1.0±0.1	190±30	1.9±0.8	-	-	2±1

^aThe indices show the molar fraction calculated *via* NMR. The numbers e.g. 19K demonstrate the molar mass examined by SEC. From characterization data, the presence from diblock copolymer impurities is likely. All values regarding the mechanical properties were determined using 3 different specimens of each copolymer, except for TPE-9 (2 specimens).

TPE-4 and TPE-5 based on the PCitroGEC_{20k} middle block also showed higher toughness and elongation at break, because of the high content in PLLA (Figure 7, c). TPE-4 comprises 60 mol% and TPE-5 38 mol% of the PCitroGEC block. Comparing the triblock copolymers with PCitroGEC_{24K}, the trend in toughness is once more evident (Figure 7, c)). With a higher amount of PLLA, the toughness increases (Table 4). TPE-6 (53 mol% PCitroGEC) and TPE-8 (31 mol% CitroGEC) show both a lower elongation at break than TPE-7 with 42 mol% PCitroGEC. TPE-9 and TPE-10 were prepared using PCitroGEC₂₆ as a macroinitiator. Both polymers show a toughness of around 2 MN/mm². Since PLLA is stiffer than PCitroGEC, the triblock with 41 mol% PCitroGEC exhibits a lower E -modulus than the triblock with 34 mol%. As explained, copolymers rich in PCitroGEC show low E -moduli (of 0.15 to 1.0 MPa) and elongation of break up to 600%, *i. e.* very soft materials are obtained.

A comparison of the results with those of Jia et al. shows that they are in the same range, although the PCHC-*b*-POC-*b*-PCHC triblock copolymers exhibit a much higher molar mass. The authors synthesized PCHC-*b*-POC-*b*-PCHC triblock copolymers with molar masses in the range from 353 000 to 372 000 g/mol and 19 - 25 wt% of the hard PCHC block. These materials show similar low *E*-moduli of 1.43 to 2.5 MPa and elongation at break of 331 to 1052%.²⁰

The elastic properties were studied exemplarily for two TPEs of similar molar composition, but varied molar mass and mechanical properties. Samples of TPE-5 and TPE-8 were subjected to cyclic tensile testing, in which a pre-defined maximum stress was applied and released in a total of 10 cycles with no time delay (Figures 8 and S 34). Both samples show a continuous decrease in *E*-modulus (flattening of slope) per cycle, which is also referred to as “stress-softening”. According to literature, this deformation-induced change in mechanical properties is ascribed to a disruption of the hard domains of the cylindrical morphology into smaller domains, which do not reform (by diffusion) during the short timeframe of the cyclic tensile experiment. Successive cycles show a similar response to cycle 1 and initially feature a strong decrease in strain increments between each cycle (compare Table S 3). Consequently, hysteresis loops become narrower, which could be caused by a subsequent morphology alignment of the PLLA hard domains. We accessed the elastic recovery rate according to an equation used by Jia et al.: *elastic recovery rate* = $(\epsilon_{\max} - \epsilon_{\text{res}}) / \epsilon_{\max}$.²⁰

$\epsilon_{\max}$ and ϵ_{res} represent the maximum and residual strain during cyclic tensile testing, respectively. Figure 8 depicts a $\epsilon_{\max}$ of 92% at a maximum stress of 0.2 MPa during the first cycle, which recovered to a ϵ_{res} of 4% upon release of stress. This manifests a resulting elastic recovery of 95% for TPE-5, whereas TPE-8 reveals an elastic recovery of 79% at the applied stresses (Table S 3). The difference of elastic recovery can partially be explained by the difference in maximum stress applied, which was tailored to the respective TPE's ϵ_{break} . In general, modulus recovery is improved at lower strain, but is essentially impacted by the morphology.^{62,63} Frick et. al reported a low residual strain for PLA-*b*-PI-*b*-PLA TPEs at low deformations for all morphologies, whereas strains of 300% lead to a residual strain of 25% for the lamellar and cylindrical morphologies. TPE-5, subjected to a lower stress, features an excellent elastic recovery, whereas TPE-8 experiences an initial strain of 259% and returning in a state of 57% residual strain. The occurrence of residual strain could be attributed to a strain-induced alignment of the lamellar morphology with a lower energy. Even after the release of strain, the TPEs'

return in an unaligned state is energetically less favourable, causing an incomplete elastic recovery.

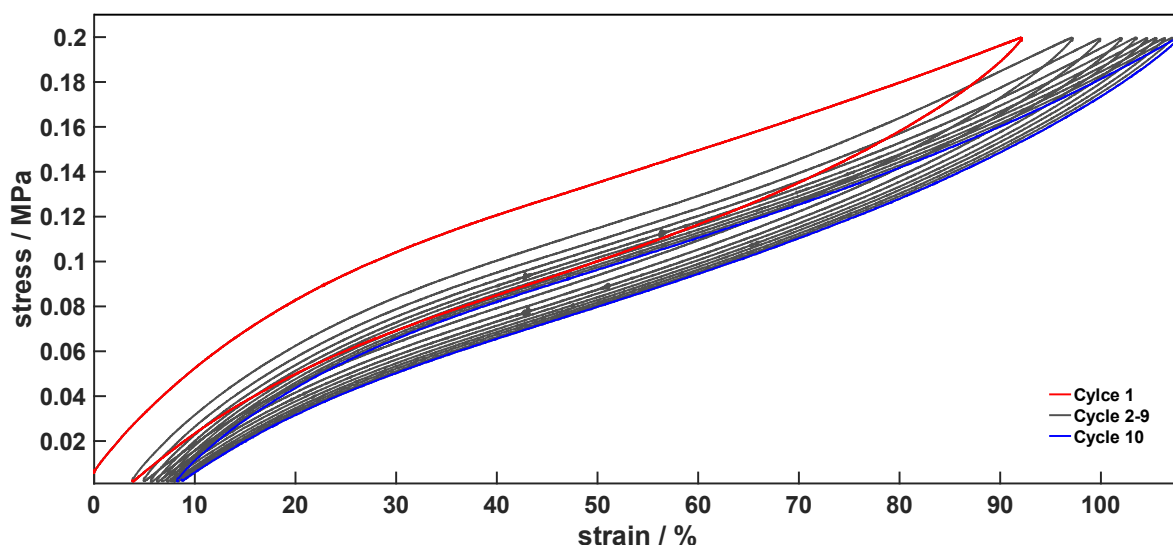


Figure 8: Cyclic tensile curves for TPE-5, performing an ultimate stress of 0.2 MPa and no delay between cycles. Each cycle reveals an elastic recovery of 92-95%.

In summary, all copolymers exhibit elastic behavior with the exception of the triblock copolymers with PCitroGEC content below 31 mol% (TPE-2, TPE-3). In addition, all copolymers featuring elastic behavior show low E -moduli of 0.15 to 1.0 MPa, comparable to human soft tissue as cartilage and vascular elastin (E in the range 0.3-10 MPa), which renders them applicable for soft tissue engineering.⁶⁴⁻⁶⁷ Similar E -moduli are required to reduce the mismatch between the natural soft tissue and the material used for the implant.^{64,65} Furthermore, they show high elasticity with an elastic elongation up to 600%. This characteristic is also important for tissue engineering materials since they need to maintain dimensional stability.

Conclusion

In this work, we have introduced PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers, composed of renewable monomers derived from terpenes and starch as starting materials. We have demonstrated a straightforward synthesis route, using catalytic ROP to copolymerize CO₂ with CitroGE, leading to the novel, highly flexible polycarbonate midblock/macroinitiator with an exceptionally low T_g around 222 K, as obtained by a combination of DS and TM-DSC. The PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymer was successfully synthesized by utilizing DBU-catalyzed ROP of LLA. Two T_g s were detected for all copolymers. The crystallization of PLLA in triblock copolymers rich in PCitroGEC is impeded, due to confinement as well as thermal history effects, resulting in the

absence of a T_m . The molar masses of these triblock copolymers are in the range, where nanophase separation occurs. The phase diagram comprises weakly ordered spheres, cylinders in the absence of long range order, hexagonally-packed cylinders, and lamellae. Stress-strain measurements were conducted and demonstrate the elasticity (elongation up to 600%) of these polycarbonate-polyester TPEs with nearly no plastic deformation. Furthermore, the measurements revealed a low E -modulus of 0.15-1.0 MPa (TPEs with elastic behavior). This elastic behavior, supplemented by the known biocompatibility and biodegradability of the polymer components renders the PLLA-*b*-PCitroGEC-*b*-PLLA triblock copolymers suitable as promising materials in soft tissue engineering and regenerative medicine.

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Supporting Information

Experimental Sections

Materials

The solvents and reagents were applied as acquired, unless otherwise stated. Carbon dioxide (>99.999%) was bought from Westfalen AG (Münster, Germany). Bis(triphenylphosphine)iminium chloride ([PPN]Cl) was received from abcr GmbH. (*R,R*)-(salcy)-Co(III)Cl was prepared as described by Ford *et al.*³⁹ L,L-Lactide (LLA) was provided by BASF SE and recrystallized in toluene before use. All solvents were purchased from Sigma Aldrich, Fischer Chemical (Pittsburgh, PA, USA), and Honeywell (Morris Plains, NJ, USA) and used without further purification. All reagents were purchased from Sigma Aldrich, Arcos Organics (Pittsburgh, PA, USA), Alfa Aesar (Kandel, Germany), or TCI (Oxford, UK). Deuterated solvents were obtained from Deutero GmbH (Kastellaun, Germany).

Instrumentation

Nuclear Magnetic Resonance (NMR) Spectroscopy.

¹H NMR spectra at 300 MHz and ¹³C NMR spectra at 75 MHz were recorded on a Bruker Avance III HD 300 (5 mm BBFO-Head with z-gradient) at 23 °C. ¹H NMR spectra at 400 MHz and ¹³C NMR spectra at 100 MHz were recorded on a Bruker Avance III HD 400 (5 mm BBFO Smartprobe with z-gradient) at 23 °C. The spectra are referenced internally to the residual proton signal of the deuterated solvent.

Size Exclusion Chromatography (SEC).

SEC was completed in DMF (1 mL/min, 50 °C) containing 1 g/L lithium bromide as an additive, using an Agilent 1100 series SEC system equipped with a HEMA 300/100/40 Å column cascade, UV (254 nm), and RI detector. Calibration was accomplished using poly (ethylene glycol) (PEG) standards acquired from Polymer Standard Service (PSS). SEC measurements were accomplished in THF (1 mL/min, 30 °C) on a SDV column set from PSS (PSS SDV 10³ Å / 10⁵ Å, 10⁶ Å), equipped with a UV (254 nm) and RI detector. Calibration was carried out using polystyrene standards (PSS GmbH). Recycling SEC measurements were performed in chloroform (CHCl₃) (3.5 mL/min, 30 °C) on a Jaelgel-4H column set from Japan Analytical Industry equipped with a UV (254 nm) and RI

detector. Calibration was carried out using polystyrene standards (PSS). PSS WinGPC UniChrom software was used for all data recording and processing.

For SEC-mutli-angle light scattering (MALS) experiments a PSS SECurity system with degasser, isocratic pump, UV detector (VWD) and RI detector was coupled to a PSS SLD700 7-angle static light scattering detector. THF was used as mobile phase with a set of PSS SDV 5 μ m columns (PSS SDV 5 μ m guard column 10³ Å / 10⁵ Å / 10⁶ Å) at 23°C. Polystyrene standards (PSS GmbH) were used for calibration.

Differential Scanning Calorimetry (DSC).

DSC curves were recorded using a Mettler Toledo DSC 823, applying indium, zinc and n-octane as calibration standard. For each sample, two cooling and heating cycles were conducted at heating rates of 10 K·min⁻¹ under nitrogen atmosphere in a temperature range of -150 °C to 50 °C or -150 °C to 180 °C for the homopolymers and triblock copolymers, respectively. Glass temperatures (T_g s) were determined from the second heating run. To evaluate the absence of a melting peak of PLLA in the second heating run of all TPEs, we determined the (apparent) melting temperature (T_m) and melting enthalpy (ΔH_m) obtained during the first heating run (Table S 2).

Temperature Modulated Differential Scanning Calorimetry (TM-DSC).

Temperature-modulated differential scanning calorimetry (TM-DSC) measurements were made with a Q2000 DSC (TA Instruments) using cooling/heating rates in the range of 10 – 1 K·min⁻¹ and oscillation periods from 20 to 150 s. A specific rate/period pair was employed for each measurement according to^{40,41}

$$\beta = \frac{\Delta T_g}{cP} 60s/min \quad (1)$$

Here, β is the cooling/heating rate, ΔT_g is the range of T_g , c is the number of cycles across the T_g width, and P is the oscillation period. The rate/period pairs used were as follows: 20 s, 10 K·min⁻¹; 40 s, 5 K·min⁻¹; 60 s, 3.3 K·min⁻¹; 100 s, 2 K·min⁻¹. TM – DSC measurements were made within the temperature range from 193 to 373 K.

Fourier-Transformations-Infrared Spectroscopy.

FT-IR spectra were recorded using a *Nicolet* iS10 FT-IR spectrometer (Thermo Scientific, Waltham, MA, USA) equipped with a diamond ATR unit.

Matrix-Assisted Laser Desorption Ionization Time-of-Flight Mass Spectrometry (MALDI-ToF).

MALDI-ToF analysis was performed with a MALDI ToF MS Autoflex Max by Bruker in linear mode. Samples were dissolved in dichloromethane (DCM) at a concentration of 1 mg/mL. As a matrix *trans*-2-[3-(4-*tert*-butylphenyl)-2-methyl-2-propenyliden] malononitrile (DCTB) with NaTFA or KTFA was used. The measurement mmass 5.5.0 software was used for data analysis.

Tensile Testing.

Tensile tests were carried out using a material testing machine Z005 (Zwick/Roell, Germany). Tensile tests were accomplished by exposing the stamped polymer strips (5 mm x 45 mm) to uniaxial tension. Samples with thicknesses around 0.3 – 0.6 mm were strained with a rate of 20 mm/min at room temperatures. A predefined load of 0.02 N was applied. Stress-strain measurements were carried out 3 times for each copolymer. All films were prepared by slow evaporation from a chloroform solution followed by full removal of the solvent under reduced pressure. The E-modulus (E) was determined by calculating the slope of the stress-strain curves before the yield point. The yield point of the films was calculated by the intersection of the tangents of the elastic field and the plastic field before the strain hardening. The toughness is displayed by the area under the strain stress curves. The elongation at break (ϵ_{break}) and stress at break (σ_{break}) is the point, where film rupture occurs. The elastic recovery was investigated by cyclic tensile testing of selective polymer films according to literature.²⁰ The stamped polymer stripes of TPE-5 and TPE-8 were subjected to a maximum stress of 0.2 MPa and 1.5 MPa (loading process) and then lowered to 0.002 MPa and zero stress (unloading process), respectively. Overall, 10 cycles were performed with no time delay between cycles. The recovery rate was calculated via the following equation:

$$\text{elastic recovery} = (\epsilon_{\text{max}} - \epsilon_{\text{res}}) / \epsilon_{\text{max}} \quad (2)$$

ϵ_{max} represents the maximum strain at the applied maximum stress, whereas ϵ_{res} marks the residual strain of the polymer stripes after stress release.

Small-Angle X-Ray Scattering (SAXS).

SAXS measurements were made using CuK α radiation (RigakuMicroMax 007 x-ray generator, Osmic Confocal Max-Flux curved multilayer optics). 2D diffraction patterns were recorded on an Mar345 image plate detector at a sample-detector distance of 2076 mm. Intensity distributions as a function of the modulus of the total scattering vector, $q = (4\pi/\lambda) \sin(2\theta/2)$, where 2θ is the scattering angle, were obtained by radial averaging

of the 2D datasets. Samples in the form of thick films (~ 1 mm) were prepared by slow solvent casting. Temperature-dependent measurements of 1 hour long were made by heating the films from 303 K to 453 K in 30 K steps followed by 1h equilibration at each temperature and subsequent cooling to 303 K.

Dielectric Spectroscopy (DS).

DS measurements as a function of temperature (T) were performed with a Novocontrol Alpha frequency analyzer. The measurements at ambient pressure were performed within the range from 193 to 423 K in steps of 5 K for frequencies in the range from 10^{-2} to 10^7 Hz. The sample cell consisted of two electrodes, 20 mm in diameter and 50 μm in thickness, maintained by Teflon spacers. Samples were prepared as melts by pressing the electrodes to the spacer thickness under vacuum. The complex dielectric permittivity $\varepsilon^* = \varepsilon' - i\varepsilon''$, where ε' is the real and ε'' is the imaginary part, was obtained as a function of frequency, ω , and temperature, T , i.e., $\varepsilon^*(T, \omega)$.^{42,43} The analysis of the DS curves was based on the empirical equation of Havriliak and Negami (HN)

$$\varepsilon_{\text{HN}}^*(T, \omega) - \varepsilon_{\infty}(T) = \frac{\Delta\varepsilon(T)}{\left[1 + (i\omega\tau_{\text{HN}}(T))^m\right]^n} \quad (3)$$

where $\varepsilon_{\infty}(T)$ is the high-frequency permittivity, $\tau_{\text{HN}}(T)$ is the characteristic relaxation time of the equation, $\Delta\varepsilon(T) = \varepsilon_0(T) - \varepsilon_{\infty}(T)$ is the relaxation strength, m and n (with limits $0 < m, mn \leq 1$) describe, respectively, the symmetrical and asymmetrical broadening of the distribution of relaxation times, and finally ω ($= 2\pi f = 1/\tau$) is the angular frequency of the external electric field. A term describing the conductivity contribution was included in the fitting procedure as $\sigma_0(T)/i\varepsilon_f\omega$, where σ_0 is the dc conductivity, and ε_f is the permittivity of free space. From τ_{HN} , the relaxation times at maximum loss, τ_{max} , were obtained analytically from the HN equation as follows

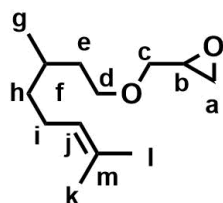
$$\tau_{\text{max}} = \tau_{\text{HN}} \sin^{-1/m} \left(\frac{\pi m}{2(1+n)} \right) \sin^{1/m} \left(\frac{\pi mn}{2(1+n)} \right) \quad (4)$$

These relaxation times correspond to the relaxation times of the segmental process. At lower frequencies, ε'' rises because of the conductivity ($\varepsilon'' = \sigma/(\omega\varepsilon_f)$). This conductivity contribution has also been taken into account during the fitting process. Except for the measured ε'' , the derivative of the real part of the dielectric permittivity, ε' , ($d\varepsilon'/d\ln\omega \approx (2/\pi)\varepsilon''$) was used in the analysis of the dynamic behavior.

Synthetic Procedures

CitroGE Monomer Synthesis

CitroGE was synthesized in a phase transfer catalysis according to a literature-known procedure.¹ Citronellol (20 mL, 0.11 mol, 1 eq.) and tetrabutylammonium hydrogen sulfate (TBAHS, 1.61 g, 0.40 mmol, 0.04 eq.) were dissolved in an aqueous sodium hydroxide solution (50 wt%) and stirred vigorously at room temperature. The mixture was cooled to 0 °C and then epichlorohydrin (45 mL, 0.57 mol, 5.18 eq.) was added incrementally over a period of 30 min. After stirring for 3.5 h at room temperature, the reaction solution was added to ice water, extracted three times with diethyl ether, and washed with saturated sodium chloride solution to neutrality. The organic phases were combined and dried with sodium sulfate. The solvent was removed under pressure and the residue was fractionally distilled. Citronellyl glycidyl ether was obtained as a colorless liquid. Yield: 44% (10.39 g, 48.93 mmol).



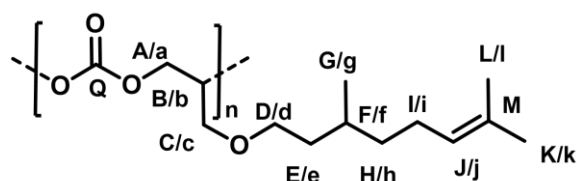
¹H NMR (300 MHz, CDCl₃) δ = 5.13 – 5.05. (m, 1H, j), 3.77 – 3.61 (m, 1H, c), 3.62 – 3.42 (m, 2H, d), 3.42 – 3.31 (m, 1H, c'), 3.20 – 3.06 (m, 1H, b), 2.83 – 2.55 (m, 2H, a), 2.09 – 1.86 (m, 2H, i), 1.68 (s, 3H, l), 1.61 (s, 3H, k), 1.63 – 1.07 (m, 5H, e+f+h), 0.89 (d, 3H, g) ppm.

Synthesis of PCitroGEC Homopolymers

We exemplarily describe the synthesis protocol for PCitroGEC_{26K} (Table 1, entry 4). All PCitroGEC homopolymers were synthesized in the same manner using different amounts of catalyst system (Table 1).

A 150 mL Roth autoclave was dried at 40 °C under reduced pressure. Citronellyl glycidyl ether (CitroGE) (2.2 mL, 1.89 mmol), (*R,R*)-(salcy)-CoCl (11.7 mg, 0.018 mmol) and [PPN]Cl (10.5 mg, 0.0018 mmol) was filled in the autoclave, equipped with a stirring-bar, in an inert argon atmosphere. The reaction mixture was stirred at a carbon dioxide

pressure of 55 bar at 20 °C for 17 h. CO₂ was then released; the crude product was dissolved in DCM and the catalyst was deactivated with 2 mL of a solution of 5%_{vol} HCl (aq) in methanol. The product was precipitated twice in ice-cold methanol as a non-solvent. The precipitated product was collected by centrifugation at 4500 rpm at 0 °C for 10 min. The colorless viscous polymer was then dried under reduced pressure for 24h. A yield of 57% polymer was obtained.



¹H NMR (300 MHz, CDCl₃): δ = 5.16 – 5.06 (m, 1H, j), 5.06 – 4.98 (m, 1H, b), 4.52 – 4.29 (m, 2H, a), 3.63 (d, 2H, c) 3.56 – 3.40 (m, 2H, d), 2.10 – 1.85 (m, 2H, i), 1.70 (s, 3H, k), 1.62 (s, 3H, l), 1.65 – 1.10 (m, 5H, e+f+h), 0.91 (d, 3H, g) ppm.

¹³C NMR (75 MHz, CDCl₃): δ = 154.40 (Q), 131.24 (M), 124.86 (J), 74.48 (B), 70.26 (D), 68.44 (C), 66.14 (A), 37.35 (E), 36.51 (H), 29.63 (F), 25.84 (I), 25.56 (K), 19.64 (G), 17.77 (L) ppm.

M_n (SEC, DMF, PEG calibration) = 26 kg·mol⁻¹; $\bar{D}$ (SEC, DMF, PEG calibration) = 1.23.

M_n (SEC, THF, PS calibration) = 41 kg·mol⁻¹; $\bar{D}$ (SEC, THF, PS calibration) = 1.24.

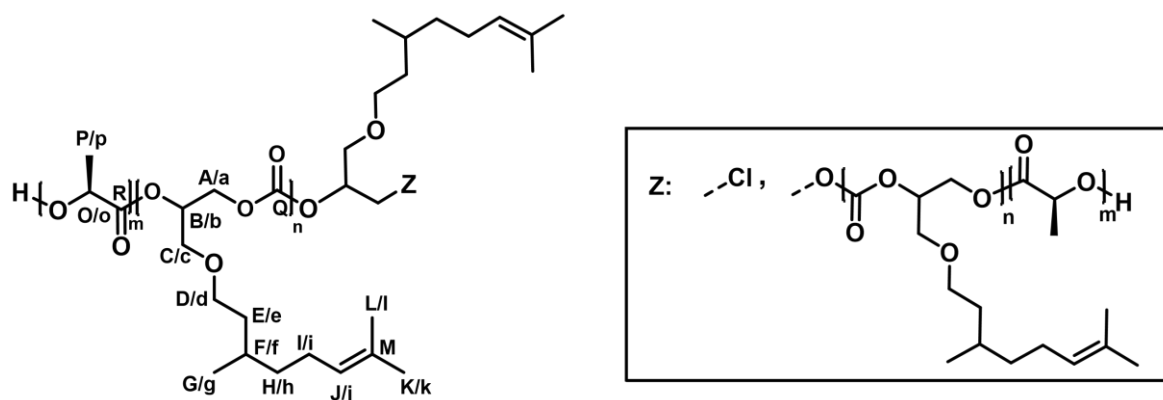
$T_{g,1}$: -56 °C.

Synthesis of PLLA-*b*-PCitroGEC-*b*-PLLA Triblock Copolymers.

The synthesis procedure below describes preparation of the novel ABA triblock copolymer, namely PLLA_{0.35}-*b*-PCitroGEC_{0.31}-*b*-PLLA_{0.35} (TPE-2). All other ABA triblock copolymers were synthesized accordingly.

The ROP of L,L-Lactid (LLA) using the organocatalyst 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) is described exemplarily for TPE-2 and was performed according to established literature procedures, applying minor changes.⁴⁴ The macroinitiator PCitroGEC and LLA were respectively dissolved in benzene and freeze-dried *in vacuo* to remove residual water. DBU was dried over CaH₂ before use. All chemicals were transferred into a glovebox (MBRAUN, UNILAB, < 0.1 ppm of O₂ and < 0.1 ppm of H₂O)

to perform the triblock copolymer synthesis. The macroinitiator (0.4148 g, 0.025 mmol, 1 eq.) and LLA (0.415 g, 2.88 mmol, 114.5 eq.) were dissolved in 1.66 mL dichloromethane (5.32 mL / 1 g LLA) in a screw cap vial. Subsequently, 0.45 mL of a DBU (0.01 mol% of LLA) stock solution (0.0001 mL / mL DCM) was added to initiate the polymerization. The solution was stirred for 50 min at room temperature (r.t.) and quenched by adding benzoic acid. The resulting triblock copolymer was precipitated three times in methanol and dried *in vacuo*. A viscous liquid was obtained in yields of 77%.



^1H NMR (400 MHz, CDCl_3): δ = 5.15 (q, 1H, o), 5.10 – 5.03 (m, 1H, j), 5.03 – 4.92 (m, 1H, b), 4.51 – 4.16 (m, 1H, a), 3.63 – 3.53 (m, 2H, c), 3.52 – 3.40 (m, 2H, d), 2.05 – 1.87 (m, 2H, i), 1.66 (s, 3H, k), 1.62 – 1.45 (m, 7H, p+l+f), 1.42 – 1.20 (m, 2H, e), 1.20 – 1.05 (m, 2H, h), 0.86 (d, 3H, g) ppm.

^{13}C NMR (75 MHz, CDCl_3): δ = 169.73 (R), 154.33 (Q), 131.25 (M), 124.84 (J), 74.47 (B), 70.25 (D), 69.11 (O), 68.46 (C), 66.15 (A), 37.33 (E), 36.48 (H), 29.58 (F), 25.84 (I), 25.53 (K), 19.63 (G), 17.77 (L), 16.75 (P) ppm.

M_n (SEC, DMF, PEG calibration) = 22 $\text{kg}\cdot\text{mol}^{-1}$; D (SEC, DMF, PEG calibration) = 1.34.

$T_{g,1}$: -50 $^{\circ}\text{C}$ (PCitroGEC) $T_{g,2}$: 46 $^{\circ}\text{C}$ (PLLA)

NMR Characterization of CitroGEC

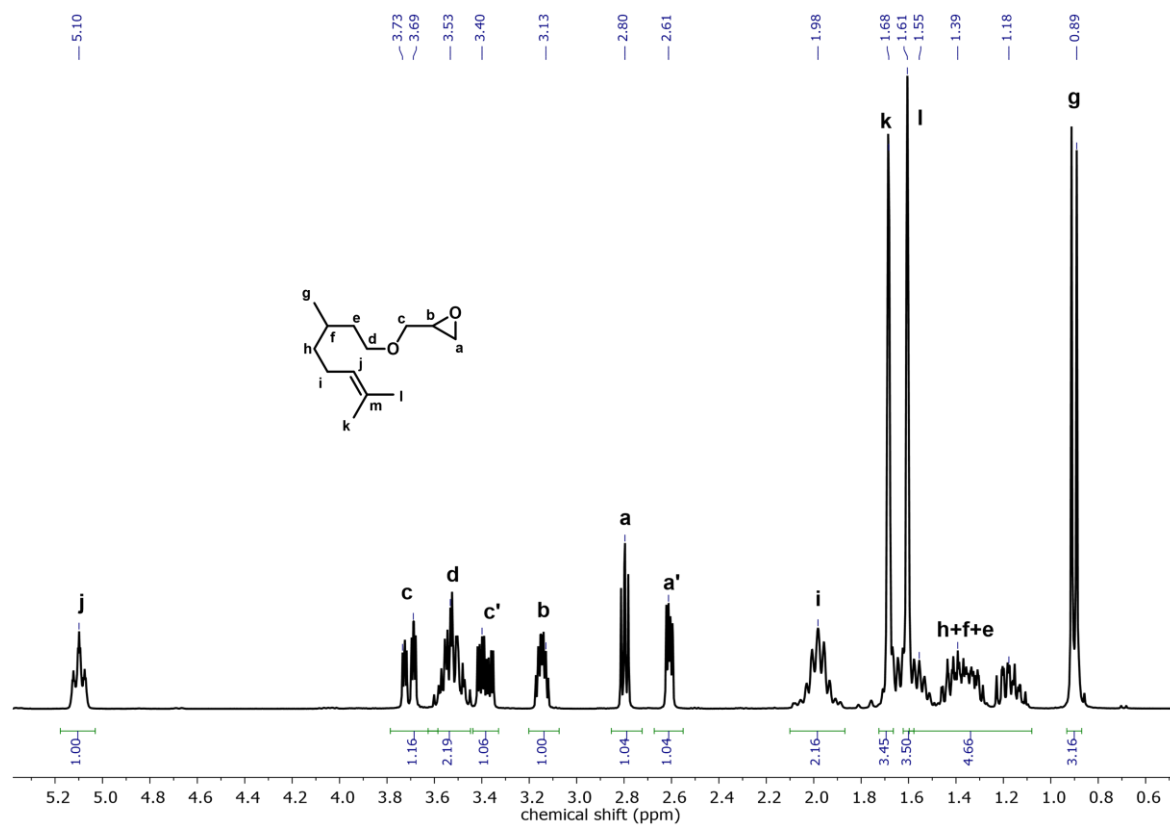


Figure S 1: ^1H NMR spectrum (300 MHz, CDCl_3) of CitroGE after distillation.

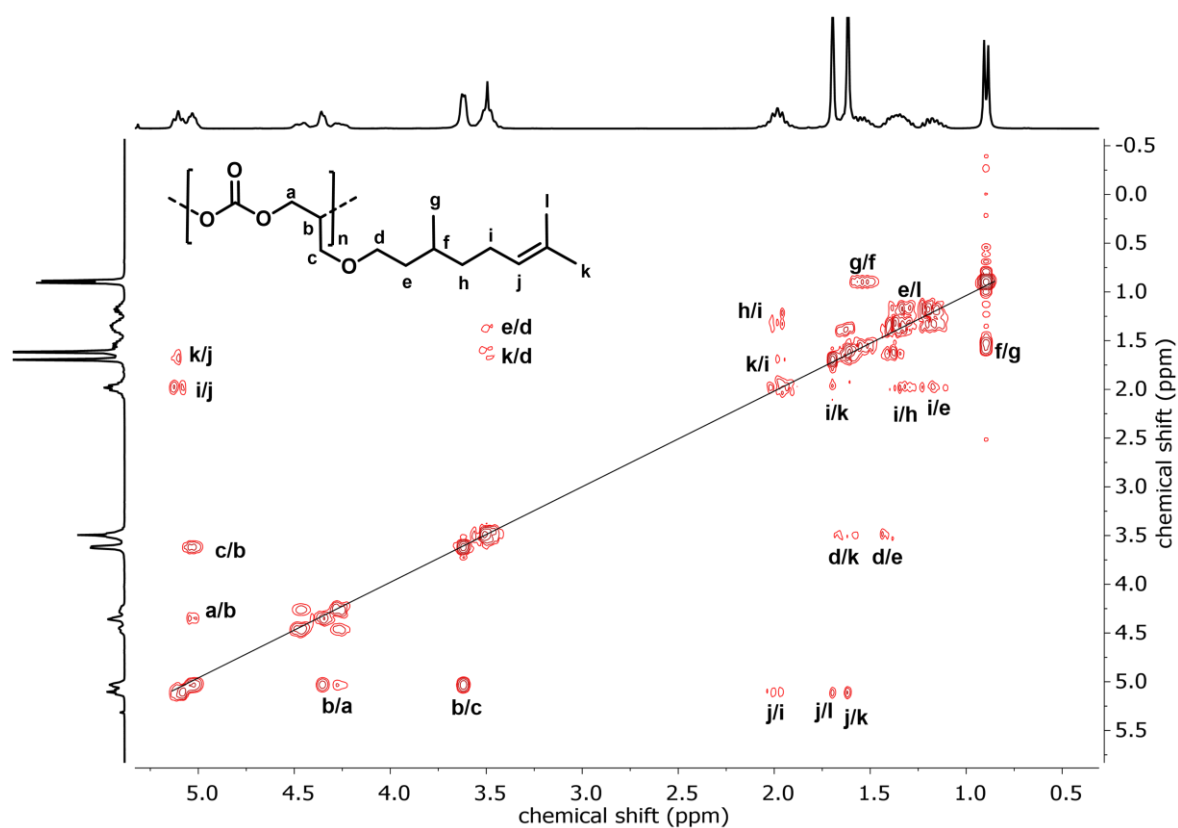


Figure S 4: ^1H - ^1H COSY NMR (300 MHz, CDCl_3) spectrum of PCitroGEC_{26K} homopolymer.

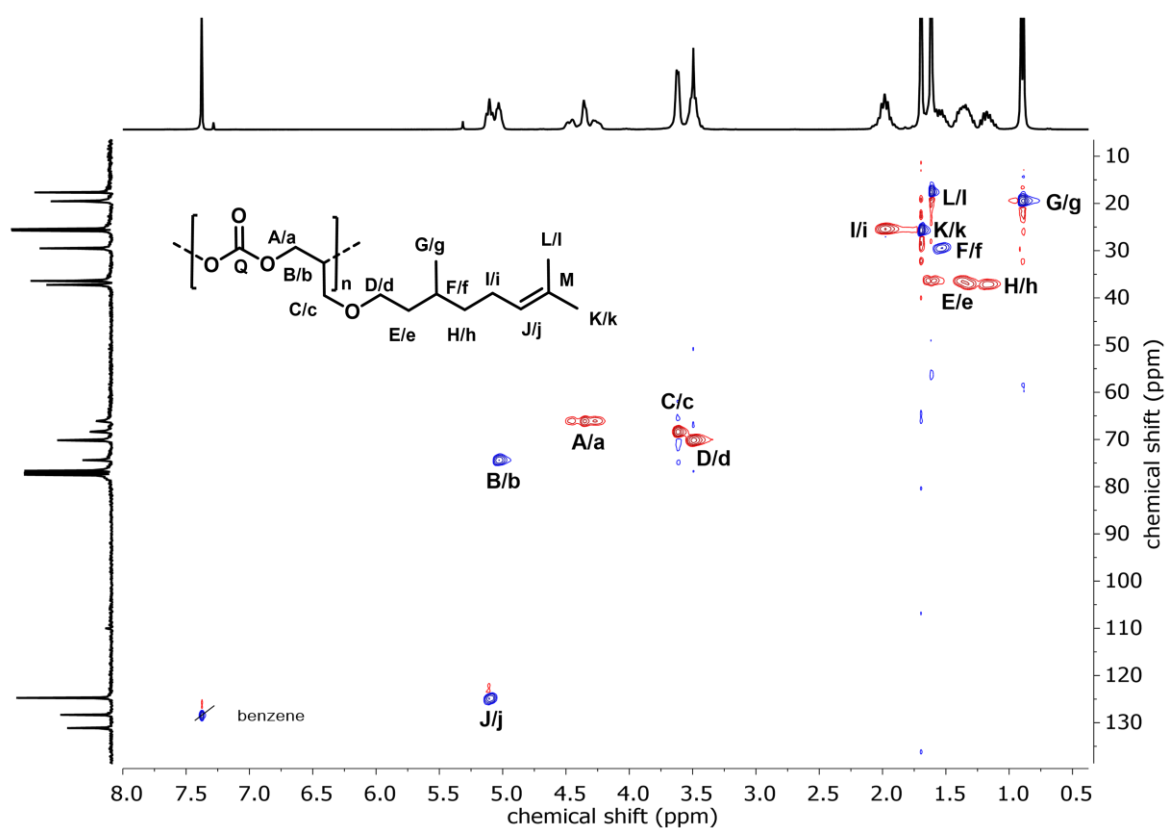


Figure S 5: ^1H - ^{13}C HSQC NMR spectrum (300 MHz/ ^1H , 75 MHz/ ^{13}C) of PCitroGEC_{26K}.

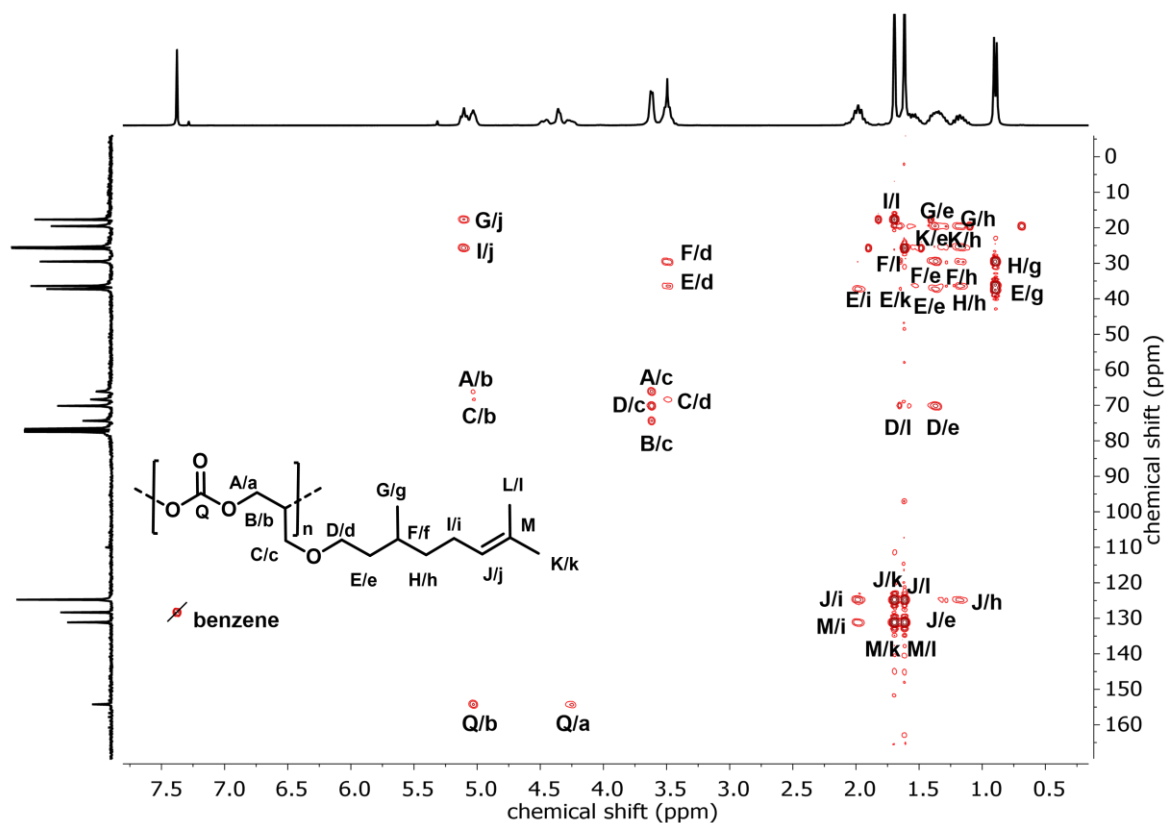


Figure S 6: ^1H - ^{13}C HMBC NMR spectrum (300 MHz/75 MHz, CDCl_3) of PCitroGEC_{26K}.

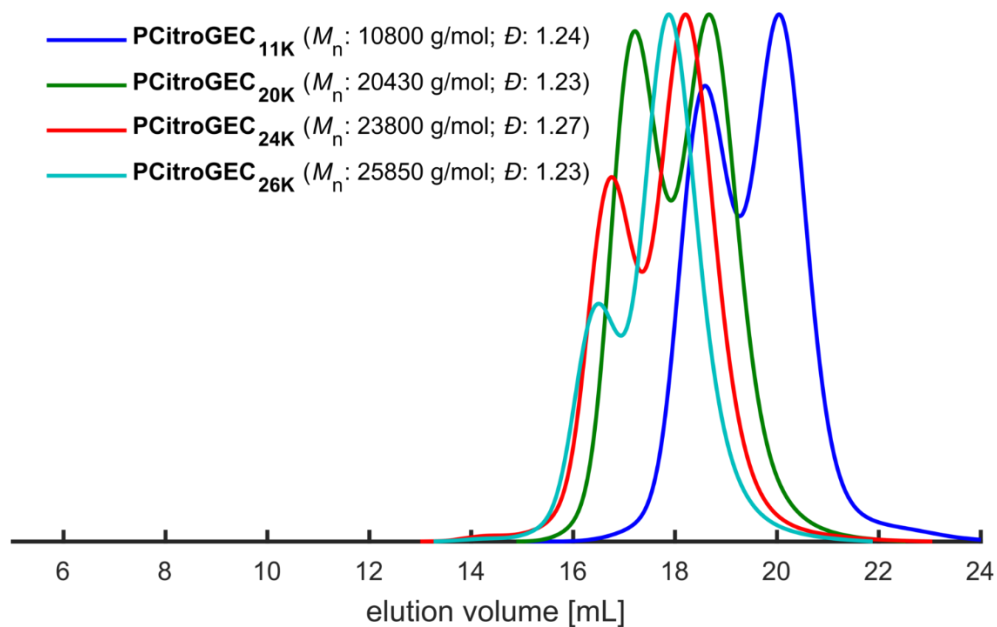


Figure S 7: SEC traces of the PCitroGEC macroinitiators (eluent: DMF, standard: PEG).

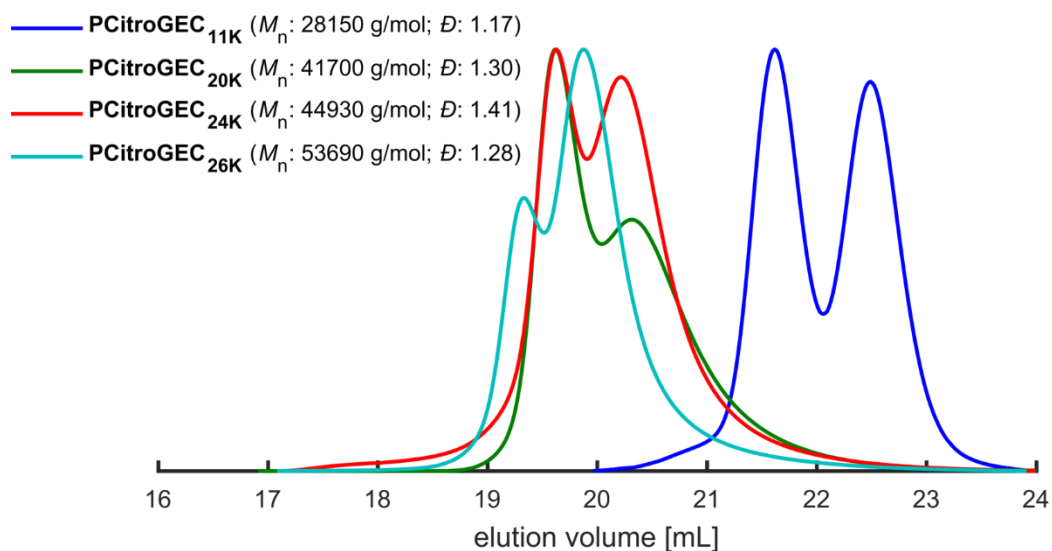


Figure S 8: SEC traces of PCitroGEC macroinitiators for TPE synthesis (eluent: THF, standard: PS).

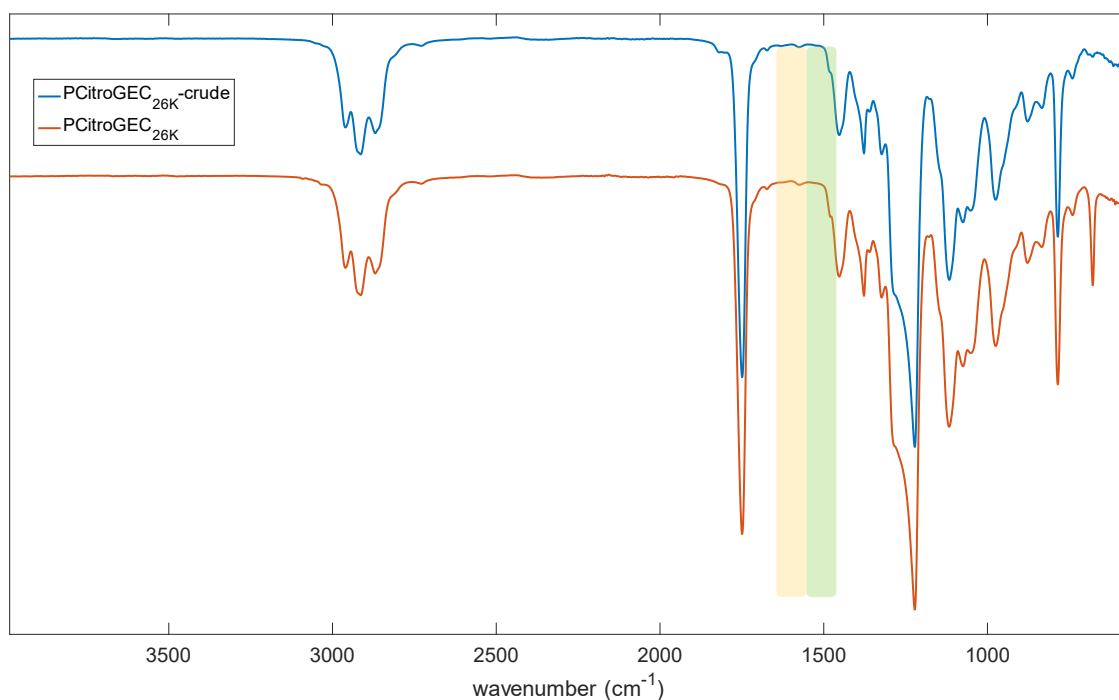


Figure S 9: IR spectra of PCitroGEC_{26K}: in blue is the crude product of the polymer illustrated showing the intensive band of the polycarbonate at 1749 cm⁻¹ (highlighted in green) and the weak band of the cyclic carbonates at 1800 cm⁻¹ (highlighted in yellow). In orange is the IR spectrum of PCitroGEC_{26K} after precipitation is shown. No band of cyclic carbonates is detectable here.

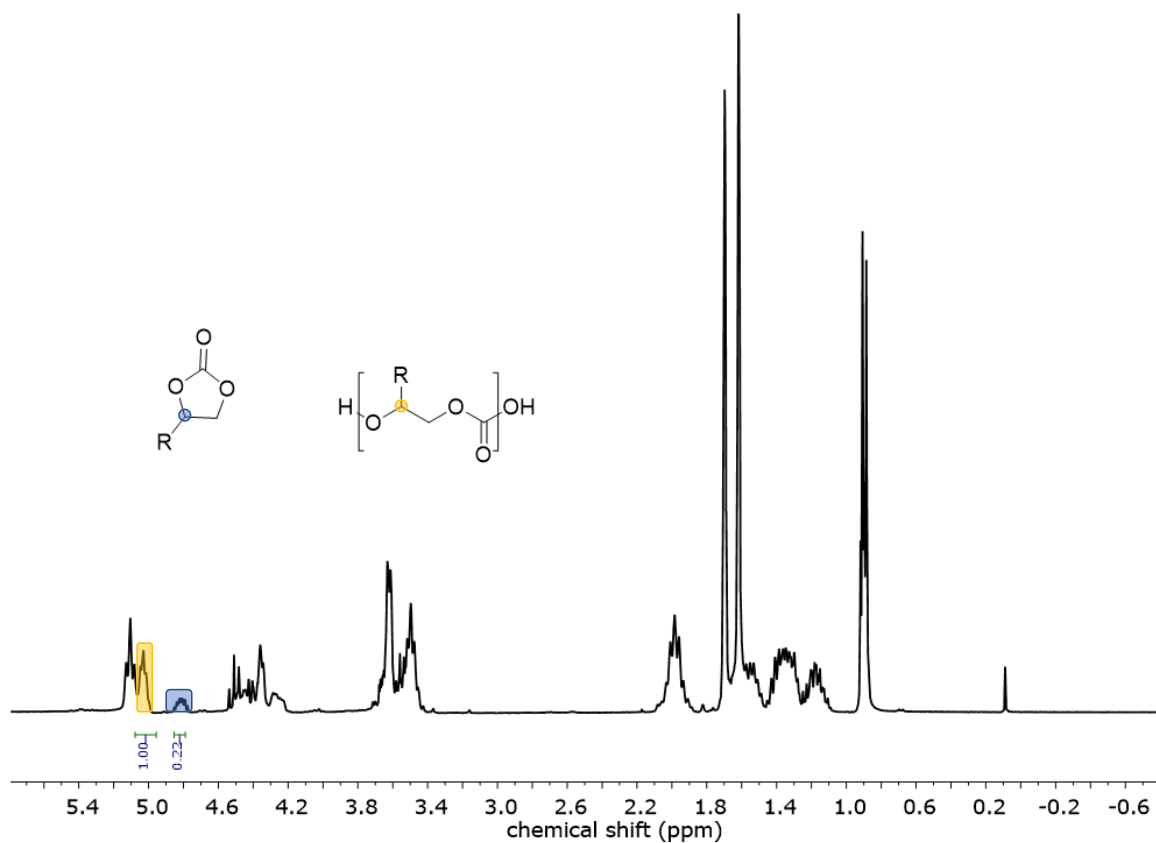


Figure S 10: ^1H NMR spectrum (300 MHz, CDCl_3) of the crude product of PCitroGEC_{11K}. The proton signal of the polycarbonate is marked in yellow, the proton of the cyclic carbonate is illustrated in blue. Using these integrals of the signals, the molar fraction of cyclic carbonates was calculated.

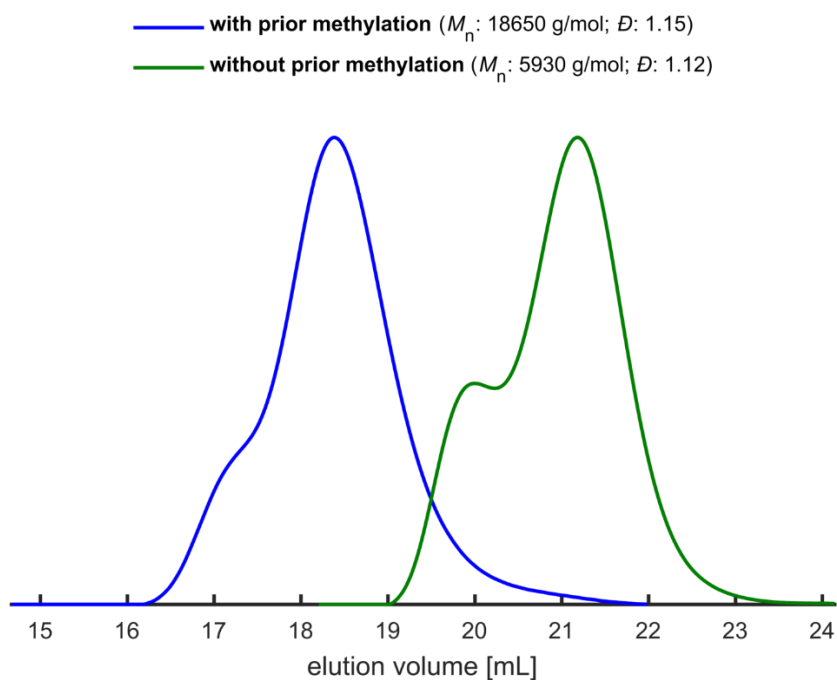


Figure S 11: SEC traces of PCitroGEC using 0.2 mol% of the catalyst without prior methylation of CitroGEC (green) and with prior methylation of CitroGEC (blue) (eluent: DMF, standard: PEG).

To prove the substitution of the initiating chloride species by a hydroxide ion, we conducted preparative SEC after the polymer work up. A model PCitroGEC_{18K,DMF} homopolymer was fractionated and analyzed via MALDI-ToF analysis. The end group analysis in Figure S 12 not only confirms the hydroxyl end groups for the high molar mass peak (yellow arrows), but also for the lower molar mass peak (orange arrows). An additional MALDI-ToF spectrum of fraction 6 (Figure S 13), solely containing the lower molar mass homopolymer, further supports the above findings.²

Table S 1: Model PCitroGEC_{18K,DMF} homopolymer used for preparative SEC and subsequent MALDI-ToF analysis.

Entry	Sample ^a	Catalyst (mol%)	Conversion ^b (%)	CC ^{b,c} (%)	M_n^d (kg·mol ⁻¹)	$\bar{D}^d$
1	PCitroGEC _{18K,DMF}	0.6	97	1	4600	1.09

^aCitroGEC was not pretreated with MeI/NaH. ^bCalculated using ¹H NMR spectroscopy. ^cCC illustrates the cyclic carbonates content. ^dDetermined via SEC using DMF as eluent and PEG as standard.

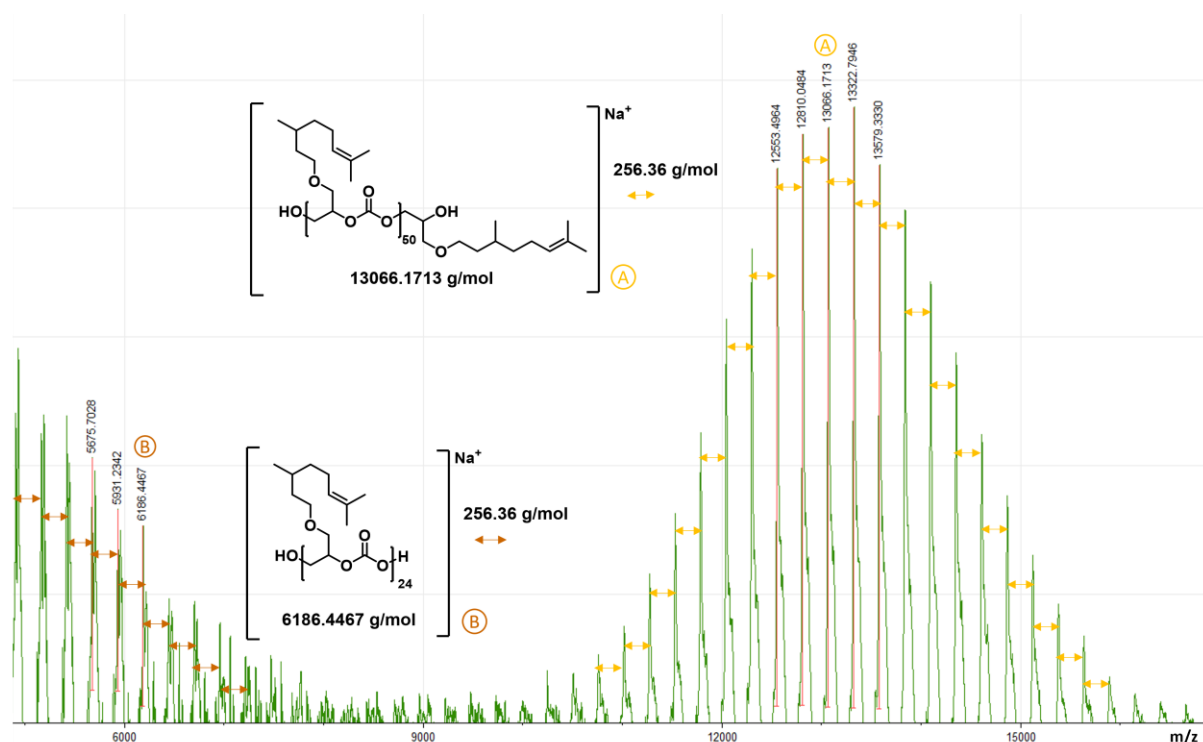


Figure S 12: MALDI-ToF MS of PCitroGEC₁₈ (DCTB, NaTFA), reflecting the high molar mass distribution of the fractionated sample. Figure adopted and altered with permission.²

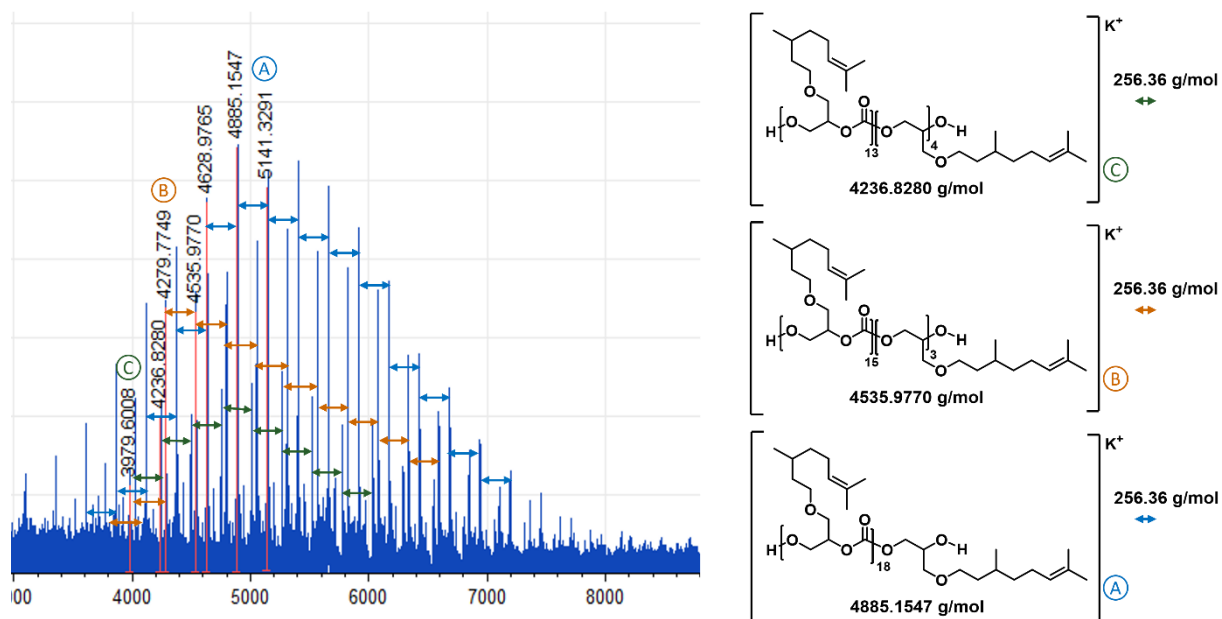


Figure S 13: MALDI-ToF spectrum of fraction 6 of PCitroGEC₁₈, proving the hydroxyl-functionality for the low molar mass distribution. Figure adopted and altered with permission.²

Characterization of PLLA-*b*-PCitroGEC-*b*-PLLA Triblock Copolymers

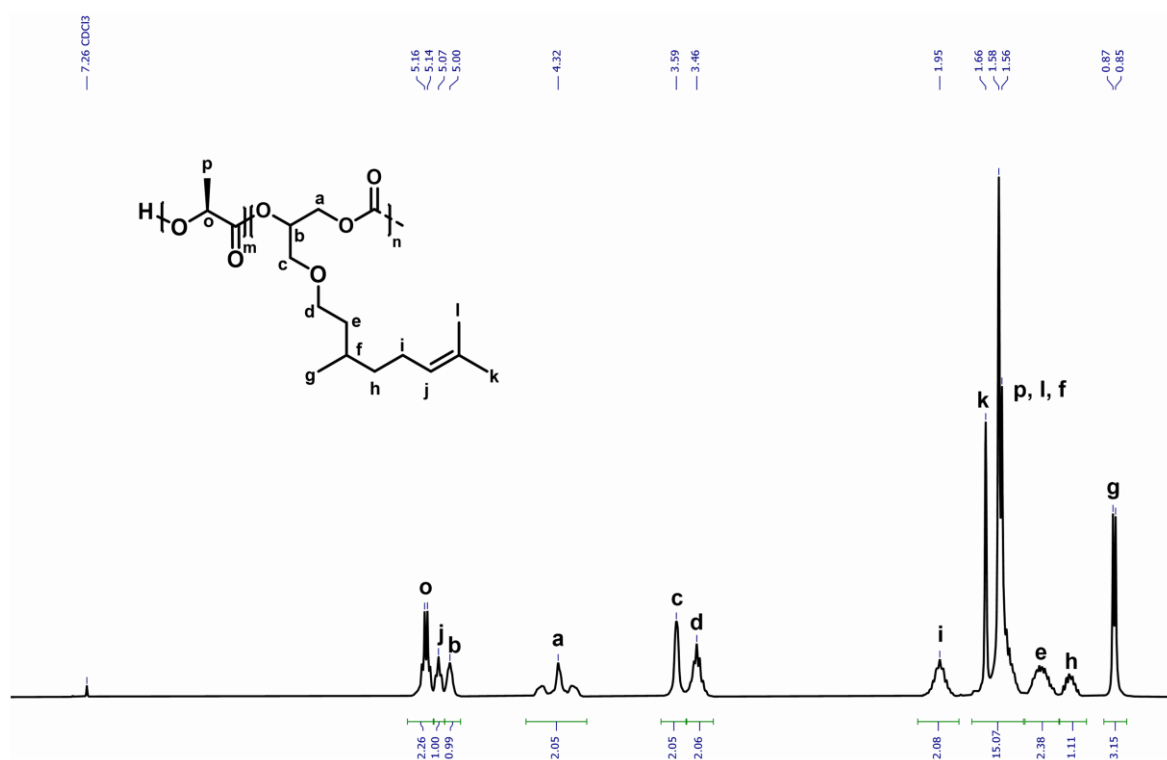


Figure S 14: ^1H NMR spectrum (400 MHz, CDCl_3) of PLLA_{0.35}-*b*-PCitroGEC_{0.31}-*b*-PLLA_{0.35} (TPE-2).

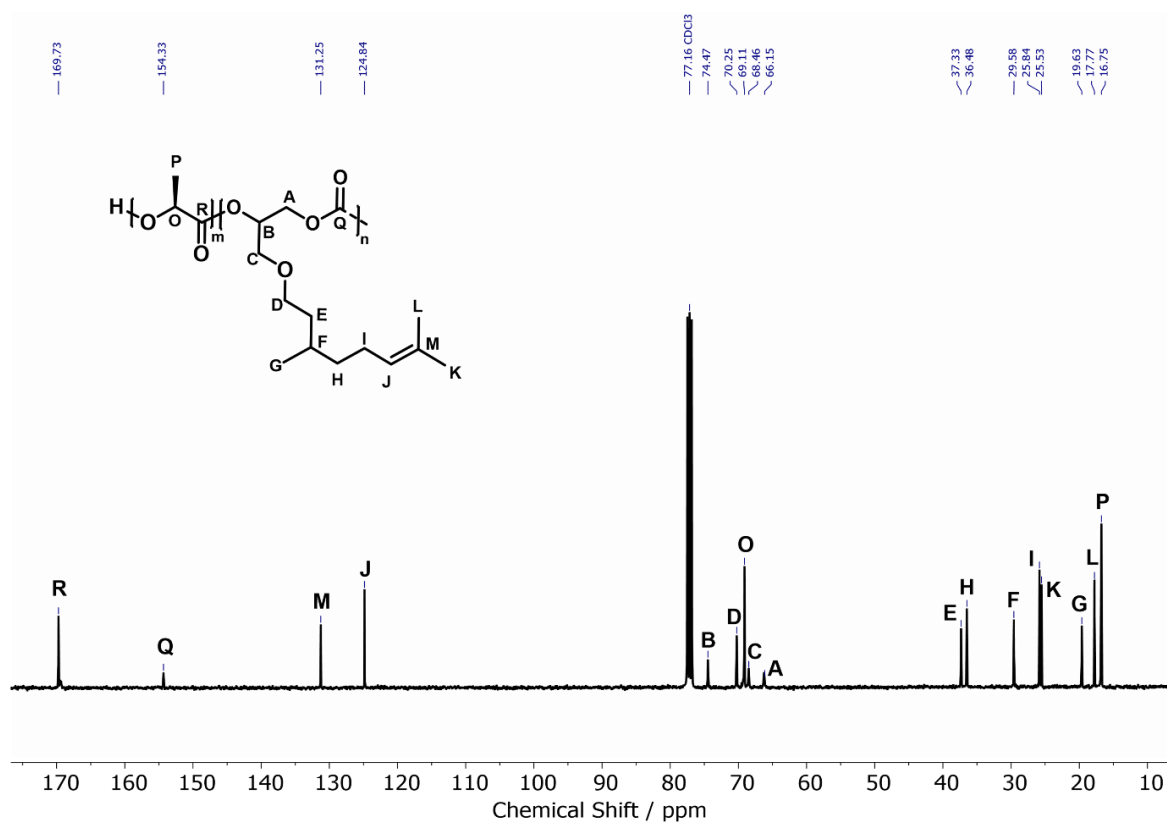
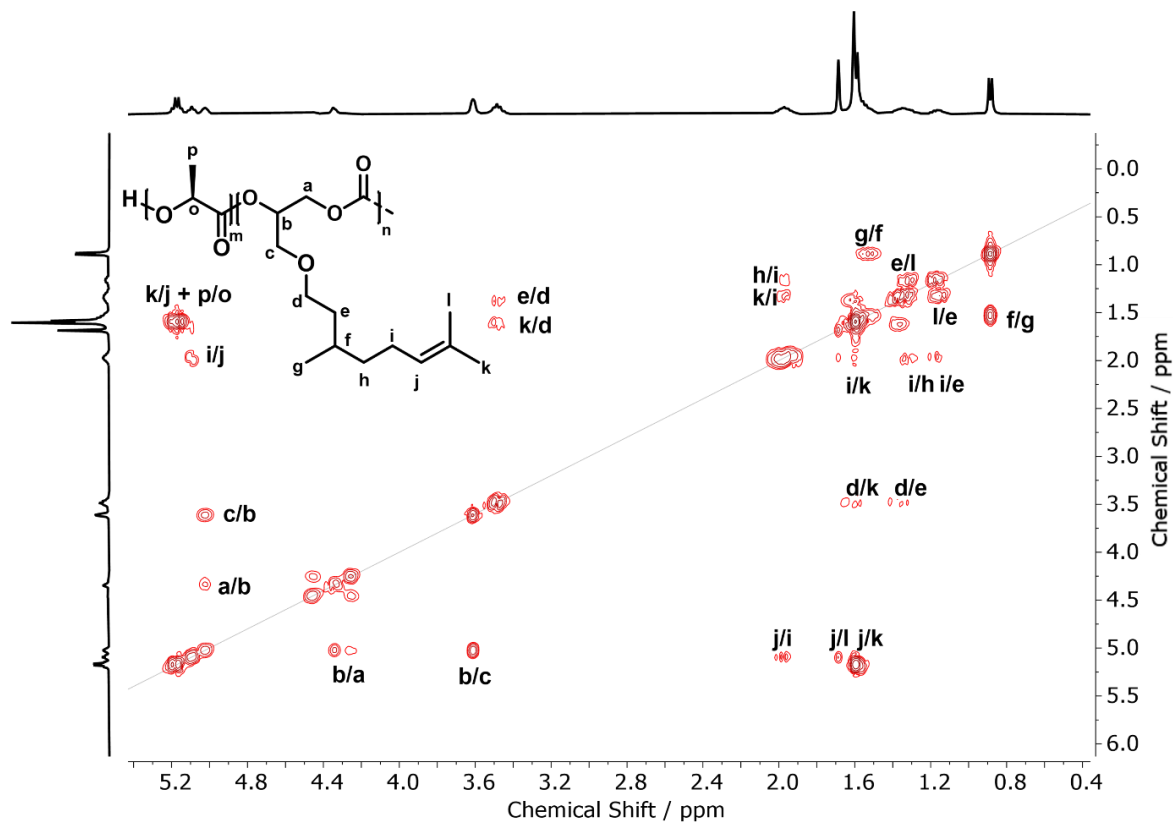
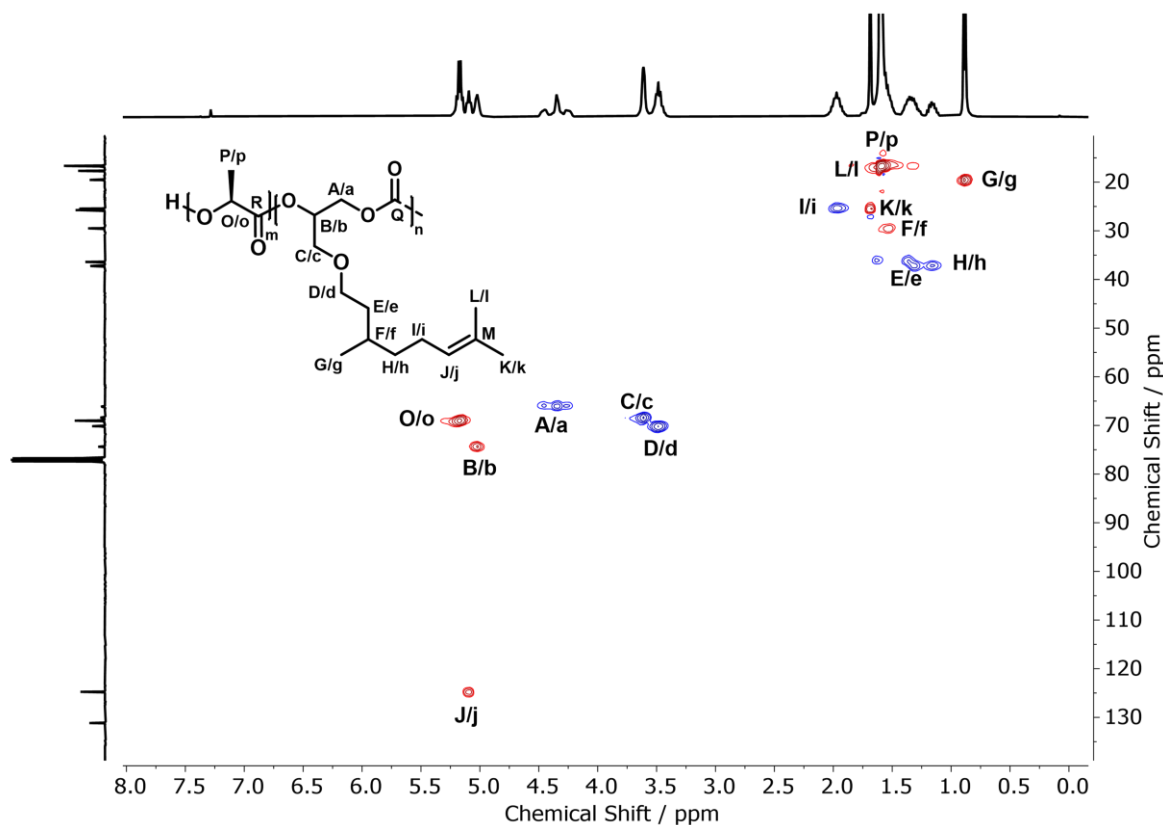


Figure S 15: ^{13}C NMR spectrum (75 MHz, CDCl_3) of $\text{PLLA}_{0.35}\text{-}b\text{-PCitroGEC}_{0.31}\text{-}b\text{-PLLA}_{0.35}$ (TPE-2).Figure S 16: $^1\text{H}\text{-}^1\text{H}$ COSY NMR spectrum (400 MHz, CDCl_3) of $\text{PLLA}_{0.35}\text{-}b\text{-PCitroGEC}_{0.31}\text{-}b\text{-PLLA}_{0.35}$ (TPE-2).Figure S 17: $^1\text{H}\text{-}^{13}\text{C}$ HSQC NMR spectrum (400 MHz/75 MHz, CDCl_3) of $\text{PLLA}_{0.35}\text{-}b\text{-PCitroGEC}_{0.31}\text{-}b\text{-PLLA}_{0.35}$ (TPE-2).

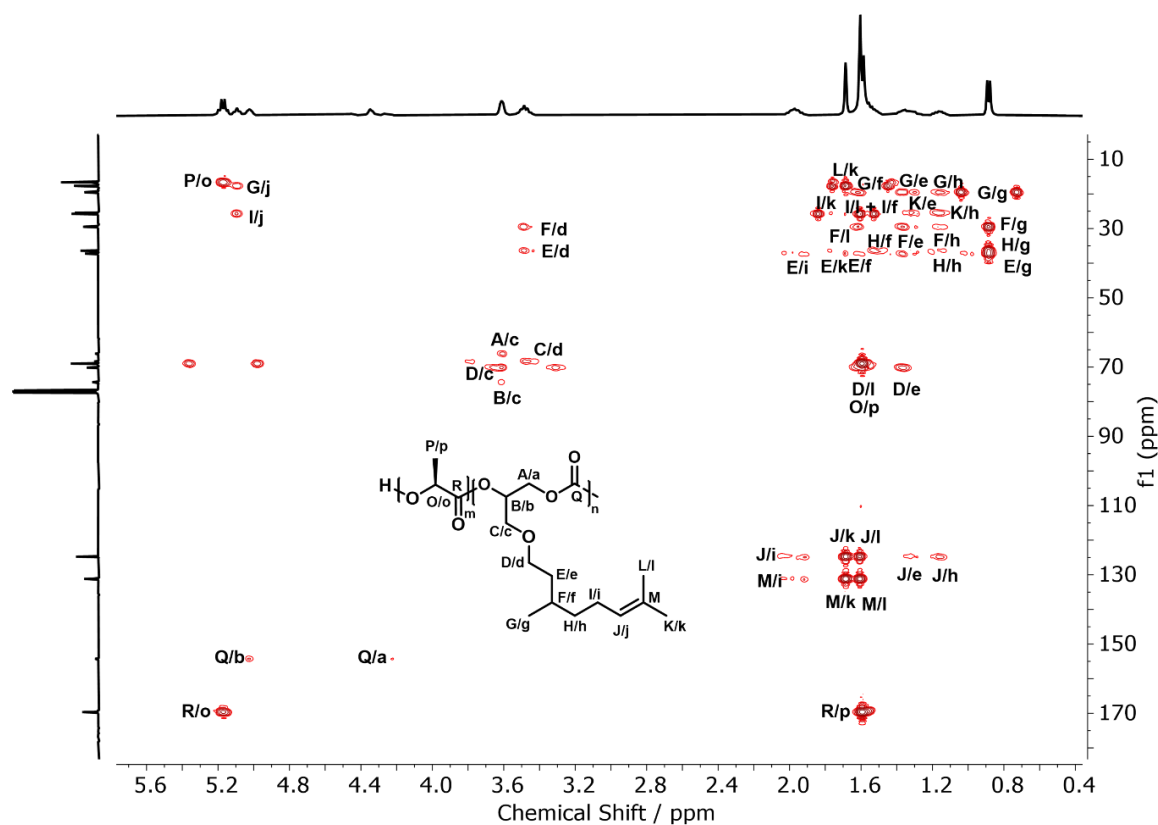


Figure S 18: ^1H - ^{13}C HMBC NMR spectrum (400 MHz/75 MHz, CDCl_3) of $\text{PLLA}_{0.35}\text{-}b\text{-PCitroGEC}_{0.31}\text{-}b\text{-PLLA}_{0.35}$ (TPE-2).

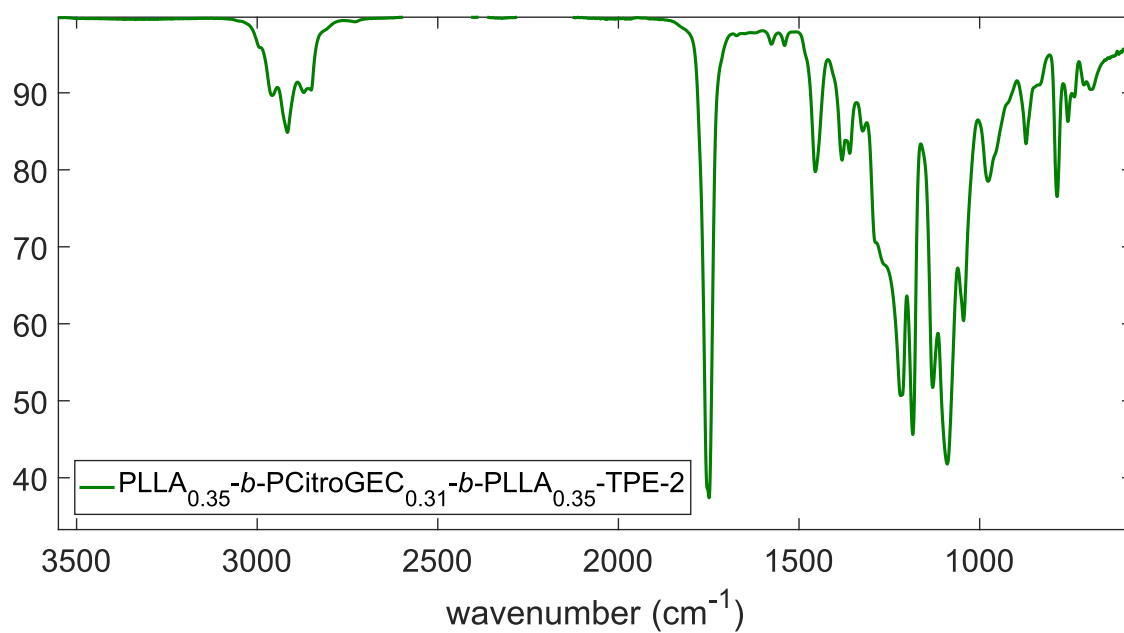


Figure S 19: IR spectrum of $\text{PLLA}_{0.35}\text{-}b\text{-PCitroGEC}_{0.31}\text{-}b\text{-PLLA}_{0.35}$ (TPE-2).

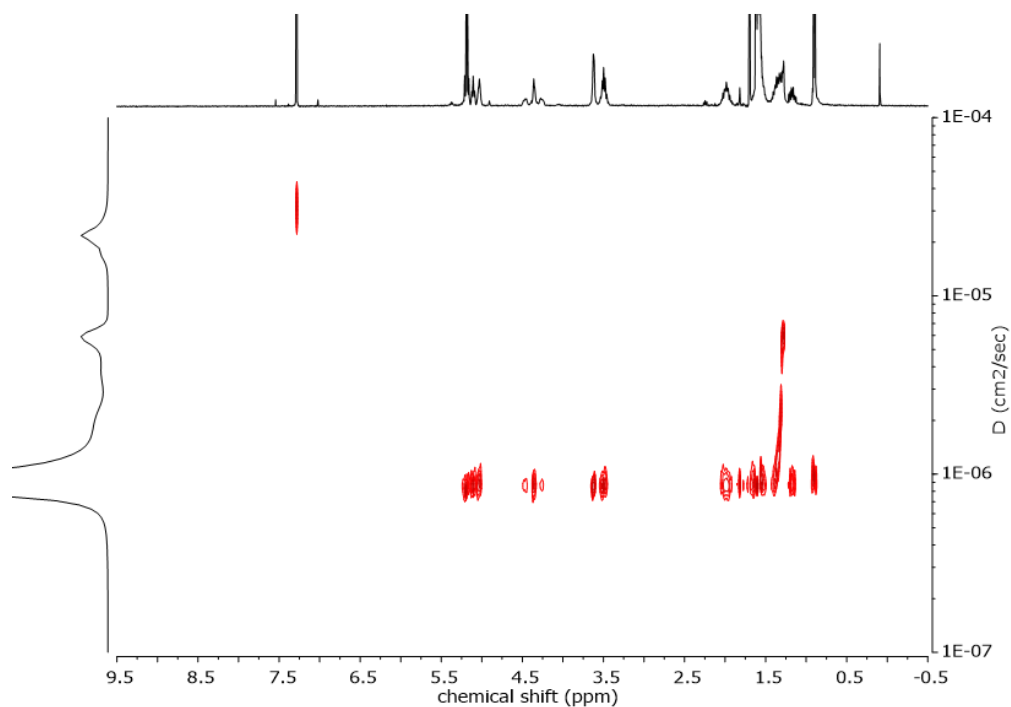


Figure S 20: DOSY NMR spectrum (400 MHz/75 MHz, CDCl_3) of P PLLA_{0.35}-*b*-PCitroGEC_{0.31}-*b*-PLLA_{0.35} (TPE-2). The signal at 7.2 ppm with a higher diffusion coefficient belongs to the CDCl_3 solvent. The other signals at 1.45 ppm feature a higher diffusion coefficient and can be attributed to solvent impurities.

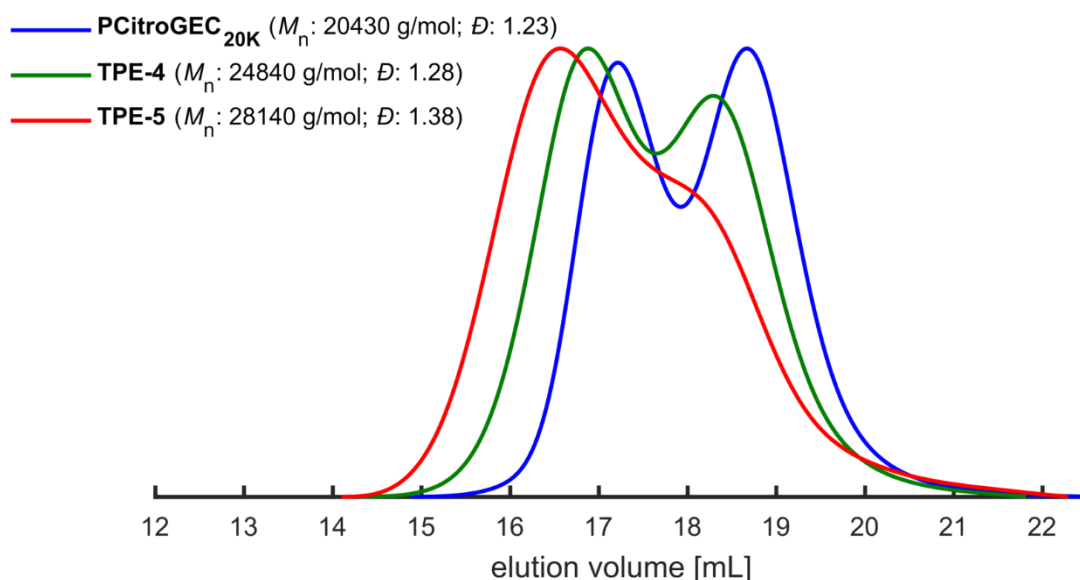


Figure S 21: SEC traces of the ABA triblock copolymers (eluent: DMF, standard: PEG) derived from PCitroGEC_{20K}. All triblock copolymers are presented together with their initial PCitroGEC macroinitiator to highlight the shift to higher molar masses.

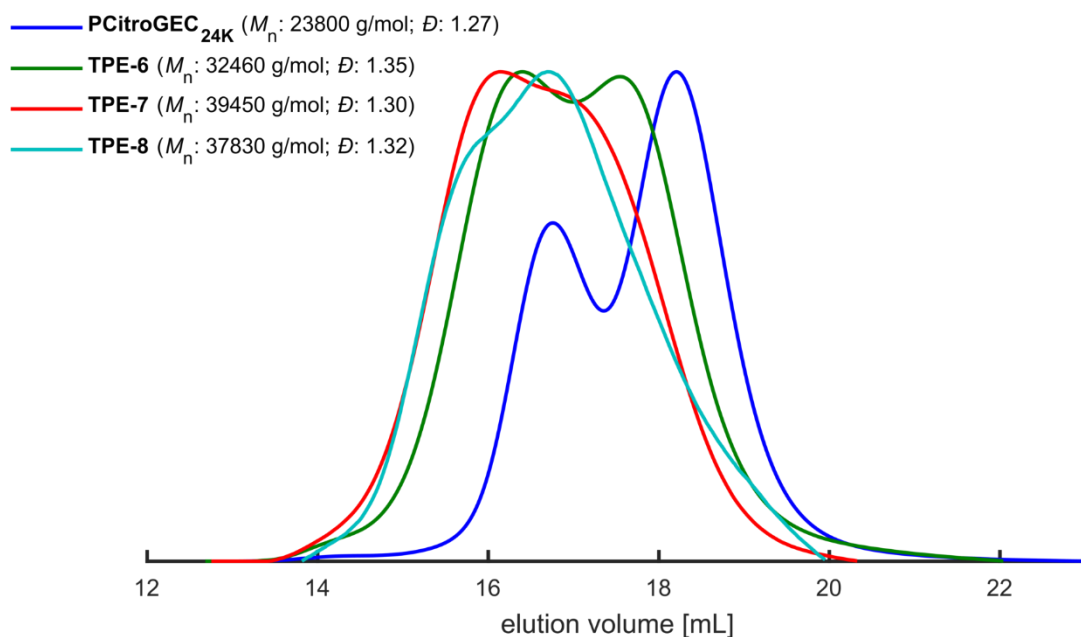


Figure S 22: SEC traces of the ABA triblock copolymers (eluent: DMF, standard: PEG) derived from PCitroGEC_{24K}. All triblock copolymers are presented together with their initial PCitroGEC macroinitiator to highlight the shift to higher molar masses.

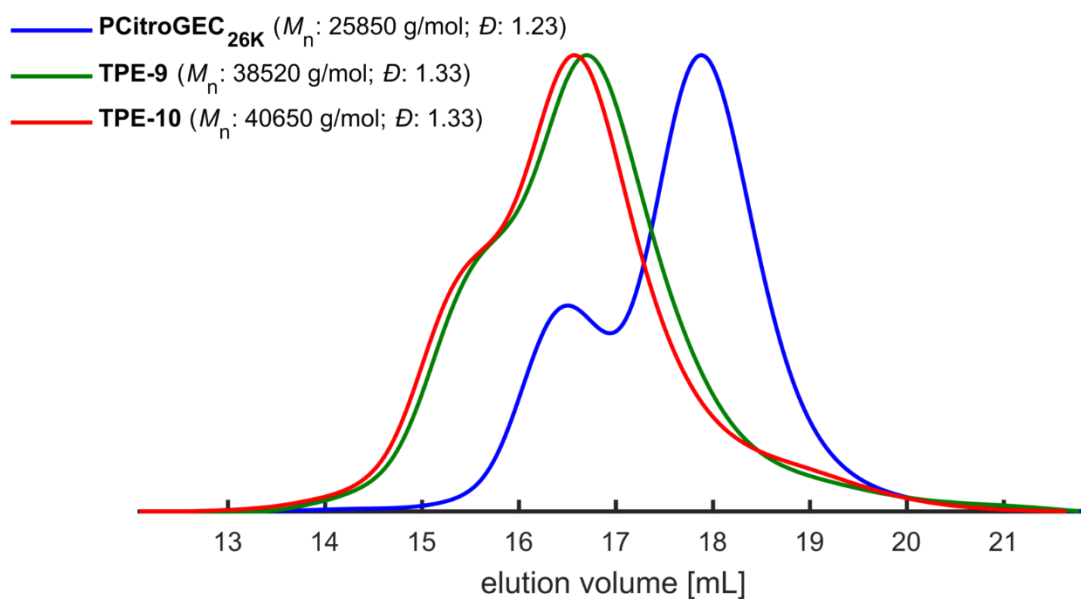


Figure S 23: SEC traces of the ABA triblock copolymers (eluent: DMF, standard: PEG) derived from PCitroGEC_{16K}. All triblock copolymers are presented together with their initial PCitroGEC macroinitiator to highlight the shift to higher molar masses.

Absolute M_w of PCitroGEC via SEC-Multi-Angle Light Scattering Analysis (SEC-MALS)

For the determination of the absolute weight average molecular weight (M_w), PCitroGEC homopolymers were evaluated via SEC-MALS (Table 1).

The data was recorded and processed by WinGPC UniChrom (PSS GmbH). The setup was normalized with reference material poly(styrene) #ps2088 (M_w 87600Da, PSS GmbH). According to an approach by Lavric et al., true molar mass evaluation without knowledge of the dn/dc of the polymer is feasible. This SEC-MALS calibration approach shows that only an arbitrary reference polymer is required to determine the absolute mass of a polymer (Figure S 24). Hence, evaluation of the M_w of the samples was completed with a Zimm plot with linear fit function and via method “factor*concentration” as concentration determination method.³ For calculation of the M_w , the higher molar mass fractions of the partially crosslinked (due to inadequate storage) products PCitroGEC_{24K} and PCitroGEC_{26K} were not taken into account. The integration limits used are shown in Figure S 24.

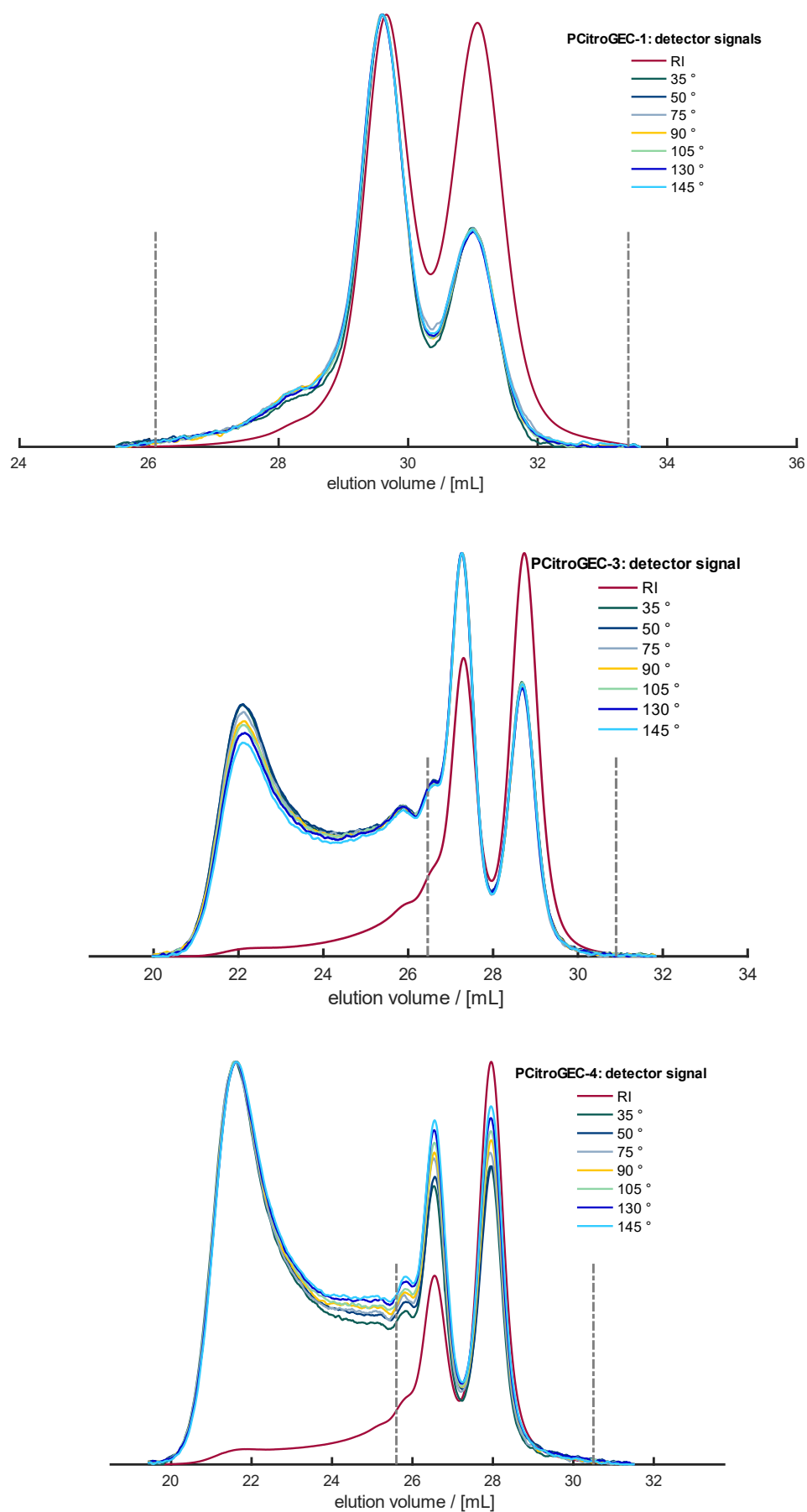


Figure S 24: SEC-MALS traces (RI and seven MALS traces) of PCitroGEC_{11K}, PCitroGEC_{24K} and PCitroGEC_{26K} (top to bottom) including integration limits for determination of absolute molar mass (dashed grey lines).

Thermal Characterization

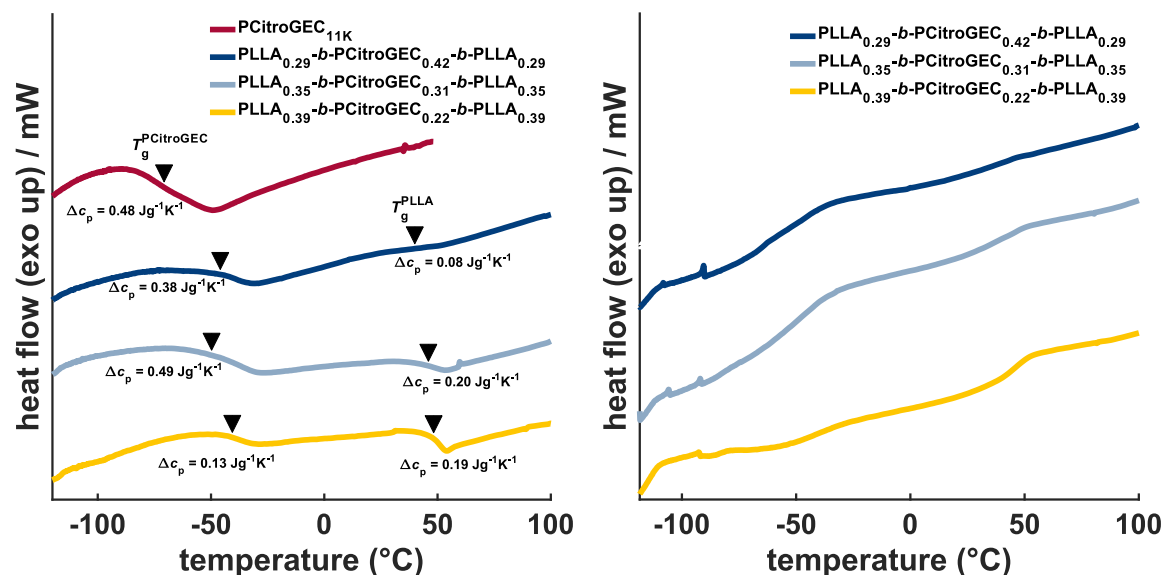


Figure S 25: DSC measurements of PCitroGEC_{11K} macroinitiator and the corresponding triblock copolymers in a temperature range of -130 to 100 °C. Left thermograms represent the second heating cycles at a rate of 10 K·min⁻¹. The second cooling cycles are shown on the right, demonstrating the absence of PLLA recrystallization. Arrows indicate the respective glass transition temperature.

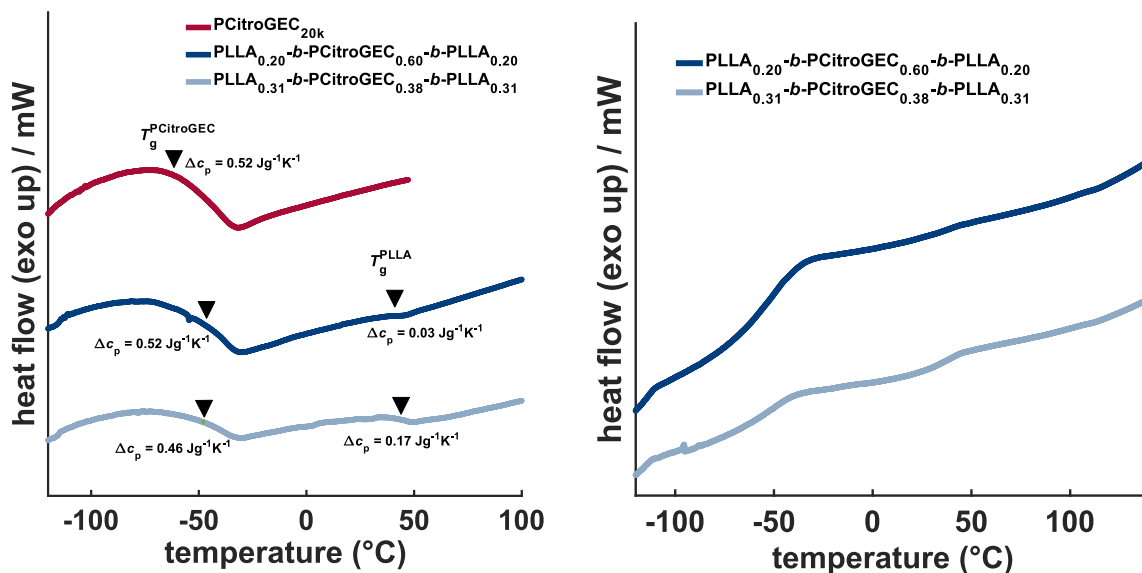


Figure S 26: DSC measurements of PCitroGEC_{20K} macroinitiator and the corresponding triblock copolymers in a temperature range of -130 to 100 °C. Left thermograms represent the second heating cycles at a rate of 10 K·min⁻¹. The second cooling cycles are shown on the right, demonstrating the absence of PLLA recrystallization. Arrows indicate the respective glass transition temperature.

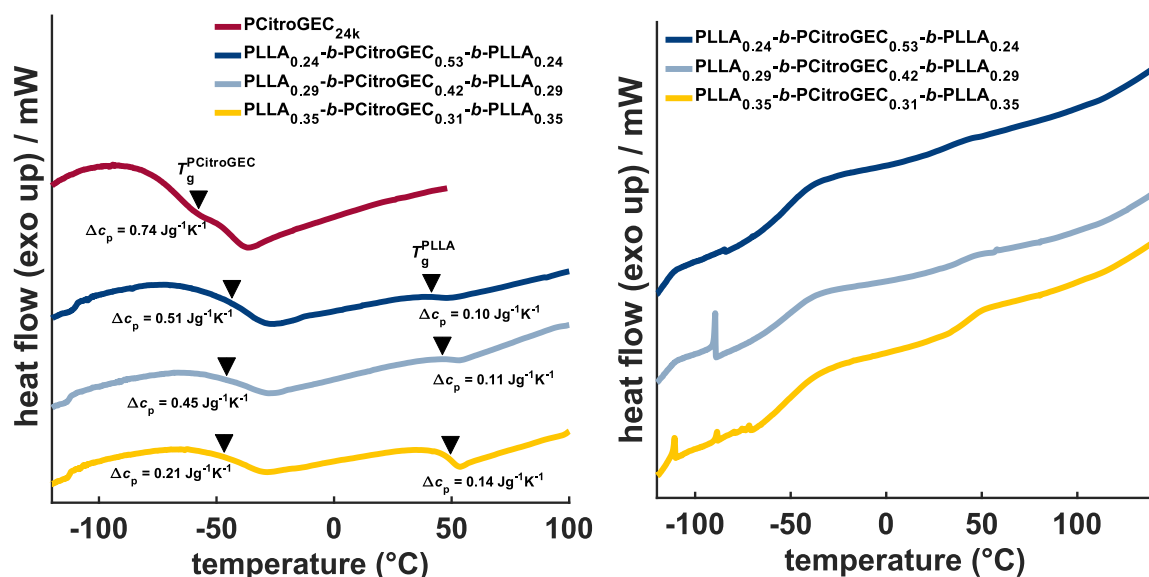


Figure S 27: DSC measurements of PCitroGEC_{24K} macroinitiator and the corresponding triblock copolymers in a temperature range of -130 to 100 °C. Left thermograms represent the second heating cycles at a rate of 10 K·min⁻¹. The second cooling cycles are shown on the right, showing no PLLA recrystallization. Arrows indicate the respective glass transition temperature.

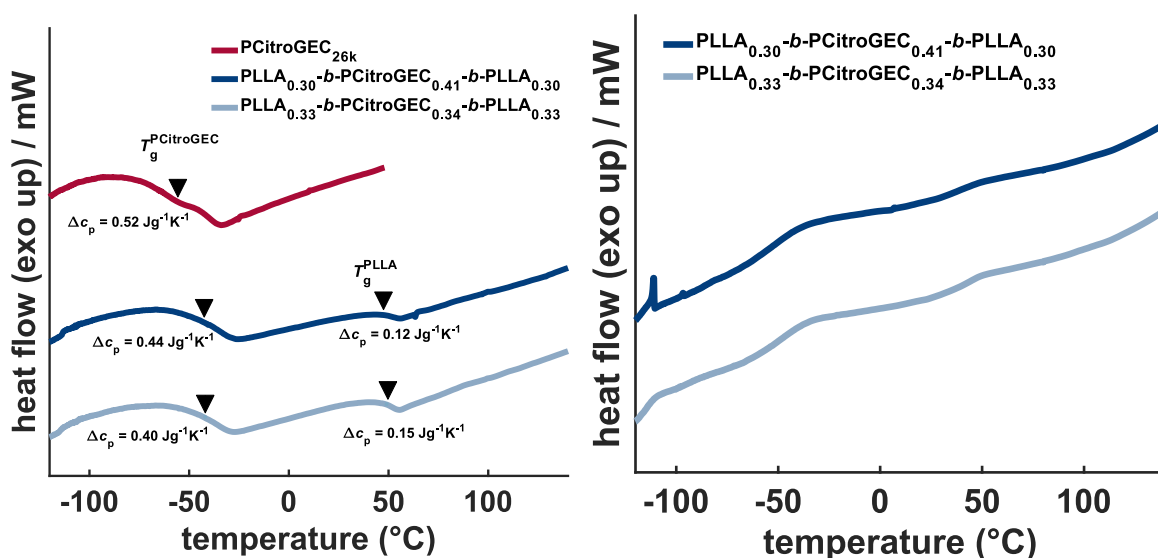


Figure S 28: DSC measurements of PCitroGEC_{26K} macroinitiator and the corresponding triblock copolymers in a temperature range of -130 to 100 °C. Left thermograms represent the second heating cycles at a rate of 10 K·min⁻¹. The second cooling cycles are shown on the right, demonstrating the absence of PLLA recrystallization. Arrows indicate the respective glass transition temperature.

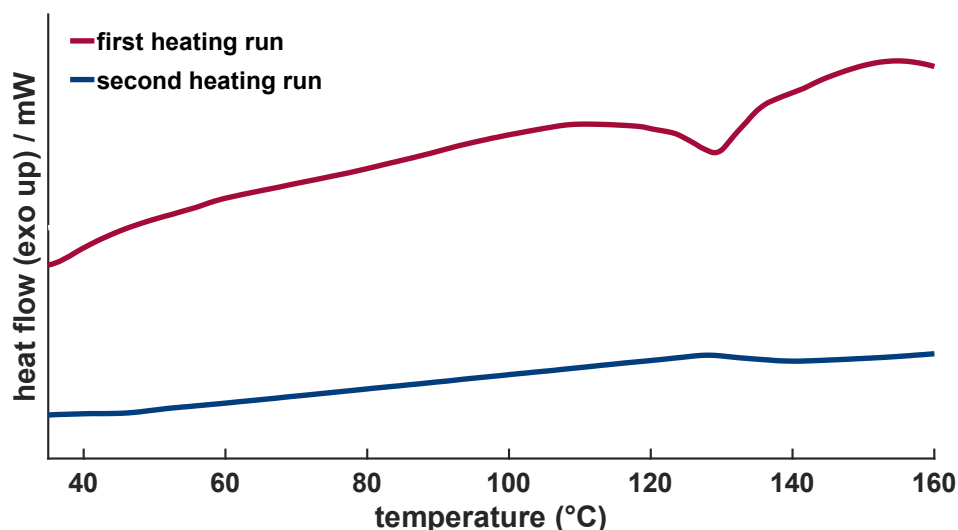


Figure S 29: Thermograms of the first and the second heating cycle of TPE-4. The first heating cycle (red) shows a melting peak T_m of 129 °C (402 K), whereas no melting peak is observed in the second heating cycle (blue). The heating rate corresponds to 10 K·min⁻¹.

Table S 2: Values of melting temperature and enthalpy as well as calculated PLLA crystallinity from the first heating run of TPE-4.

Sample	$M_{n, total}^a$ (kg · mol ⁻¹)	f_{PLLA}^b	$M_{n, PLLA}^{a,b}$ (kg · mol ⁻¹)	w_{PLLA} (%)	T_m^c (K)	ΔH_{PLLA}^c (J · g ⁻¹)	$X_{c, PLLA}^d$ (%)
TPE-4	25	0.4	10	0.4	402	3.7	10

^aDetermined via SEC using DMF as an eluent and PEG as standard. ^bDetermined by ¹H NMR spectroscopy. ^cDetermined by DSC with a heating rate of 10 K·min⁻¹. ^dCalculated by $X_{c, PLLA} = \frac{1}{w_{PLLA}} \frac{\Delta H_{PLLA}}{\Delta H_{0, PLLA}}$; ⁴ $\Delta H_{0, PLLA} = 93.1 \text{ J} \cdot \text{g}^{-1}$ for 100% crystalline PLLA homopolymer.⁵

Morphology

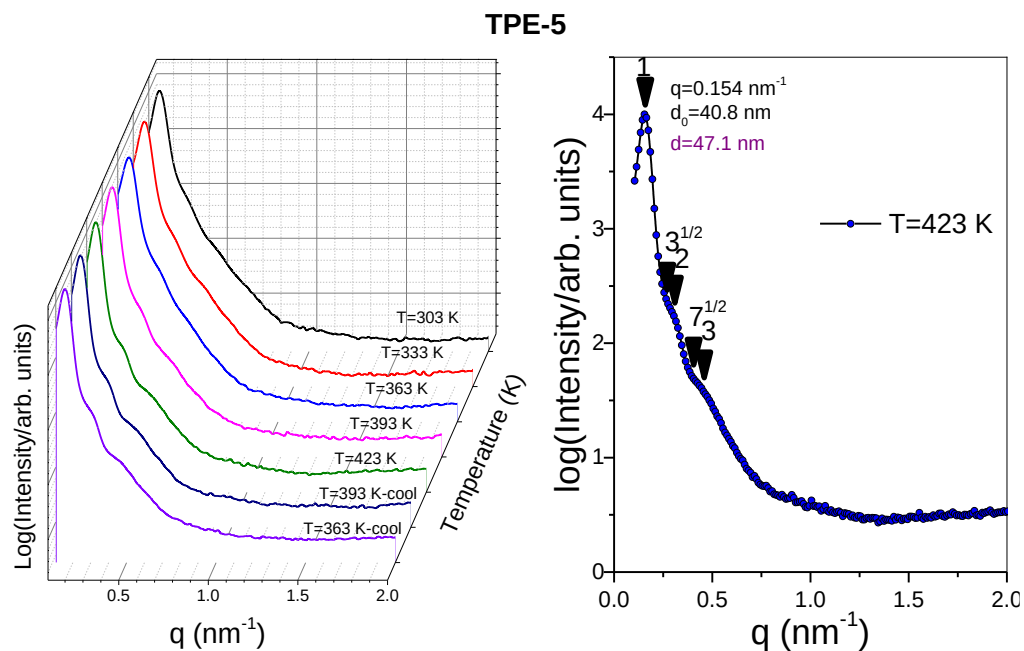


Figure S 30: (a) Variable temperature SAXS patterns for TPE-5 obtained on heating and subsequent cooling. (b) Bragg peaks at $T = 423$ K indicate the formation of cylinders (CYL) in the absence of long-range order.

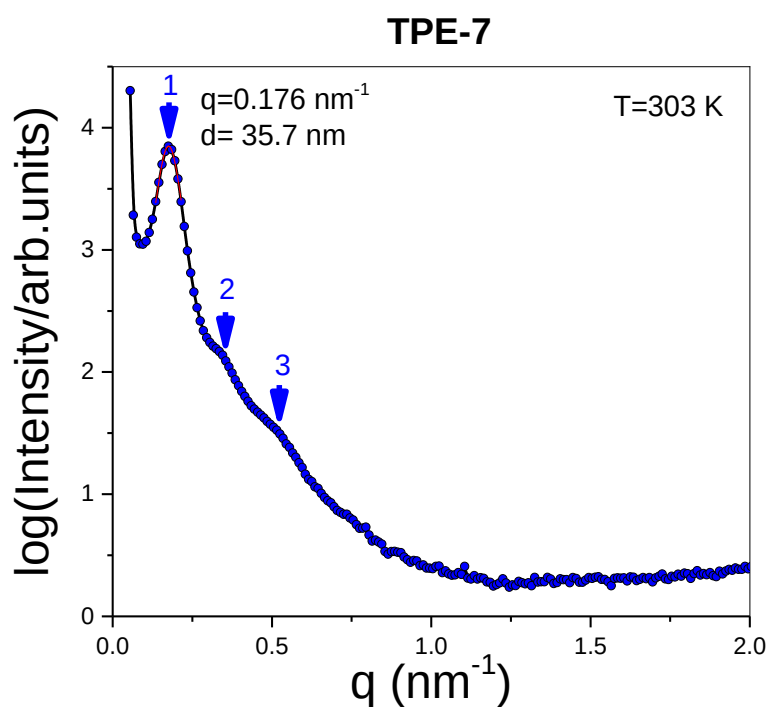


Figure S 31: SAXS pattern of TPE-7 at 303 K and Bragg peaks associated with a LAM morphology.

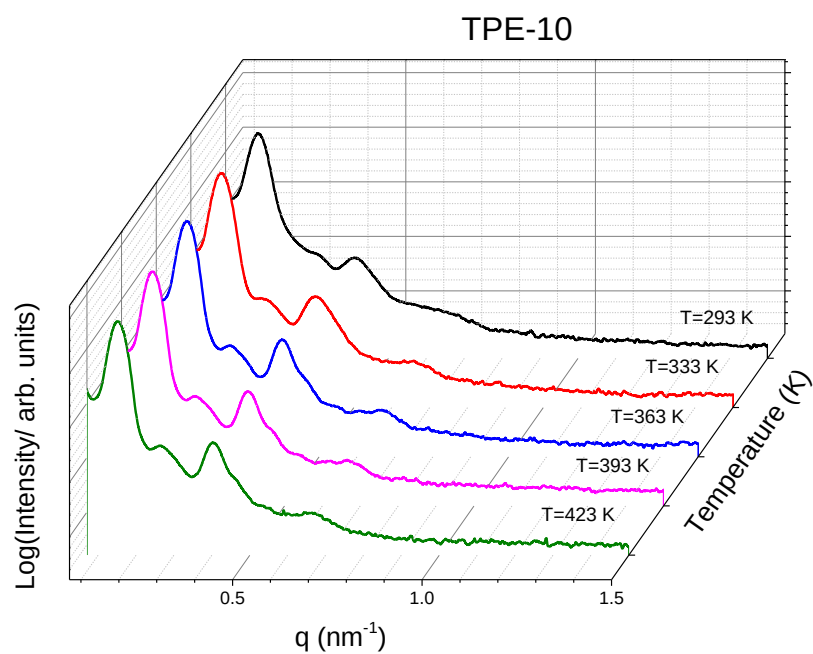


Figure S 32: Heating above the T_g of the PLLA block improves order in TPE-10.

Mechanical Characterization

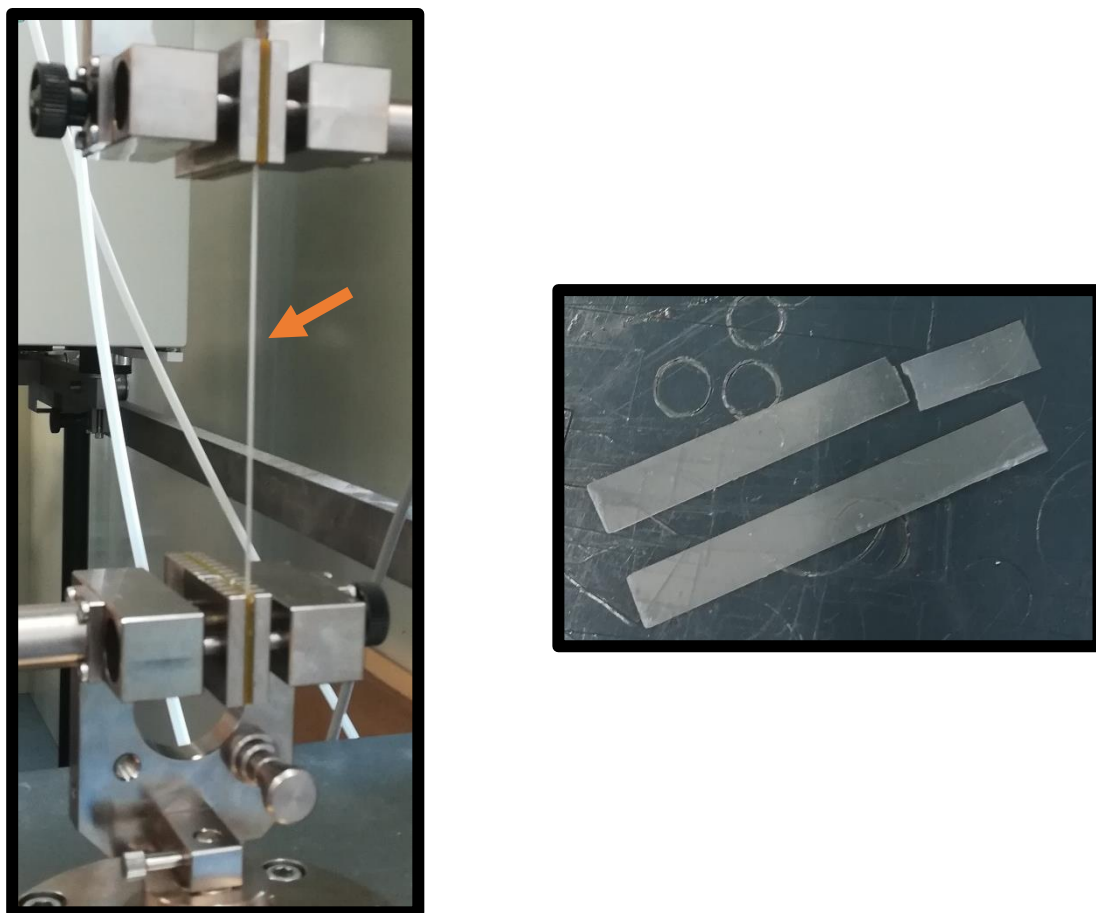


Figure S 33: Image of the strained film of TPE-1 (left); strained (torn) and the unstrained film of TPE-1 (right).

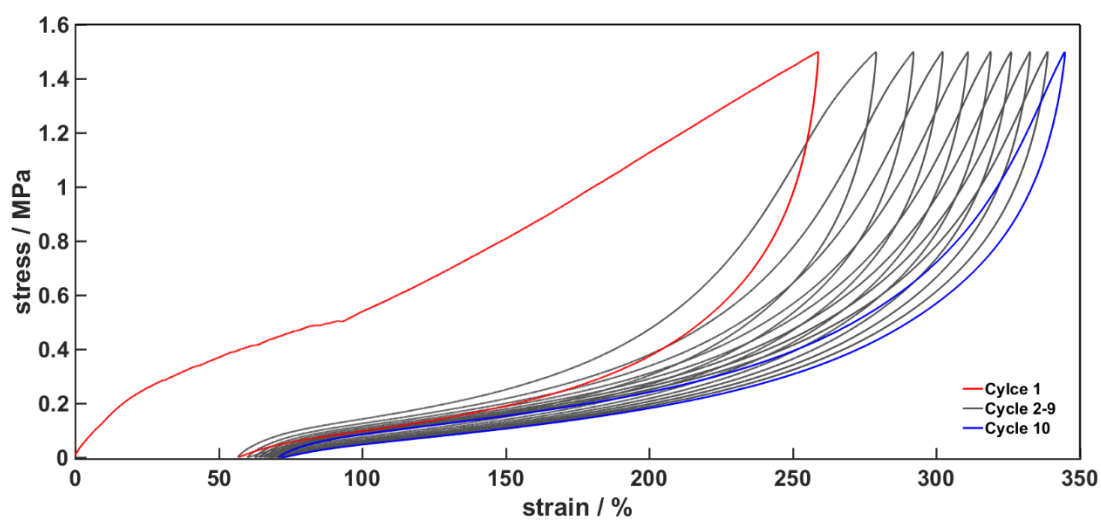


Figure S 34: Cyclic tensile curves for TPE-8, showing an ultimate stress of 1.5 MPa and no delay between cycles. Each cycle reveals an elastic recovery of 78 – 79%.

Table S 3: Data set of cyclic tensile testing for the calculations of the elastic recovery for TPE-5 and TPE-8. The elastic recovery was calculated according to the following equation: $\text{elastic recovery} = (\epsilon_{\max} - \epsilon_{\text{res}}) / \epsilon_{\max}$.⁶

sample	cycle	$\epsilon_{\max}$ (%) ^a	ϵ_{res} (%) ^a	<i>elastic recovery (%)</i>
TPE-5	1	92.0229	3.7899	95.9
	2	97.2046	5.01617	94.8
	3	99.6472	5.7337	94.3
	4	102.049	6.23812	93.9
	5	103.478	6.87914	93.4
	6	104.607	7.32765	93.0
	7	105.363	7.75582	92.6
	8	106.28	8.00577	92.5
	9	107.077	8.26159	92.3
	10	107.668	8.70995	91.9
TPE-8	1	258.793	56.8353	78.0
	2	292.003	60.0012	79.5
	3	291.962	62.5495	78.6
	4	302.138	64.2991	78.7
	5	311.000	65.8024	78.8
	6	318.822	67.2509	78.9
	7	325.996	68.3456	79.0
	8	332.608	70.0532	78.9
	9	338.699	70.8772	79.1
	10	344.674	71.9799	79.1

^aValues represent raw data from mechanical analysis.

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Chapter 4

Stereoregular Poly(Phenyl Glycidyl Ether)s

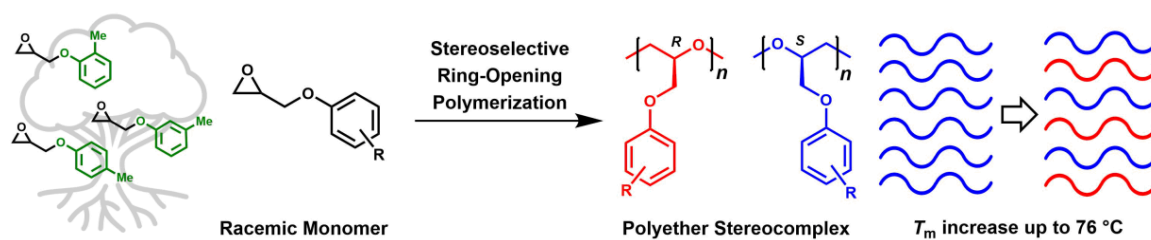
4 Stereoregular Poly(Phenyl Glycidyl Ether)s: *In Situ* Formation of a Polyether Stereocomplex from a Racemic Monomer Mixture

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To be submitted.



Abstract

Polymer stereocomplex formation represents a promising research area as it can improve thermal and mechanical properties of co-crystallized polymer strands of opposite chirality. Polymers that form stereocomplexes commonly feature high stereoregularity and usually require sourcing from enantiopure monomer building blocks. Herein, we report the *in situ* polyether stereocomplex formation from racemic epoxide monomers, i.e., substituted methyl phenyl glycidyl ethers. The bio-renewable glycidyl ethers were explored in both enantio- and isoselective ring opening polymerizations (ROPs), resulting in isotactic poly(phenyl glycidyl ether). While the enantioselective ROP selectively resolves a single enantiomeric, isotactic polyether stereoisomer ($[mm]_P \geq 78\%$), the isoselective ROP leads to the concurrent formation of both isotactic (*R*)- and (*S*)-poly(phenyl glycidyl ether) stereoisomers ($[mm]_P \geq 92\%$) and thus results directly in a stereoisomer blend, which forms a stereocomplex. This is one of only a few polymer stereocomplexes generated directly during polymerization from a racemic monomer mixture. Stereocomplexes of the different poly(phenyl glycidyl ether)s show an increase in melting temperature of up to 76 °C, relative to the enantiopure parent polymers. The position of the methyl group at the phenyl ring determines both stereocomplex formation and the thermal properties of the resulting materials.

Introduction

Stereoregular polymers show mechanical and thermal properties that are superior in comparison to their atactic analogues, the most widely used example being isotactic polypropylene.^{1–3} Among stereoregular polymers, isotactic polyethers have emerged as semicrystalline materials with high stereoregularity, when prepared with suitable catalyst systems. In general, stereoselective polymerization of monosubstituted epoxides gives access to isotactic polyethers.⁴ However, despite significant advances in the field of stereoselective ROP of epoxides, achieving high monomer enantioselectivity and thus high polymer isotacticity remains challenging.^{4–7}

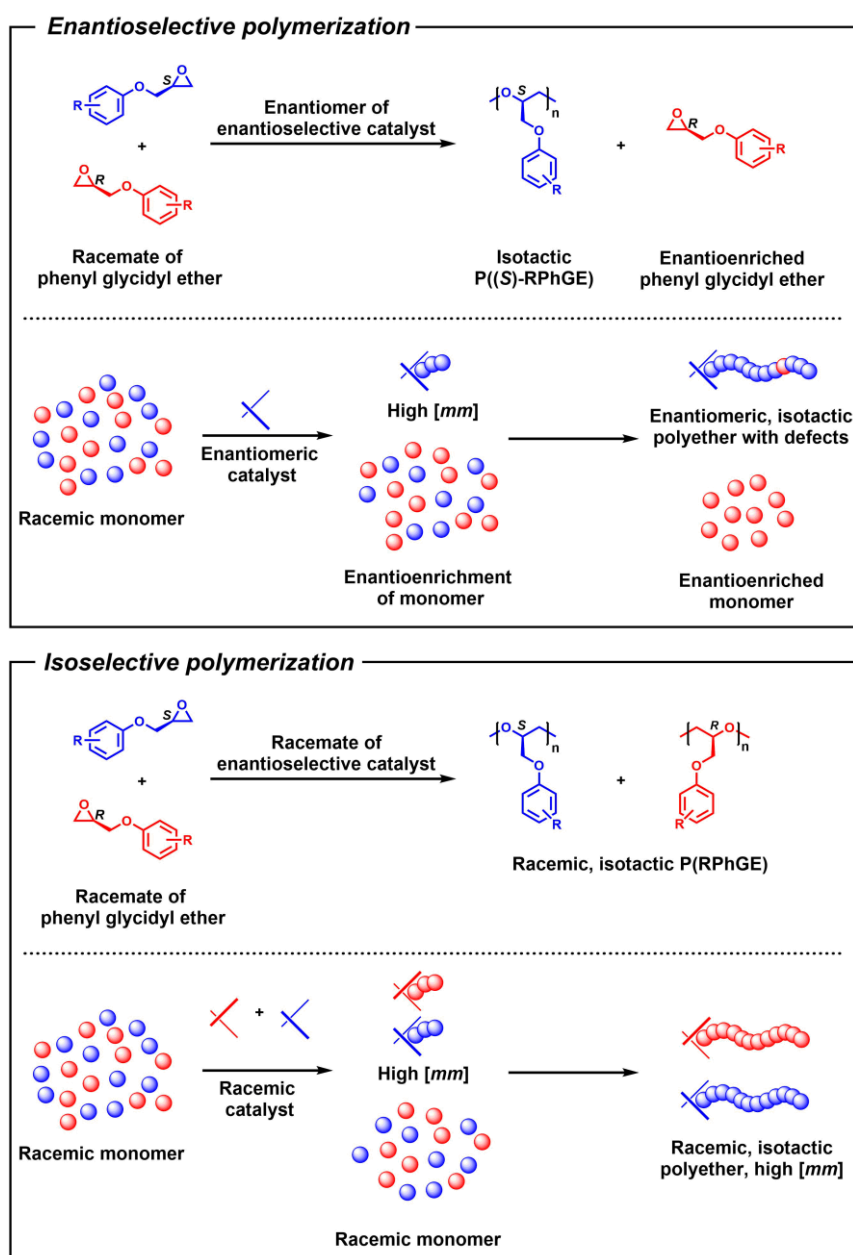


Figure 1: Enantio- and isoselective ROP of phenyl glycidyl ethers using an enantioselective catalyst.

A major objective is to maintain excellent stereoregularity at high conversion in a direct kinetic resolution polymerization of substituted epoxides, which are commonly available as racemates. Figure 1 introduces two strategies to produce isotactic polyethers directly from a phenyl glycidyl ether racemate, avoiding a kinetic resolution step of the monomer prior to polymerization.

In 2008, Hirahata et al. discovered a highly enantioselective chiral bimetallic cobalt complex for the kinetic resolution polymerization of epoxides and synthesis of enantiopure polyethers.⁶ In this rapid, enantioselective polymerization, the enantiopure catalyst preferentially consumes one enantiomer of the racemate, resulting in an enantioenriched monomer and an isotactic polyether with yields limited to 50% (Figure 1, top).^{6,8} Yet, the enantioenrichment of the monomer with preceding polymerization results in a higher probability of incorporation of stereodefects at high conversion. To maximize the yield of the isotactic polyether, the racemic form of the bimetallic cobalt catalyst allows for the concurrent polymerization of both enantiomers in an isoselective ROP to full conversion (Figure 1, bottom). Capitalizing on the unprecedented high activity of this catalyst towards a broad scope of monosubstituted epoxides, Thomas et al. obtained a variety of racemic polyethers with improved tacticities and high melting temperatures (T_m s). Despite the highly isotactic and enantiopure nature of the polymers, stereocomplexation was not manifest in this system.⁹

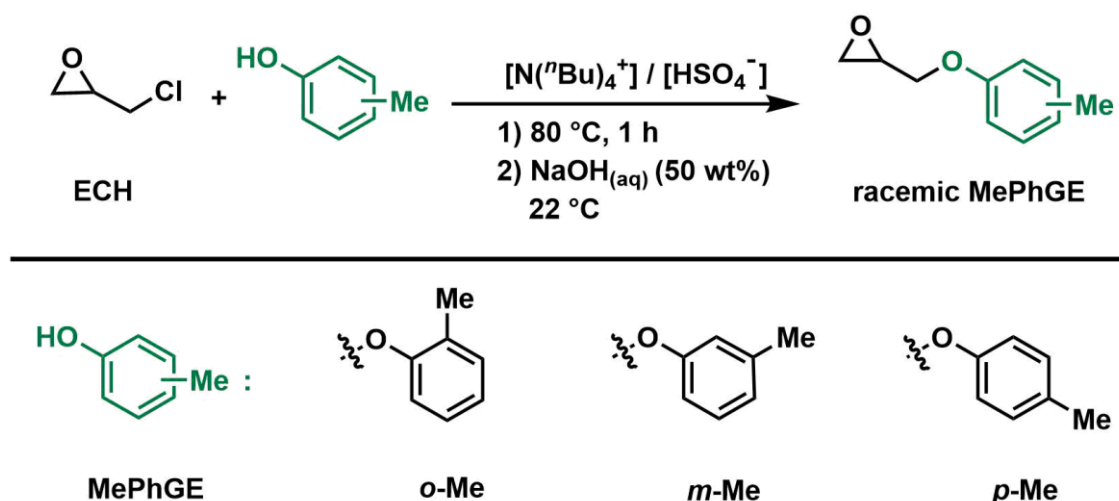
Yet, stereocomplexation represents a highly compelling strategy to elevate polymer properties beyond one single stereoregular, enantiopure polymer analogue.^{10,11} In most cases, stereocomplexation is achieved by mixing two enantiomerically complementary polymers in equivalent amounts, resulting in enhanced properties compared to the enantiopure polymers, such as a higher T_m , higher degrees of crystallinity, and consequently improved mechanical properties.^{3,12} Only a handful of studies have reported the *in situ* stereocomplex formation from racemic monomers during polymerization.^{13–17} The stereoselective interaction leading to stereocomplexation is governed by dipole–dipole interactions or hydrogen bonding and leads to an enhanced molecular order via co-crystallization of the complementary polymer strands.^{3,10} To date, several polymer classes, ranging from polymethylmethacrylates^{18–23} to polyesters^{24–32} to polycarbonates^{33–40}, have been found to be capable of forming stereocomplexes.³ Within the field of polymer stereocomplex formation, poly(lactic acid) (PLA) represents the most prominent and widely studied representative.^{24,41–43} In contrast, polyethers remain a relatively unexplored field in terms of polymer stereocomplex formation due to their generally low dipole-dipole interactions. To the best of

our knowledge, Buchard et al. recently published the only example of the formation of a polyether stereocomplex, synthesized via regioselective ROP of an enantiopure, natural saccharide-based oxetane.⁴⁴ Hence, the development of epoxide monomers that undergo enantioselective ROP can advance the synthesis and potential stereocomplexation of stereoregular polyethers.^{5–7,9}

In an effort to generate a polyether stereocomplex *in situ* by catalytic ROP, we report the stereoselective polymerization of a variety of racemic substituted phenyl glycidyl ethers, together with the detailed thermal behavior of the resulting polymers. All monomers were synthesized from bio-renewably sourced reactants. The constituent methyl phenols represent small-molecule compounds obtained from the deconstruction of lignin.⁴⁵ Furthermore, green epichlorohydrin (ECH) is available as a fully bio-renewable option via Solvay's Epicerol® process.^{46–48} Highly isotactic poly(phenyl glycidyl ether)s (*i*P(RPhGE)s) are synthesized utilizing the cobalt-based, bimetallic catalyst in an enantio- and isoselective ROP (Figure 1). Not only did all isotactic polyethers exhibit high melting temperatures, but *in situ* stereocomplexation evidently boosted these properties.

Results and Discussion

Targeting bio-renewable and easy-to-synthesize epoxide synthons for the preparation of these stereoregular polyethers, we synthesized three lignin-derived methyl phenyl glycidyl ether (MePhGE) isomers via phase transfer catalysis (Scheme 1).^{49,50} Phase transfer catalysis represents a facile but efficient method to prepare glycidyl ethers with versatile functionalities from commercially available reactants. To this end, ECH and the respective methyl phenol isomer (*ortho*-, *meta*-, *para*- substitution) were reacted in a one-pot, two step synthesis protocol.⁴⁹ After the reaction, purification by distillation afforded the MePhGE monomers in high purity and yields of 76 – 81%. Detailed NMR characterization (¹H, ¹³C) is provided in the Supporting Information (Figures S 3 – S 8).

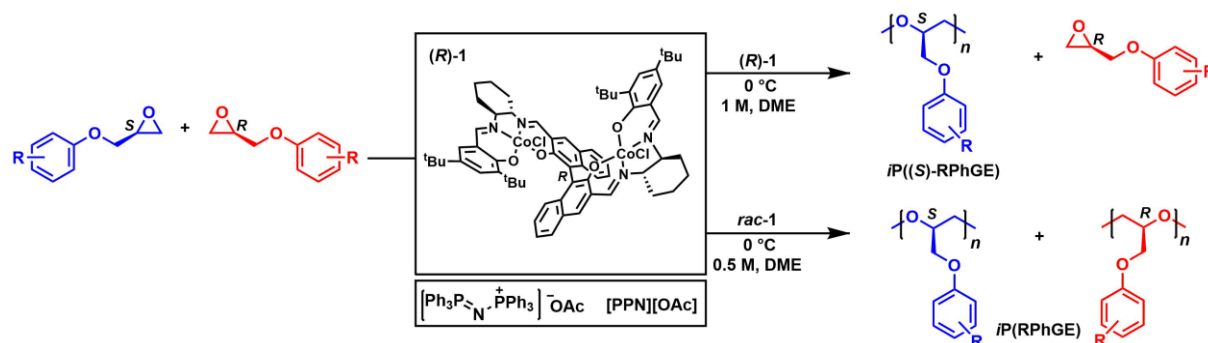


Scheme 1: Synthesis of various methyl-substituted phenyl glycidyl ethers via phase transfer catalysis, starting from ECH and the respective cresol. Both reactants are available from bio-renewable sources.

Aiming at the exploration of the racemic phenyl glycidyl ethers as polyether stereocomplex building units, we initially sought to produce and characterize the (*S*)-polyethers by using the (Binol^RSalcy^{SS})Co₂Cl₂ catalyst ((*R*)-1) and the ionic cocatalyst bis(triphenylphosphine)iminium acetate ([PPN][OAc]) in 1,2-dimethoxyethane (DME) at 0 °C (Table 1, entries 1–4).^{6,9} Low temperatures are required to ensure high enantioselectivity without catalyst deactivation (Co(III) reduction to Co (II)) due to the reaction being exothermic.^{6,9} DME as a polar solvent improves the solubility of the ionic cocatalyst.⁵¹ Previous studies of this catalyst system with a range of racemic, monosubstituted epoxides, including PhGE, provide evidence for the retention of the methine carbon configuration to occur during the polymerization.⁹ Based on these results, we inferred that the polymerization of methyl-substituted PhGE would result in identical selectivity and polymer stereoregularity as observed for *i*PPhGE (Scheme S 1). The *i*P((*S*)-RPhGE) were successfully synthesized from all

monomer racemates, respectively, (Figures S 9 – 16 and Figures 28 – 31). According to ^{13}C NMR spectra, the catalyst produces similar tacticity for all polyethers independent of the substituent. Further, the resulting ratio of stereoerrors follows $[mr] = [rm] \approx [rr]$ (Figures S 19 – 22, see Supporting Information for detailed triad analysis), which is in agreement with an enantiomorphic site control mechanism (Figure S 18).⁴ Consequently, stereoblock formation is unlikely as the triad analysis would otherwise reveal stereochemical errors of the type $[mr] = [rm] > [rr]$ (Figure S 27).⁵²

Table 1: Enantio- and isoselective polymerization of racemic phenyl glycidyl ethers using the chiral bimetallic cobalt salen complex (BinolSalcy)Co₂Cl₂ catalyst.



Entry	Catalyst	RPhGE	t_{rxn} (min)	conv. ^d (%)	M_n^e (kg/mol)	$\bar{D}^e$	$[mm]_p^f$ (%)	s- factor ^g	T_m^h (°C)	T_c^h (°C)	ΔH_m^h (J/g)
1 ^a	(R)-1	<i>p</i> -H	15	52	40.0	2.51	81	48	169	128	50
2 ^a	(R)-1	<i>o</i> -Me	30	54	44.0	2.50	78	57	185	123	59
3 ^a	(R)-1	<i>m</i> -Me	15	49	36.7	2.08	81	35	99	53	17
4 ^a	(R)-1	<i>p</i> -Me	30	52	43.7	2.01	82	50	170	143	36
5 ^b	<i>rac</i> -1	<i>p</i> -H	5	98	104.0 ⁱ	2.03 ⁱ	93	-	204, 216	156	52
6 ^c	<i>rac</i> -1	<i>o</i> -Me	100	99	44.9 ⁱ	1.93 ⁱ	92	-	191	132	67
7 ^b	<i>rac</i> -1	<i>m</i> -Me	60	96	56.1 ⁱ	2.12 ⁱ	93	-	175	127	56
8 ^b	<i>rac</i> -1	<i>p</i> -Me	100	97	82.9 ⁱ	1.91 ⁱ	94	-	214	179	64

^aGeneral polymerization conditions: [RPhGE] = 1 M in DME; [RPhGE]:[cat.]:[[PPN][OAc]] = 2000:1:2; T_{rxn} = 0 °C. ^bGeneral polymerization conditions: [RPhGE] = 0.5 M in DME; [RPhGE]:[cat.]:[[PPN][OAc]] = 2000:2:4; T_{rxn} = 0 °C. ^cGeneral polymerization conditions: [RPhGE] = 0.5 M in DME; [RPhGE]:[cat.]:[[PPN][OAc]] = 2000:1:2; T_{rxn} = 0 °C. ^dConversion (conv.) was determined gravimetrically. ^eDetermination via gel permeation chromatography (GPC) calibrated with polystyrene in THF at 35 °C if not noted otherwise. ^fPolymer tacticity $[mm]_p$ was determined by ^{13}C NMR spectroscopy at 130 °C in 1,1,2,2-tetrachloroethane-*d*₂. ^gCalculated using $s = \ln[1 - \text{conv.}(1 + (2[mm] + [mr] + [rm] - 1)^{1/2})]/\ln[1 - \text{conv.}(1 - (2[mm] + [mr] + [rm] - 1)^{1/2})]$.^{6,9,53} ^hDetermined by DSC. Reported T_m values are from second heating run, T_c values are from the first cooling cycle. ⁱDetermination by high-temperature gel permeation chromatography (HT-GPC) calibrated with polystyrene samples in 1,2,4-trichlorobenzene at 150 °C.

Subsequently, we evaluated the catalyst enantioselectivity toward the different glycidyl ethers by examining the enantiomeric purity of polymer units as a function of

conversion.⁶ As can be seen in Table 1 (entries 1 – 4), the resulting *s*-factors ($s = k_S/k_R$) display a good (*R*-1)-catalyst selectivity towards the (*S*)-enantiomer and range in a similar order of magnitude. The selectivity deviations are attributed to a steric effect of the methyl groups, potentially impacting monomer orientation within the catalyst cleft as well as the interaction with cocatalyst.⁵¹ It is worth noting that it is difficult to accurately measure *s*-factors for highly selective catalysts due to associated error of the determination of conversion and triad NMR analysis, however it is clear the catalysts are highly stereoselective.

Hypothesizing the isoselective ROP to be a powerful method to achieve an *in situ* stereocomplex formation, we next employed the racemic mixture of the catalyst to polymerize the scope of phenyl glycidyl ethers. Using this polymerization approach, dilution was required to reduce the viscosity increase during polymerization. With prolonged polymerization times, the catalyst system produced near quantitative yields of racemic *i*P(RPhGE) with superior isotacticity ($[mm] > 92\%$) compared to the enantiopure analogues (Figure S 23 – 26). An array of stacked ¹H NMR spectra of all polyether samples compares the enantiopure and racemic polyethers, showing identical sharp resonances for each pair of enantiopure and racemic *i*P(RPhGE)s (Figure S 17). Ultimately, the higher degree of crystallinity renders the polyethers insoluble in THF, necessitating examination using a high-temperature GPC (HT-GPC) in 1,2,4-trichlorobenzene at 150 °C (Table 1, entries 5 – 8, Figure S 33 – S 36). Surprisingly, GPC characterization reveals significantly higher molecular weights for the *i*P(*p*-MePhGE) and *i*P(MePhGE) compared to their *ortho*- and *meta*-substituted analogues. These results further support an effect of the substitution pattern on the monomer-catalyst compatibility. Yet, the enantiopure polyethers (entries 1 – 4) show molecular weights in a similar range for all substitution patterns. The resulting molecular weight differences as well as the improved molecular weight resolution via HT-GPC are ascribed to the use of differing columns and GPC characterization conditions (solvent, temperature). The polystyrene standard employed was identical for both GPC methods.

Differential scanning calorimetry (DSC) was used to investigate the thermal properties of the enantiomeric and racemic *i*P(RPhGE), providing a first insight into the stereocomplex formation, including steric effects induced by the phenyl substitution pattern. The enantiopure polyether derivatives are semicrystalline and feature T_m s between 99 °C and 185 °C, evidencing a strong effect of the phenyl substitution pattern on the T_m and crystallization behavior. Moreover, the absence of a glass transition temperature (T_g) for all polyether samples underlines the high degree of crystallinity of

the polyethers, which impedes the segmental motion of the polymer chains (Figures S 37 – S 45).⁵⁴ While the non-substituted *iP*(PhGE) is characterized by a T_m of 169 °C (Figure 2 (a)), the *meta*-substituted polyether *iP*((*S*)-*m*-MePhGE) exhibits a significantly lower T_m of 99 °C with a broad melting peak (Figure 2 (c)), despite similar tacticity (Table 1, entries 1 and 3). On the contrary, *ortho*- and *para*-substitution result in a slight increase of T_m compared to enantiopure *iP*((*S*)-RPhGE). Accordingly, these substitution patterns appear to enable more efficient packing of the polymer chains, as demonstrated by the sharp melting peaks (Figures 2 (b) and (d)).

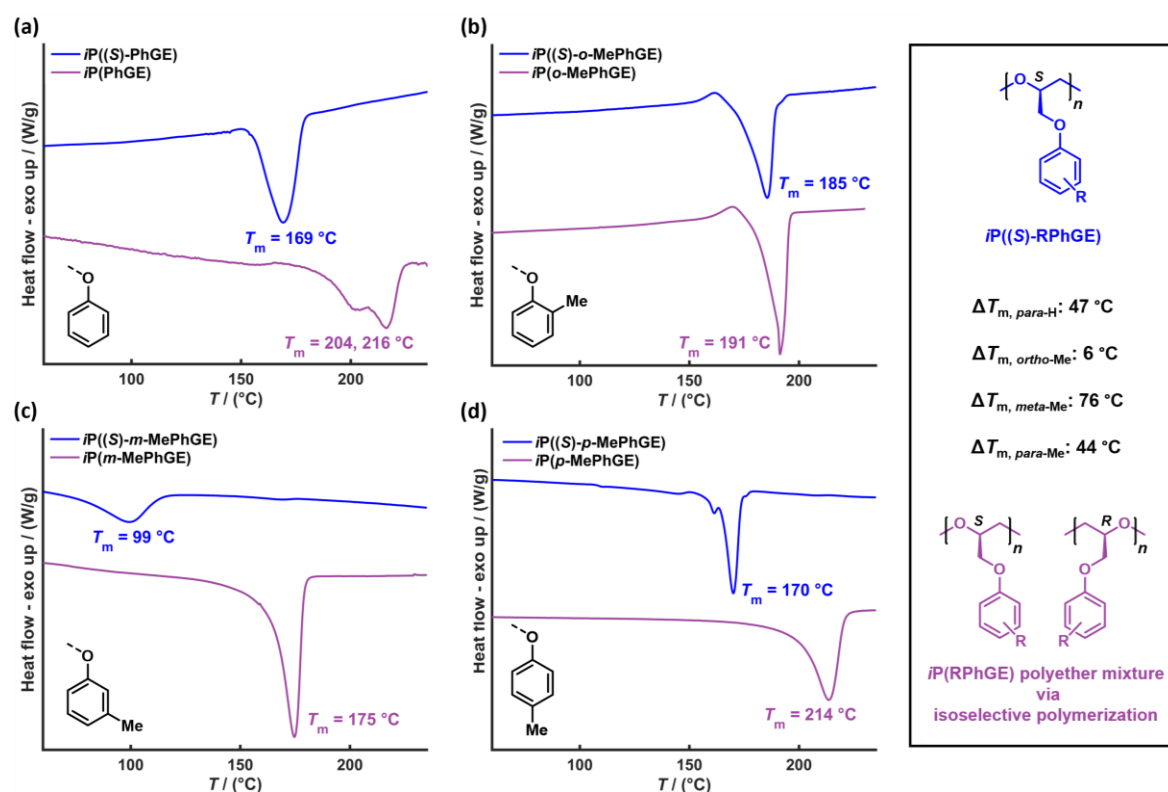


Figure 2: DSC thermograms (second heating) of stereoregular *iP*((*S*)-RPhGE) and *iP*(RPhGE) synthesized via enantio- and isoselective polymerization, respectively. The *in situ* stereocomplexation is indicated by an increase in T_m for the *iP*(RPhGE) mixtures in (a), (c) and (d), described by $\Delta T_m = T_m(\text{racemic}) - T_m(\text{enantiomeric})$.

Directing our focus to the *iP*(RPhGE) racemates obtained from isoselective ROP, the increase in T_m by up to 76 °C strongly supports stereocomplex formation (Figure 2). Not only do most of the stereocomplexed *iP*(RPhGE) polyethers show enhanced T_m values in the range from 175 to 216 °C, but also an increase in melting enthalpies (ΔH_{ms}) is visible for all polyethers blends (Table 1). In addition, they also possess an excellent capability to cocrystallize, which is expressed by a sharp, exothermic recrystallization peak upon cooling (Figures S 42 – S 45). Intriguingly, the isoselective ROP of the *meta*-substituted MePhGE leads to a T_m of 175 °C for the *iP*(*m*-MePhGE) stereocomplex, which translates to the most pronounced T_m increase of 76 °C (Figure 2 (c)). Previous investigations on polyester stereocomplexes demonstrated bulky pendant groups to be

a driving factor in stereocomplexation owing to their steric hindrance.³² For the *meta*-substitution, this result highlights favorable interaction of opposite enantiomeric, isotactic *iP*(*m*-MePhGE) chains compared to those of enantiomerically pure nature. This leads to improved crystallinity as seen by ΔH_m , which has more than tripled (Table 1, entries 3 and 7). Equally, irrespective of a methyl or proton substituent in *para*-position, a similar cocrystallization behavior and T_m values of 216 °C and 214 °C are revealed for *iP*(PhGE) and *iP*(*p*-MePhGE), respectively. These similarities are also reflected in the thermal properties of the enantiomerically pure analogues, yet there is a more notable increase in ΔH_m for *iP*(*p*-MePhGE) (Figure 2 (a) and (d), Table 1). In contrast, only a small difference in T_m occurs for *iP*(*o*-MePhGE) ($\Delta T_m = 6$ °C with $\Delta T_m = (T_{m(\text{racemic})} - T_{m(\text{enantiomeric})})$) while identical powder X-ray diffraction (PXRD) profiles indicate no significant enhancement of the stereoselective chain interactions between chains of opposite chirality (Figure S 1).

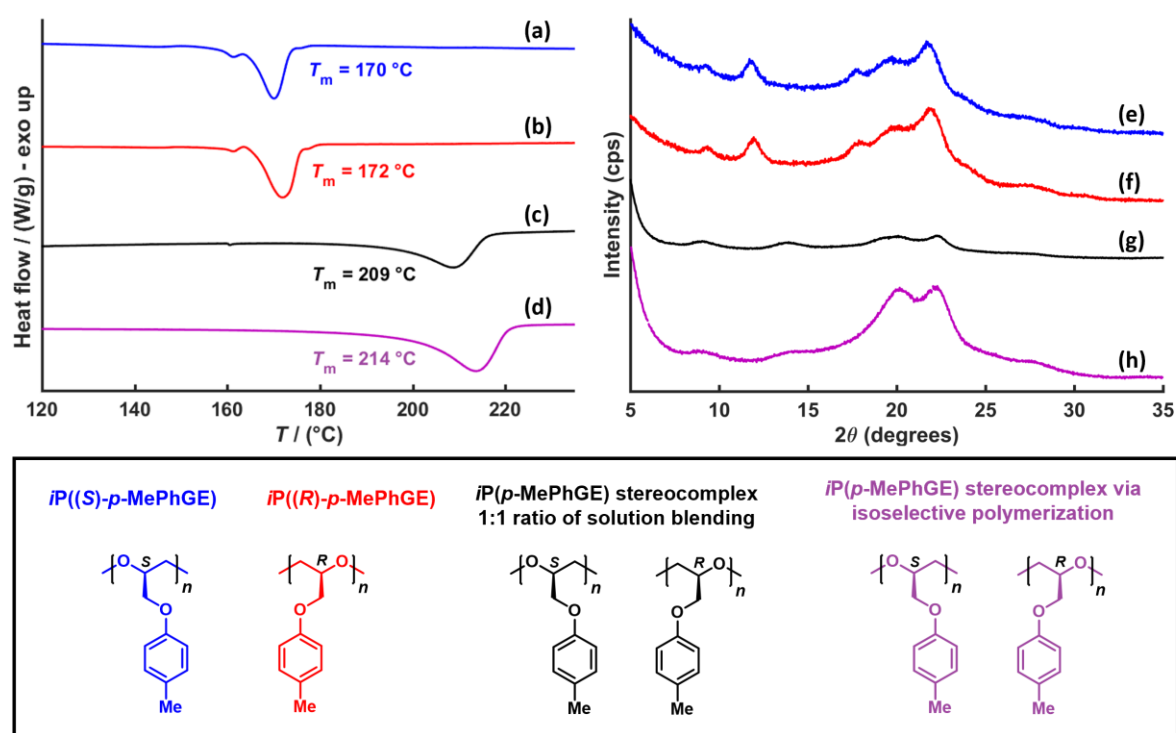


Figure 3: DSC thermograms (left) and PXRD profiles (right) of enantiomeric and racemic *iP*(*p*-MePhGE): (a) and (e) *iP*((*S*)-*p*-MePhGE), (b) and (f) *iP*((*R*)-*p*-MePhGE), (c) and (g) *iP*(*p*-MePhGE) stereocomplex produced by a 1:1 blend of *iP*((*S*)-*p*-MePhGE) with *iP*((*R*)-*p*-MePhGE), and (d) and (h) *iP*(*p*-MePhGE) stereocomplex by isoselective polymerization.

Having observed an increase in T_m for all racemic *iP*(RPhGE) structures relative to their enantiopure counterparts, we sought to investigate *iP*(*p*-MePhGE) as a model stereocomplex in a control experiment. Although the aforementioned enhanced thermal properties are ascribed to stereocomplexation, the increase in T_m is also consistent with improved tacticities for the racemic *iP*(RPhGE). To provide evidence for an effective

stereoselective interaction, we mimicked the racemic *iP*(*p*-MePhGE) by solution blending both enantiomeric polyethers, namely *iP*((*S*)-*p*-MePhGE) and *iP*((*R*)-*p*-MePhGE) (Table S 1) in hot THF solution at a ratio of 1:1. The solvent was slowly evaporated to allow for co-crystallization of the polymers of opposite chirality. As displayed in Figure 3 (left), the DSC analysis reveals a T_m of 209 °C of the mixed polyether stereocomplex, which is approximately 39 °C higher than that of the enantiomeric parent polymers. In comparison, the *in situ* stereocomplex provided by the isoselective polymerization is characterized by a similar T_m of 214 °C. Both *para*-stereocomplexes, generated by mixing and polymerization, show a sharp recrystallization exotherm T_c at 174 °C and 179 °C, respectively (Table S 1, Figure S 45 and 46). Comparing the ΔH_m values, a lower ΔH_m of the blended stereocomplexes underlines a reduced crystallinity (Table S 1, entries 3 and 4). As the degree of crystallinity is known to depend on tacticity, we correlate the differences of T_m , T_c and ΔH_m to the slightly lower tacticity of the enantiopure samples.

Finally, PXRD was conducted to further confirm the *in situ* formation of the *iP*(*p*-MePhGE) stereocomplex. Figure 3 (right) comprises the PXRD pattern of both enantiomeric polyethers, *iP*((*S*)-*p*-MePhGE) and *iP*((*R*)-*p*-MePhGE), as well as of *iP*(*p*-MePhGE) stereocomplex via mixing and polymerization. As anticipated, the enantiopure polyethers (*S* and *R*) exhibit an identical diffraction pattern, with diffraction peaks at 9.3°, 11.9°, 17.9°, 19.7° and 21.7° (Figures 3 (e) and (f)). Similar relative intensities of the reflections additionally manifest a comparable crystalline order, which is consistent with the thermal analysis (Table S 1). The PXRD patterns of the *iP*(*p*-MePhGE) stereocomplexes differ from those of the enantiomeric samples and show two distinct signals at 20.2° and 22.2° as well as two smaller, broad reflections at 9.1° and 13.9° (Figure 3 (g) and (h)). Strikingly, the stereocomplex produced by mixing gives a much lower peak intensity (additional visualization in Figure S 2), which agrees with the formation of the more crystalline stereocomplex *in situ* than by physical blending (Table S 1). Taken together, the differences in T_m s as well as the diffraction patterns of the enantiomeric and racemic *iP*(*p*-MePhGE) evidence the formation of a stereocomplex. Furthermore, we conclude that the *in situ* formation enables more homogenous stereocomplexation compared to solution blending. In summary, varying the substitution pattern of the phenyl side chain permits tunability of the stereocomplexes' thermal properties, which warrants further study.

Conclusion

To the best of our knowledge, these findings show the first *in situ* polyether stereo-complex formation via stereoselective ROP of racemic phenyl glycidyl ethers. The polyethers are based on three methyl phenyl glycidyl ether isomers, which provide the option to be fully bio-sourced. Capitalizing on highly active bimetallic cobalt complexes, (Binol^RSalcy^{SS})Co₂Cl₂ and (Binol^SSalcy^{RR})Co₂Cl₂, the phenyl glycidyl ether isomers were polymerized both via enantio- and isoselective ROP. Selectivity factors of the enantioselective ROP were determined via triad analysis ($[mm]_P > 78\%$), ranging from 35 to 57. Moreover, the use of a racemic catalyst in the isoselective ROP using a racemic glycidyl ether mixture led to the synthesis of *i*P(RPhGE) in quantitative yields with improved tacticities ($[mm]_P > 92\%$). The substitution pattern of the respective glycidyl ethers sterically determines both the selectivity factors and the thermal properties. Thermal characterization of the semicrystalline polyethers revealed an increase of the T_m for racemic mixtures by up to 76 °C following stereocomplexation, despite the absence of any strong dipole interactions. The change of the crystalline order due to stereocomplexation was proven by PXRD.

This work demonstrates that the isoselective ROP provides a mild and fast synthesis strategy for the generation of a hitherto elusive polyether stereocomplex *in situ*, avoiding prior kinetic resolution for separation of the enantiopure building blocks. The polymerization of readily available monomer racemates in one step addresses the superior feasibility by its high conversion in contrast to enantio- or regioselective polymerizations. Further investigation of an extended scope of renewable phenyl glycidyl ethers may enable tailor-made polyether stereocomplexes, controlled by the phenyl substitution pattern as well as the substituent itself. Ultimately, this novel class of polyether stereocomplexes is intriguing with respect to biobased polyether-based materials with new property profiles.

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Supporting Information

Experimental Sections

Materials, Methods and General Considerations

Reactions containing air- and/or water-sensitive compounds were conducted under an inert atmosphere in a nitrogen-filled glovebox (MBraun Labmaster glovebox) or using standard Schlenk line techniques. All chemicals were purchased from commercial suppliers and were used as received, unless otherwise stated. Solvents were degassed and passed through a solvent purification system (Glass Contour, Laguna, CA) prior to use. Deuterated solvents were purchased from Cambridge Isotope Laboratories (CIL).

Phenyl glycidyl ether (PhGE) was dried by stirring over CaH_2 for 24 h before vacuum-transferring and degassing via freeze-pump-thaw cycles. Methyl phenyl glycidyl ethers (MePhGE) were dissolved in dry toluene and dried azeotropically overnight using Schlenk line vacuum. All monomers were stored in a glove box under a nitrogen atmosphere. The chiral bimetallic cobalt salen catalysts $(\text{Binol}^S\text{Salcy}^{RR})\text{Co}_2\text{Cl}_2$ and $(\text{Binol}^R\text{Salcy}^{SS})\text{Co}_2\text{Cl}_2$ as well as the cocatalyst bis(triphenylphosphine)iminium acetate $([\text{PPN}][\text{Oac}])$ were synthesized as previously reported.^[1,2] Both cobalt catalyst and $([\text{PPN}][\text{Oac}])$ were dried under Schlenk vacuum for 2 days and subsequently stored under nitrogen in a glovebox.

Standard nuclear magnetic resonance (NMR) spectroscopy was performed at 25 °C at 500 MHz with a Bruker AVANCE III or Bruker AVANCE III HD, both with BBO Prodigy cryoprobe. The NMR experiments for all isotactic polymers were conducted at 130 °C in 1,1,2,2-tetrachloroethane- d_2 (TCE- d_2), unless otherwise specified. For quantitative ^{13}C NMR, relaxation delay (d1) = 3, number of scans (ns) = 1024. NMR spectra were processed with MestReNova software 14.2.0. Chemical shifts (δ) of all spectra were referenced internally to residual protium of the deuterated solvent (^1H NMR spectra: CDCl_3 = 7.24 ppm, TCE- d_2 = 6.00 ppm) and the deuterated solvent itself (^{13}C NMR spectra: CDCl_3 = 77.23 ppm, TCE- d_2 = 73.78 ppm). NMR spectroscopy data is denoted as follows: chemical shift, multiplicity (s = singlet, d = doublet, t = triplet, q = quartet, m = multiplet, br = broad), coupling constant (Hz) and integration.

Number-averaged molecular weights (M_n) and molecular weight distributions ($\mathcal{D}$) were determined by gel permeation chromatography (GPC). GPC measurements were carried out on an Agilent 1260 Infinity GPC System equipped with an Agilent 1260 Infinity autosampler and a refractive index detector. The Agilent GPC system, equipped with

two Agilent S3 PolyPore columns (5-micron, 4.6 mm ID), were eluted with THF at 30 °C at 0.3 mL/min and were calibrated using monodisperse polystyrene standards.

GPC characterization of crystalline, high molecular weight samples was performed using an Agilent 1260 Infinity II high temperature GPC equipped with a RI detector. The column set (three 300 x 7.5 mm Agilent PL-Gel Olexis columns and one 50 x 7.5 mm PL-Gel Olexis guard column) was eluted with 1,2,4-trichlorobenzene containing 0.01 wt% of 3,5-di-tert-butyl-4-hydroxytoluene (BHT) at 1.0 mL/min at 150 °C. Data were measured relative to a polystyrene calibration curve (Varian and Polymer Standards Service).

Differential scanning calorimetry (DSC) measurements of polymer samples were performed on a Mettler-Toledo Polymer DSC instrument equipped with a chiller and an autosampler. Samples were prepared in aluminum pans. The polyether samples were analyzed applying the following temperature protocol: heating from 20 °C to 230 °C, cooling from 230 °C to 0 °C and then heating from 0 °C to 230 °C. Both cooling and heating processes were conducted at a rate of 10 °C/min under a nitrogen atmosphere. Data was processed using StarE software. All thermal properties (T_c , T_m) were evaluated from the second heating cycle to remove any thermal history effects.

Powder X-ray diffraction (PXRD) profiles were recorded on a Rigaku Ultima IV diffractometer equipped with Cu K α source ($\lambda=1.54$ Å). Samples were analyzed using a step scan from 2 – 50° with a sample width of 0.02°.

Monomer Synthesis and Characterization

In the following, a representative procedure for the phase transfer catalysis yielding substituted phenyl glycidyl ethers is described exemplarily for *para*-methyl phenyl glycidyl ether (*p*-MePhGE), using an alteration of a literature-known protocol.^[3, 4]

A three-necked flask was charged with *para*-methylphenol (10.2 mL, 9.00 g, 0.0832 mol, 1.0 equiv.), epichlorohydrin (ECH, 34.6 mL, 40.81 g, 0.441 mol, 5.3 equiv.) and tetrabutylammonium hydrogen sulfate (TBAHS, 1.41 g, 0.004 mol, 0.05 equiv.), followed by heating at 80 °C for 1 h. After cooling the reaction mixture to room temperature (r.t.), stirring was continued for 2 h while an aqueous sodium hydroxide solution ($V_{\text{solution}} = 26.62$ mL, NaOH: 13.31 g, 0.33 mol, 4 equiv.) and additional TBAHS (1.41 g, 0.004 mol, 0.05 equiv.) were added dropwise using a dropping funnel. Subsequently, the crude product was extracted with ethyl acetate and the combined organic phases were washed with saturated sodium hydrogen carbonate to yield a neutral pH. The organic solvent was removed under reduced pressure after drying over MgSO_4 . Fractionated vacuum distillation was used to isolate the colorless *p*-MePhGE liquid in high purity and yields of 76% (*m*-MePhGE: 81%; *o*-MePhGE: 78%).

***para*-Methyl phenyl glycidyl ether (*p*-MePhGE)**

^1H NMR (500 MHz, CDCl_3): δ 7.12 – 7.05 (m, 2H), 6.86 – 6.79 (m, 2H), 4.18 (dd, J = 11.0, 3.3 Hz, 1H), 3.95 (dd, J = 11.0, 5.6 Hz, 1H), 3.39 – 3.30 (m, 1H), 2.90 (dd, J = 4.9, 4.1 Hz, 1H), 2.75 (dd, J = 5.0, 2.6 Hz, 1H), 2.29 (s, 3H).

^{13}C NMR (125 MHz, CDCl_3): δ 156.50, 130.89, 130.05, 114.61, 68.96, 50.33, 44.86, 20.58.

***meta*-Methyl phenyl glycidyl ether (*m*-MePhGE)**

^1H NMR (500 MHz, CDCl_3): δ 7.17 (t, J = 7.8 Hz, 1H), 6.82 – 6.77 (m, 1H), 6.77 – 6.70 (m, 2H), 4.19 (dd, J = 11.0, 3.3 Hz, 1H), 3.96 (dd, J = 11.0, 5.5 Hz, 1H), 3.39 – 3.32 (m, 1H), 2.90 (dd, J = 5.0, 4.1 Hz, 1H), 2.76 (dd, J = 5.0, 2.6 Hz, 1H), 2.33 (s, 3H).

^{13}C NMR (125 MHz, CDCl_3): δ 158.64, 139.74, 129.38, 122.21, 115.65, 111.60, 68.76, 50.33, 44.93, 21.66.

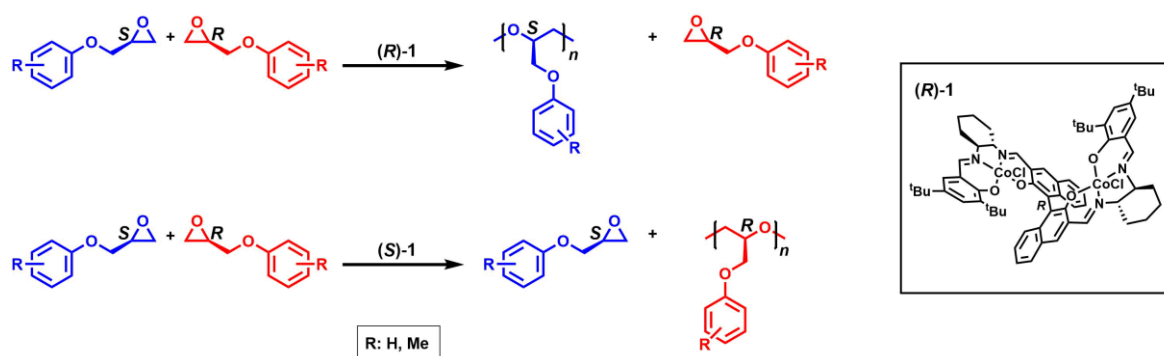
***ortho*-Methyl phenyl glycidyl ether (*o*-MePhGE)**

^1H NMR (500 MHz, CDCl_3): δ 7.18 – 7.11 (m, 2H), 6.88 (t, J = 7.4 Hz, 1H), 6.81 (d, J = 8.5 Hz, 1H), 4.23 (dd, J = 11.1, 3.1 Hz, 1H), 3.99 (dd, J = 11.0, 5.4 Hz, 1H), 3.42 – 3.34 (m, 1H), 2.91 (t, J = 4.6 Hz, 1H), 2.79 (dd, J = 5.0, 2.6 Hz, 1H), 2.25 (s, 3H).

^{13}C NMR (125 MHz, CDCl_3): δ 156.76, 130.96, 127.21, 126.92, 121.07, 111.38, 68.80, 50.49, 44.84, 16.34.

Polymerization Procedures

Previous work employing the bimetallic cobalt salen catalyst **1** gives evidence for the epoxide ring opening at the methylene carbon with retention of the methine carbon configuration. This mechanistic insight allows for determining the absolute stereoconfiguration of the synthesized, enantiomeric polyethers.^[1] Additionally, the selectivity of catalyst **1** has been determined experimentally for PhGE. The ring opening polymerization (ROP) utilizing (*R*)-**1** resulted in a (*S*)-stereoconfiguration of the polyether while (*S*)-**1** consequently leads to a (*R*)-stereoconfiguration. Relying on these results, we conclude identical behavior for the novel isotactic poly(methyl phenyl glycidyl ether)s (*i*P(MePhGE)s) (Scheme S 1).^[2]



Scheme S 1: Stereoselectivity of the enantiopure bimetallic cobalt salen catalyst **1**, determined from the ROP of PhGE.^[2]

Representative Procedure for the Enantioselective Polymerization of Racemic Glycidyl Ethers

The following procedure refers to the preparation of *iP*((*S*)-*p*-MePhGE) (entry 4, Table 1).^[2] In a glove box under a nitrogen environment, an oven-dried 2 mL vial equipped with a Teflon coated stir bar was charged with (Binol^RSalcy^{SS})Co₂Cl₂ ((*R*)-1) (0.4 mg, 0.35 μmol), [PPN][OAc] (0.4 mg, 0.69 μmol) and dissolved in 0.35 mL anhydrous 1,2-dimethoxyethane (DME). The catalyst mixture was sealed with a Teflon-lined cap, sealed with tape and pre-cooled in the glove box freezer for 20 min. Subsequently, the vial was removed from the glove box and cooled for an additional 10 min to 0 °C in an ice-bath. In the glovebox, the monomer (114 mg, 0.69 mmol) was mixed with 0.35 mL DME in a vial, transferred into a syringe with the end of the needle sealed by insertion into a septum. The monomer solution was added dropwise to the catalyst solution over 1 min and the polymerization was kept at 0 °C over the course of the reaction. The polymerization was quenched after 30 min by exposure to air and diluting with acetone. The white precipitate was washed with acetone multiple times and dried using Schlenk line vacuum. Conversion was determined by mass to be 52%. *iP*((*R*)-*p*-MePhGE) was synthesized in the same manner using (Binol^SSalcy^{RR})Co₂Cl₂ ((*S*)-1)).

iP((*S*)-*p*-MePhGE)

¹H NMR (500 MHz, TCE-*d*₂, 130 °C): δ 7.14 – 6.93 (m, 2H), 6.91 – 6.70 (m, 2H), 4.14 – 3.96 (m, 2H), 3.93 – 3.70 (m, 3H), 2.37 – 2.21 (m, 3H).

¹³C NMR (500 MHz, TCE-*d*₂, 130 °C): 156.90, 129.84, 129.60, 114.95, 78.55 (CH, *mm*), 78.45 + 78.41 (CH, *mr* + *rm*), 78.31 (CH, *rr*), 70.14 (CH₂, *mm*), 70.10 + 69.92 + 69.85 (CH₂, *mr* + *rm* + *rr*), 68.90, 20.01

iP((*S*)-*m*-MePhGE)

¹H NMR (500 MHz, TCE-*d*₂, 130 °C): δ 7.19 – 7.05 (m, 2H), 6.84 – 6.63 (m, 2H), 4.20 – 3.96 (m, 2H), 3.96 – 3.66 (m, 3H), 2.39 – 2.22 (m, 3H).

¹³C NMR (500 MHz, 1,1,2,2- TCE-*d*₂, 130 °C): 158.99, 139.08, 128.88, 121.62, 115.90, 111.89, 78.54 (CH, *mm*), 78.46 + 78.41 (CH, *mr* + *rm*), 78.35 (CH, *rr*), 70.10 (CH₂, *mm*), 70.06 + 69.91 + 69.84 (CH₂, *mr* + *rm* + *rr*), 68.63, 20.99.

***iP*((*S*)-*o*-MePhGE)**

¹H NMR (500 MHz, TCE-*d*₂, 130 °C): δ 7.21 – 7.02 (m, 2H), 6.98 – 6.73 (m, 2H), 4.21 – 3.96 (m, 2H), 3.97 – 3.67 (m, 3H), 2.31 – 2.15 (m, 3H).

¹³C NMR (500 MHz, TCE-*d*₂, 130 °C): 156.98, 130.49, 126.84, 126.50, 120.58, 111.95, 78.67 (CH, *mm*), 78.59 + 78.56 (CH, *mr* + *rm*), 78.49 (CH, *rr*), 70.22 (CH₂, *mm*), 70.19 + 69.98 + 69.95 (CH₂, *mr* + *rm* + *rr*), 68.78, 15.65.

***iP*((*S*)-PhGE)**

¹H NMR (500 MHz, TCE-*d*₂, 130 °C): δ 7.29 – 7.18 (m, 2H), 7.04 – 6.82 (m, 2H), 4.23 – 3.97 (m, 2H), 3.97 – 3.66 (m, 3H).

¹³C NMR (500 MHz, TCE-*d*₂, 130 °C): 158.95, 129.15, 120.78, 115.05, 78.50 (CH, *mm*), 78.42 (CH, *mr* + *rm*), 78.37 (CH, *mr* + *rm*), 78.31 (CH, *rr*), 70.08 (CH₂, *mm*), 70.04 + 69.90 + 69.83 (CH₂, *mr* + *rm* + *rr*), 68.68.

Representative Procedure for the Isolelective Polymerization of Racemic Glycidyl Ethers

The following procedure describes the preparation of racemic *iP*(*p*-MePhGE) (entry 8, Table 1). In a glove box under a nitrogen atmosphere, *rac*-1 (equimolar mixture of (*R,R*)(*S*)(*R,R*)-1 and (*S,S*)(*R*)(*S,S*)-1, 0.8 mg, 0.70 μmol) and [PPN][OAc] (0.8 mg, 1.4 μmol) were added to an oven-dried 2 mL vial equipped with a Teflon coated stir bar. The catalyst and cocatalyst mixture was dissolved in 0.70 mL DME. The vial was then sealed with a Teflon lined cap and additional tape, followed by pre-cooling in the glove box freezer for 20 min. Afterwards, the vial was transferred into an ice-bath outside the glove box and cooled for an additional 10 min to 0 °C. While cooling the catalyst solution, a monomer stock solution of *p*-MePhGE (114 mg, 0.69 mmol) in 0.70 mL anhydrous DME was prepared and filled into a syringe. The end of the syringe needle was sealed by inserting into a septum and transferred outside of the dry box. Subsequently, the monomer solution was added dropwise to the catalyst solution and the polymerization was kept at 0 °C. The polymerization was quenched after 100 min by exposing to air and diluting with acetone. The white solid was washed with acetone several times and dried using Schlenk line vacuum. Conversion was determined by mass to be 97%.

iP(p-MePhGE)

^1H NMR (500 MHz, TCE- d_2 , 130 °C): δ 7.21 – 6.94 (m, 2H), 6.94 – 6.71 (m, 2H), 4.17 – 3.93 (m, 2H), 3.93 – 3.60 (m, 3H), 2.41 – 2.19 (m, 3H).

^{13}C NMR (500 MHz, TCE- d_2 , 130 °C): 156.91, 129.84, 129.60, 114.95, 78.55 (CH, *mm*), 78.44 + 78.32 (CH, *mr + rm*), 78.30 (CH, *rr*), 70.14 (CH₂, *mm*), 70.10 + 69.92 + 69.86 (CH₂, *mr + rm + rr*), 68.90, 20.01.

iP(m-MePhGE)

^1H NMR (500 MHz, TCE- d_2 , 130 °C): δ 7.22 – 7.03 (m, 2H), 6.88 – 6.63 (m, 2H), 4.21 – 3.96 (m, 2H), 3.88 – 3.63 (m, 3H), 2.39 – 2.23 (m, 3H).

^{13}C NMR (500 MHz, TCE- d_2 , 130 °C): 158.99, 139.07, 128.88, 121.62, 115.91, 111.89, 78.55 (CH, *mm*), 78.46 + 78.41 (CH, *mr + rm*), 78.36 (CH, *rr*), 70.10 (CH₂, *mm*), 70.06 + 69.92 + 69.84 (CH₂, *mr + rm + rr*), 68.63, 20.99.

iP(o-MePhGE)

^1H NMR (500 MHz, TCE- d_2 , 130 °C): δ 7.17 – 7.04 (m, 2H), 6.93 – 6.75 (m, 2H), 4.17 – 4.00 (m, 2H), 3.95 – 3.79 (m, 3H), 2.29 – 2.19 (m, 3H).

^{13}C NMR (500 MHz, 1 TCE- d_2 , 130 °C): 157.00, 130.49, 126.85, 126.51, 120.58, 111.96, 78.67 (CH, *mm*), 78.60 + 78.56 (CH, *mr + rm*), 78.50 (CH, *rr*), 70.22 (CH₂, *mm*), 69.96 + 69.67 (CH₂, *mr + rm + rr*), 68.78, 15.66.

iP(PhGE)

^1H NMR (500 MHz, TCE- d_2 , 130 °C): δ 7.36 – 7.11 (m, 2H), 7.04 – 6.79 (m, 2H), 4.23 – 3.97 (m, 2H), 3.97 – 3.64 (m, 3H).

^{13}C NMR (500 MHz, TCE- d_2 , 130 °C): 158.95, 129.15, 120.79, 115.05, 78.51 (CH, *mm*), 78.42 + 78.38 (CH, *mr + rm*), 78.31 (CH, *rr*), 70.09 (CH₂, *mm*), 70.05 + 69.90 + 69.84 (CH₂, *mr + rm + rr*), 68.68.

Stereocomplex Formation and Characterization

Stereocomplex preparation by solution blending

15 mg of each polymer was dissolved in THF in a 20 mL vial and subsequently heated to 150 °C until fully dissolved. THF was allowed to evaporate and the stereocomplex was dried utilizing a Schlenk line.

Table S 1: *iP*(*p*-MePhGE) stereocomplex characteristics produced by polymerization and mixing, respectively, compared to their enantiomeric polymer analogues.

Entry	Catalyst	RPhGE	t_{rxn} (min)	<i>conv.</i> ^d (%)	M_n^e (kg/mol)	$\bar{D}^e$ (M_w/M_n)	T_c^g (°C)	T_m^g (°C)	ΔH^h (J/g)
1 ^a	(<i>R</i>)-1	<i>p</i> -Me	30	52	43.7	2.01	143	170	36
2 ^a	(<i>S</i>)-1	<i>p</i> -Me	30	41	41.1	2.26	144	172	46
3 ^b	<i>rac</i> -1	<i>p</i> -Me	100	97	82.9 ^h	1.91 ^h	179	214	64
4 ^c	-	<i>p</i> -Me	-	-	-	-	174	209	46

^aGeneral polymerization conditions: [RPhGE] = 1M in DME; [RPhGE]:[cat.]:[[PPN][OAc] = 2000:1:2; T_{rxn} = 0 °C. ^bGeneral polymerization conditions: [RPhGE] = 0.5M in DME; [RPhGE]:[cat.]:[PPN][OAc] = 2000:2:4; T_{rxn} = 0 °C. ^c1:1 mixture of enantiomeric polymers. ^dConversion (*conv.*) was determined gravimetrically. ^eDetermination via gel permeation chromatography (GPC) calibrated with polystyrene in THF at 35 °C if not noted otherwise. ^fPolymer tacticity was determined by quantitative ¹³C NMR spectroscopy at 130°C in 1,1,2,2-tetrachloroethane-*d*₂. ^gDetermined by DSC. Reported T_m values are from second heating run, T_c values are from the first cooling cycle. ^hDetermination by high-temperature gel permeation chromatography (HT-GPC) calibrated with polystyrene samples in 1,2,4-trichlorobenzene at 150 °C.

PXRD Analysis

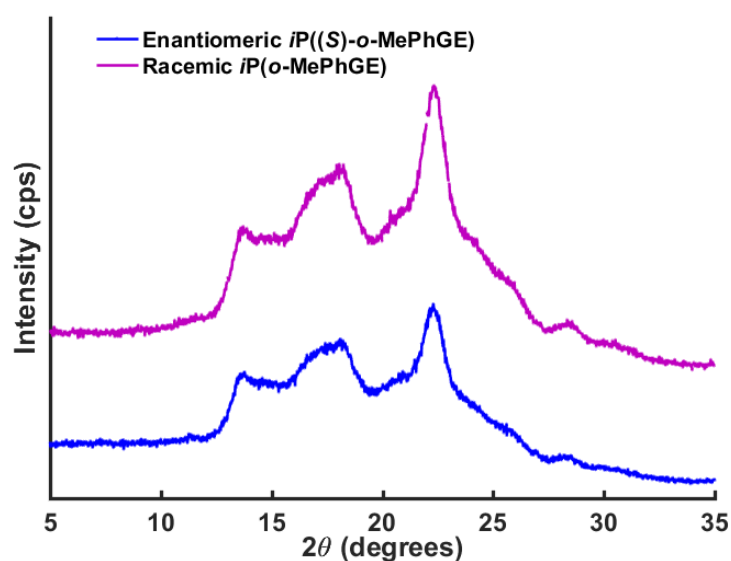


Figure S 1: PXRD profiles of enantiomeric and racemic *iP(o-MePhGE)*. The diffraction patterns feature identical diffraction peaks, disproving stereocomplexation of the racemic *iP(o-MePhGE)*.

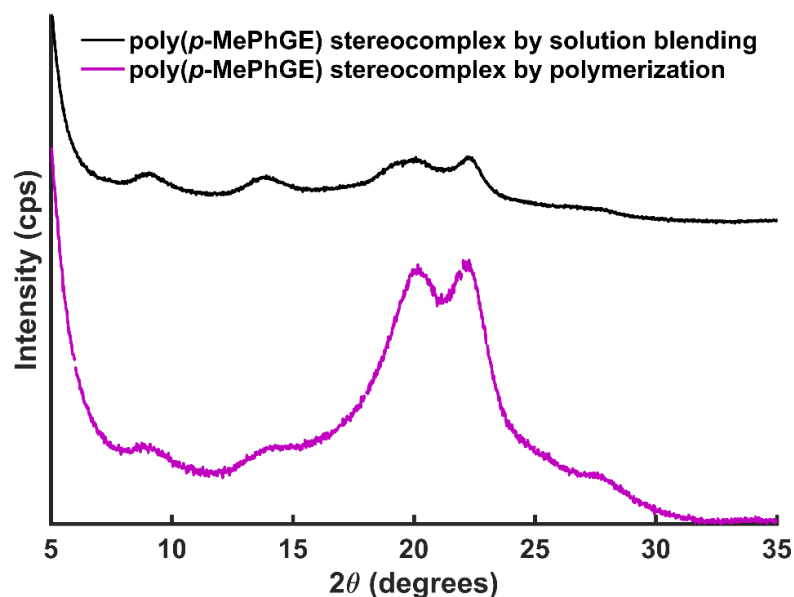
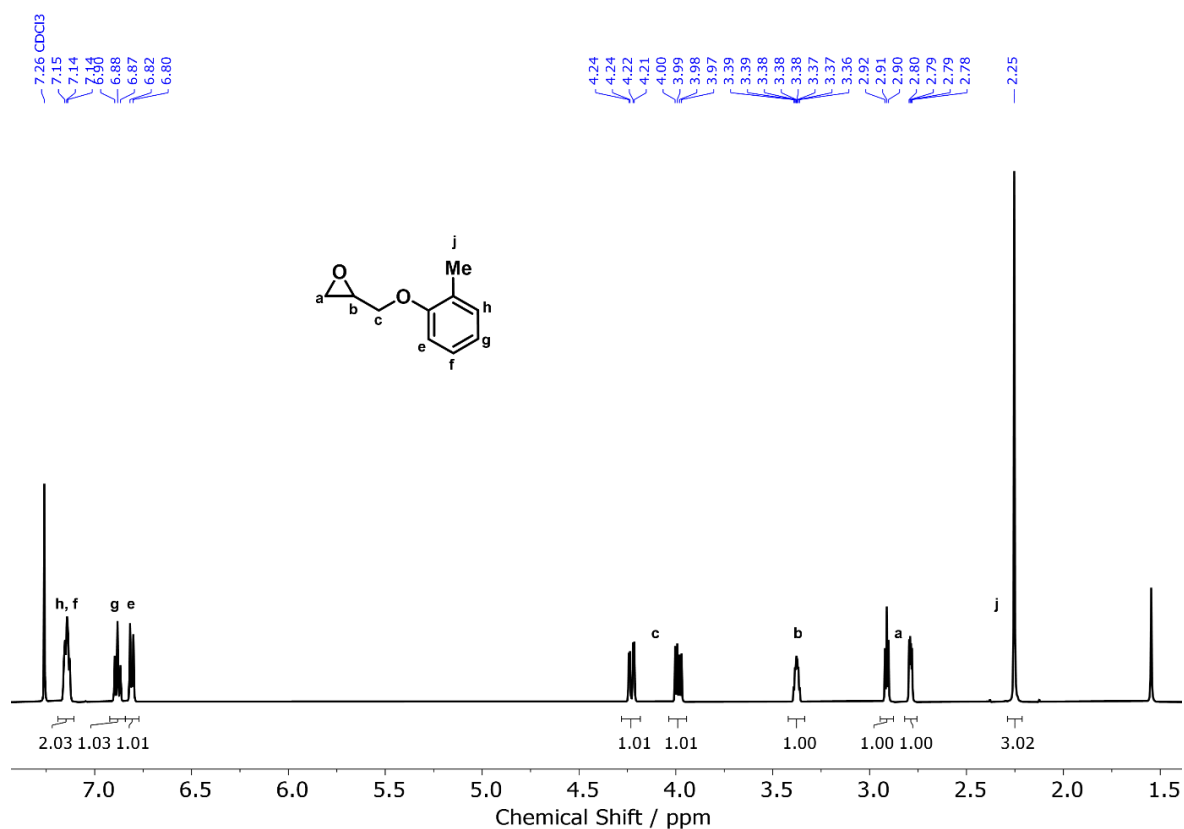
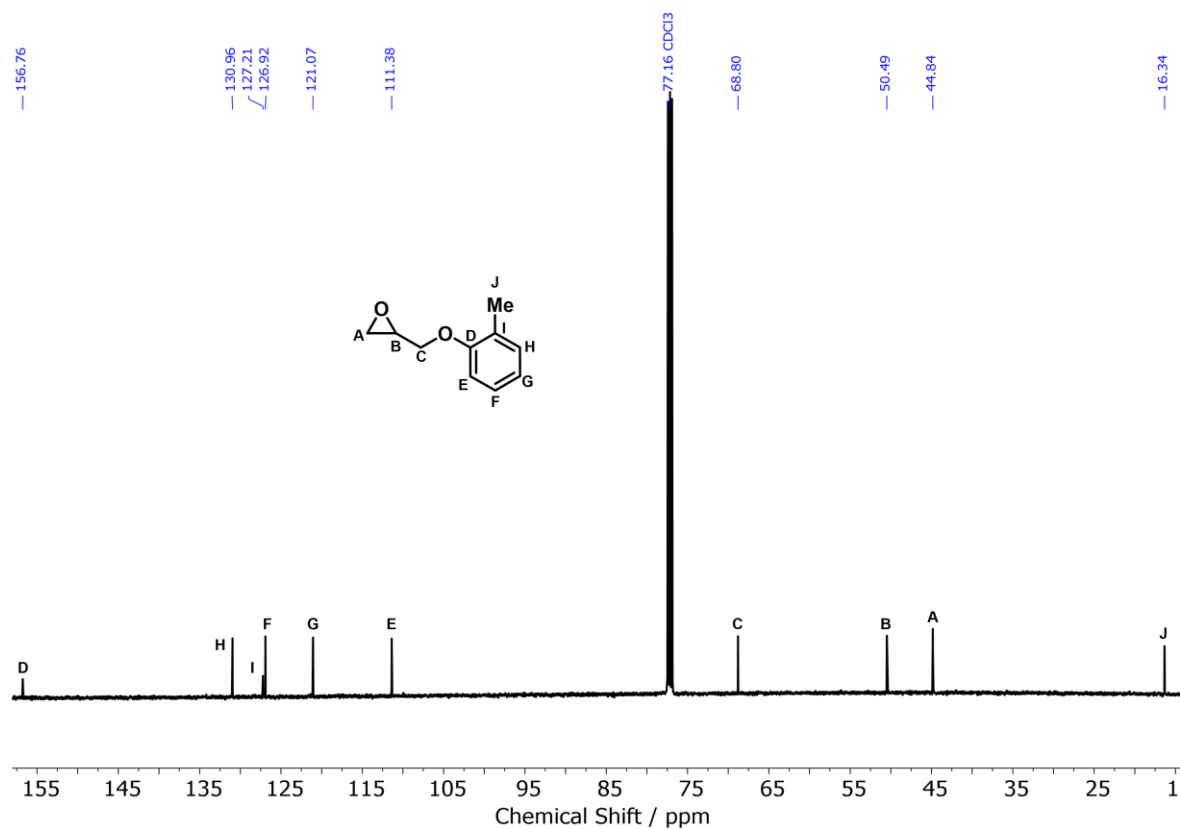
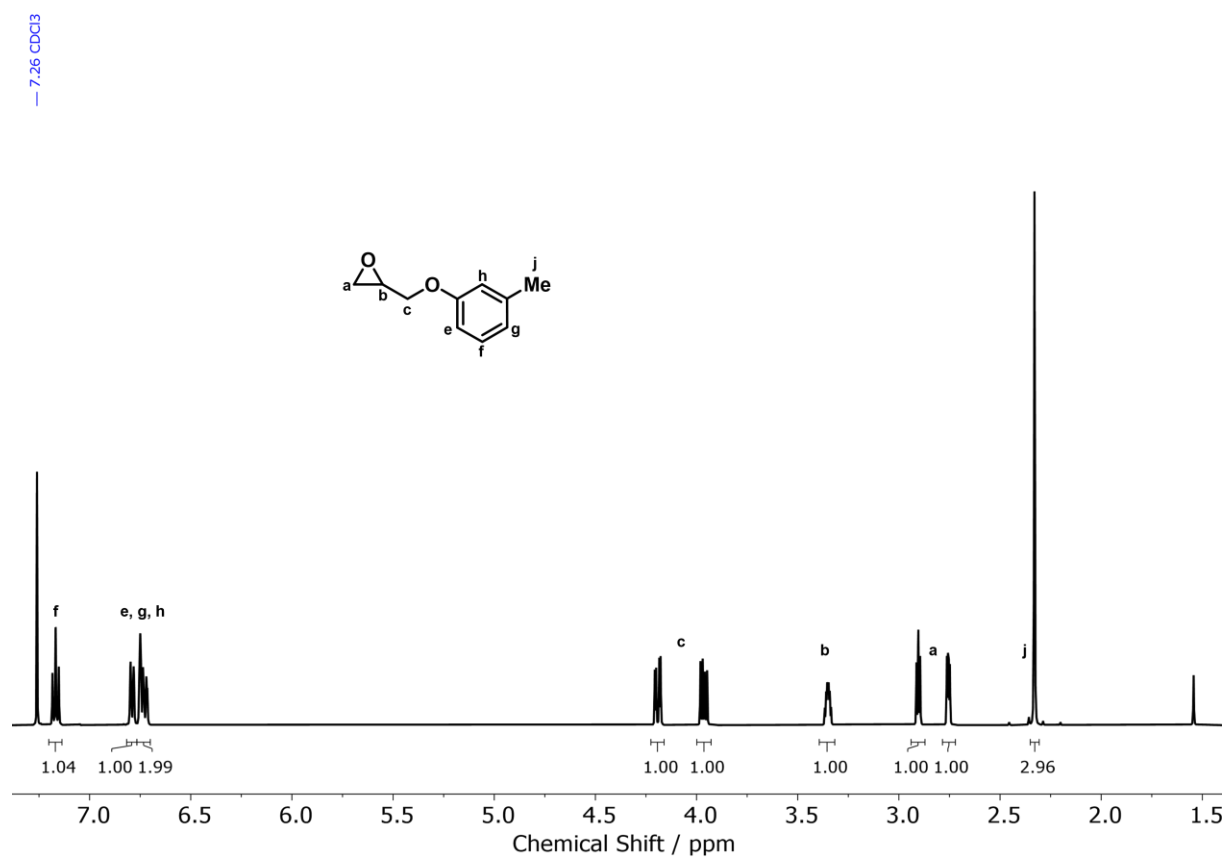
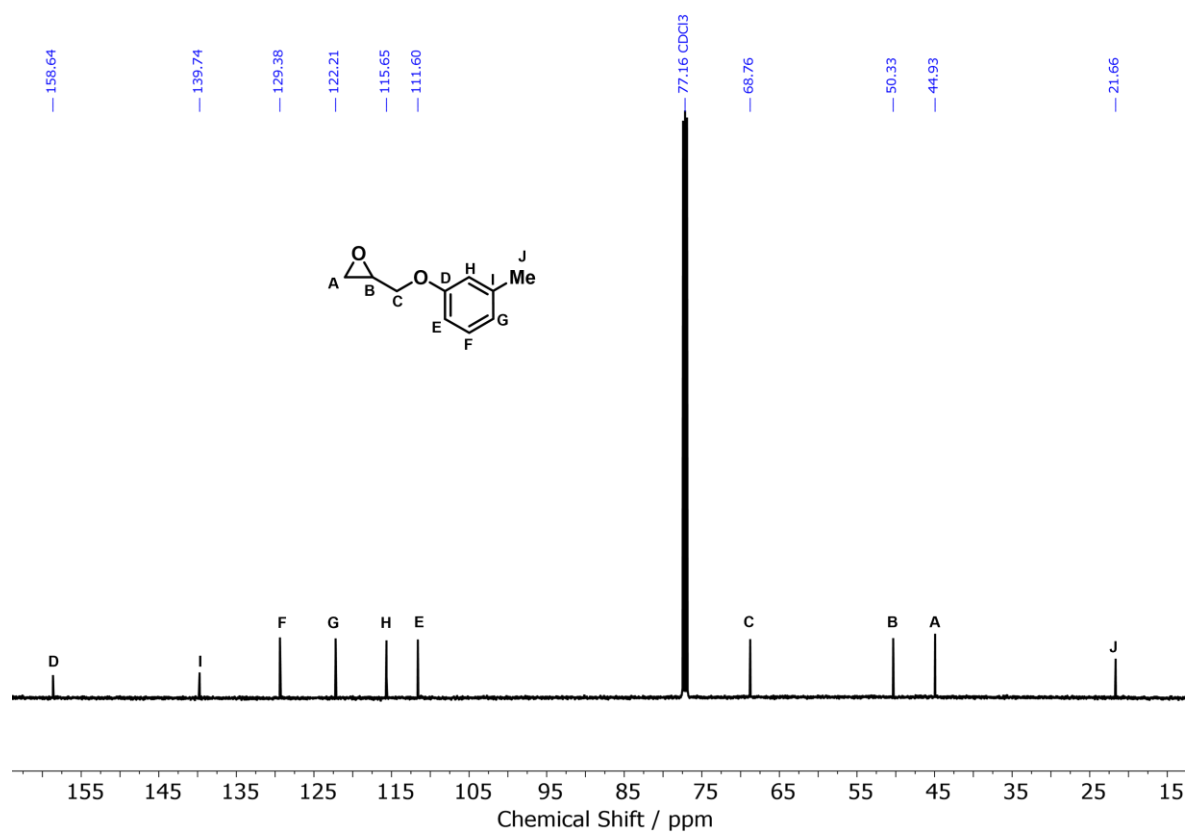
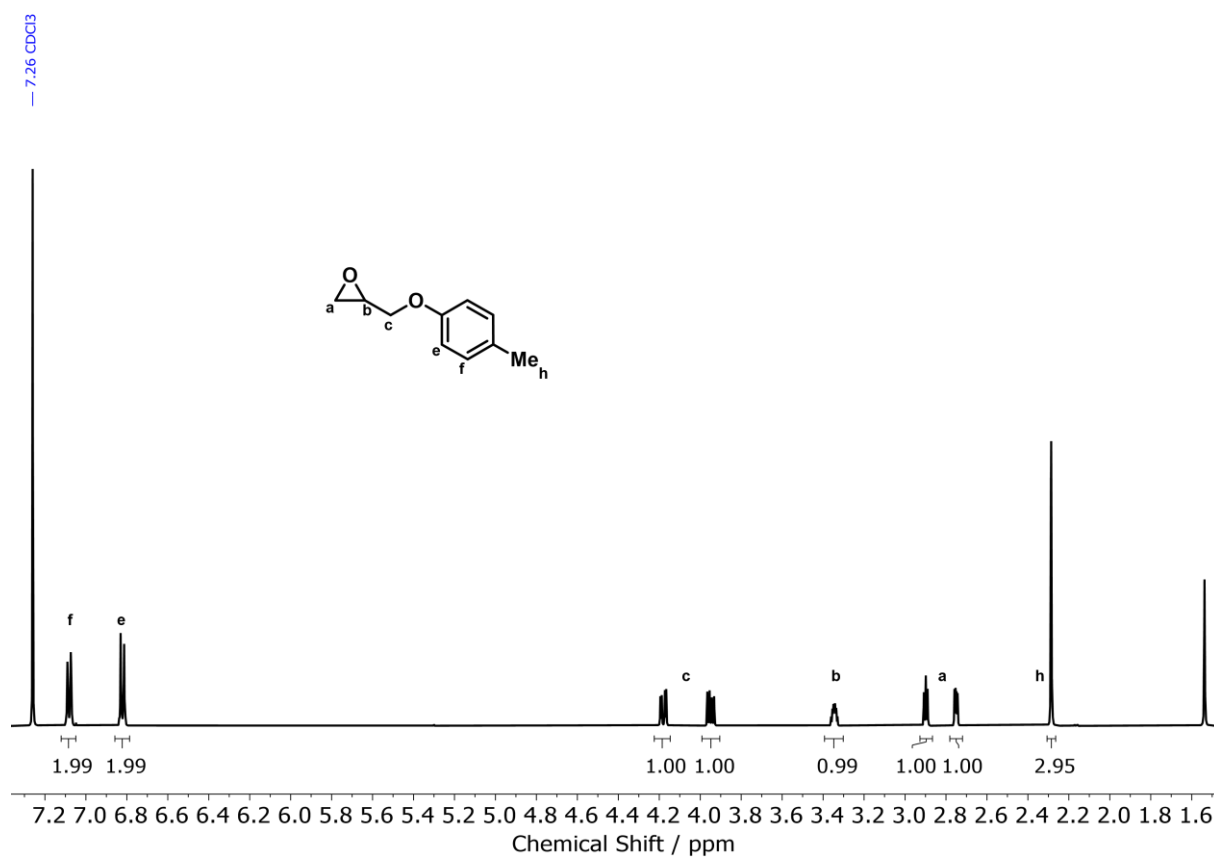
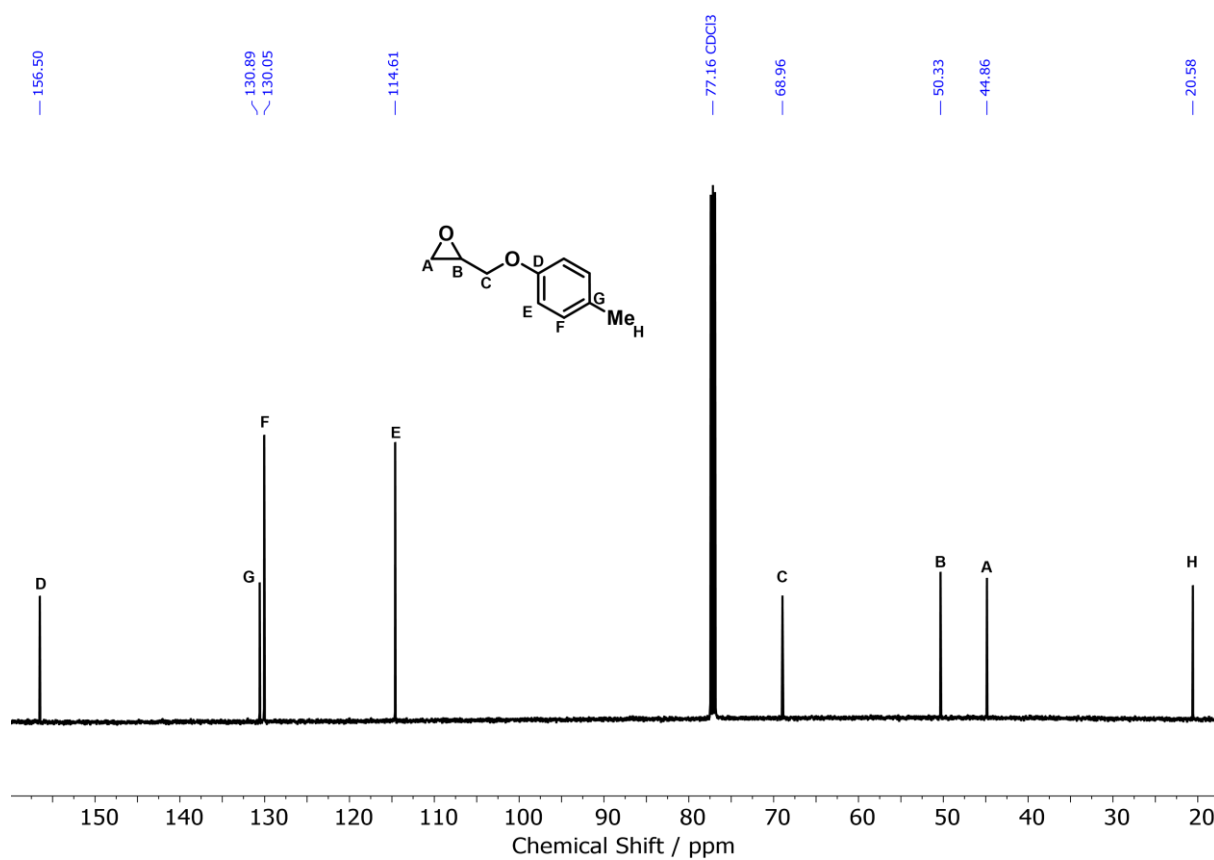


Figure S 2: PXRD profiles of the racemic *iP(p-MePhGE)* stereocomplex produced by a 1:1 blend of *iP((S)-p-MePhGE)* with *iP((R)-p-MePhGE)* (black), and *iP(p-MePhGE)* stereocomplex by isoselective polymerization (purple). Relative peak intensities indicate that the stereocomplex produced by polymerization features a higher crystallinity. Yet, both stereocomplexes show identical reflection patterns, implying a similar order of the chain packing.

NMR Spectra of Synthesized MePhGE Monomers

Figure S 3: ¹H NMR spectrum (500 MHz, CDCl₃, 25 °C) of *o*-MePhGE.Figure S 4: ¹³C NMR spectrum (125 MHz, CDCl₃, 25 °C) of *o*-MePhGE.

Figure S 5: ¹H NMR spectrum (500 MHz, CDCl₃, 25 °C) of *m*-MePhGE.Figure S 6: ¹³C NMR spectrum (125 MHz, CDCl₃, 25 °C) of *m*-MePhGE.

Figure S 7: ¹H NMR spectrum (500 MHz, CDCl₃, 25 °C) of *p*-MePhGE.Figure S 8: ¹³C NMR spectrum (125 MHz, CDCl₃, 25 °C) of *p*-MePhGE.

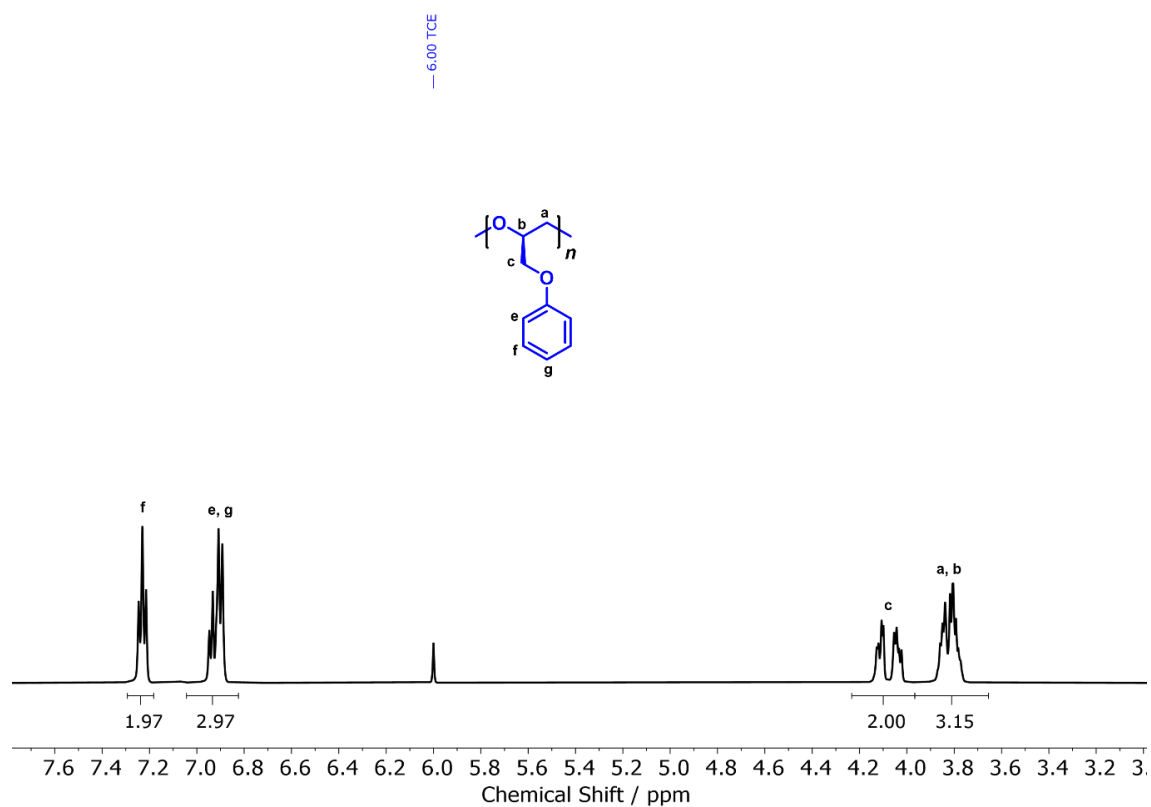
NMR Spectra of *i*P((*S*)-RPhGE)

Figure S 9: ^1H NMR spectrum (500 MHz, $\text{TCE-}d_2$, 130 °C) of enantiomeric *i*P((*S*)-PhGE), synthesized via enantioselective polymerization.

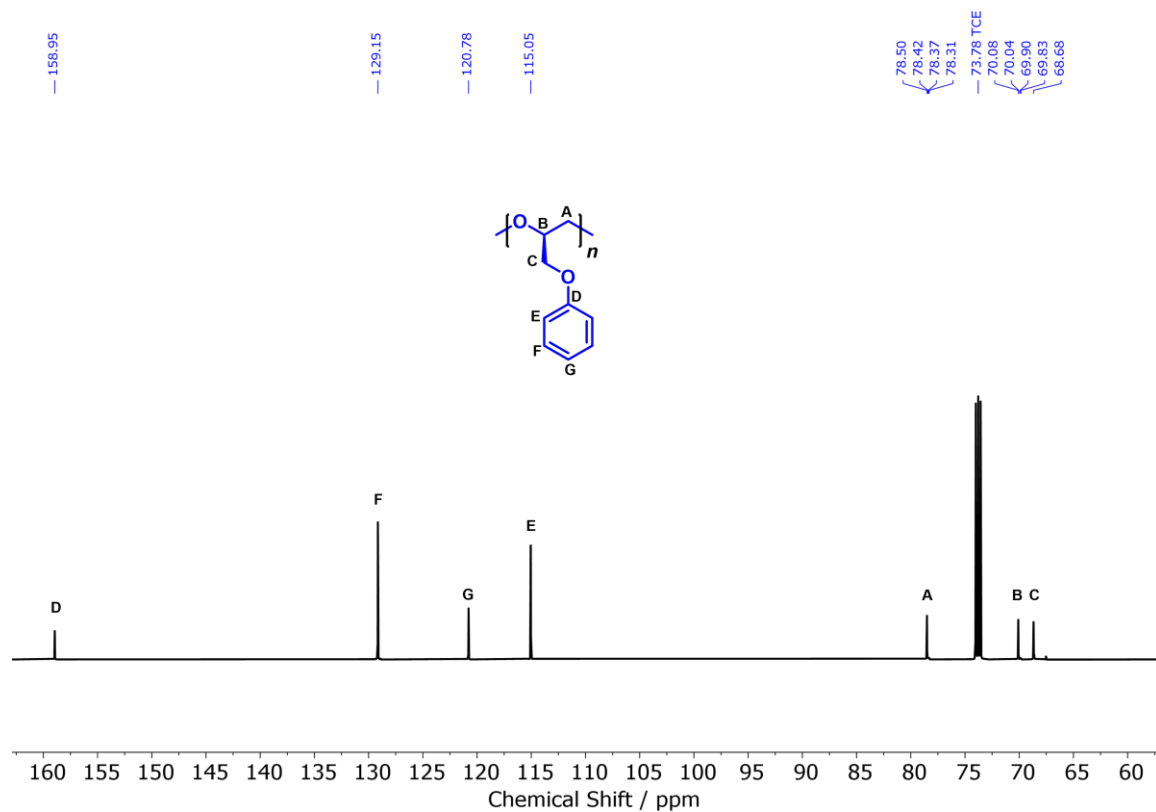


Figure S 10: ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 °C) of enantiomeric *i*P((*S*)-PhGE), synthesized via enantioselective polymerization.

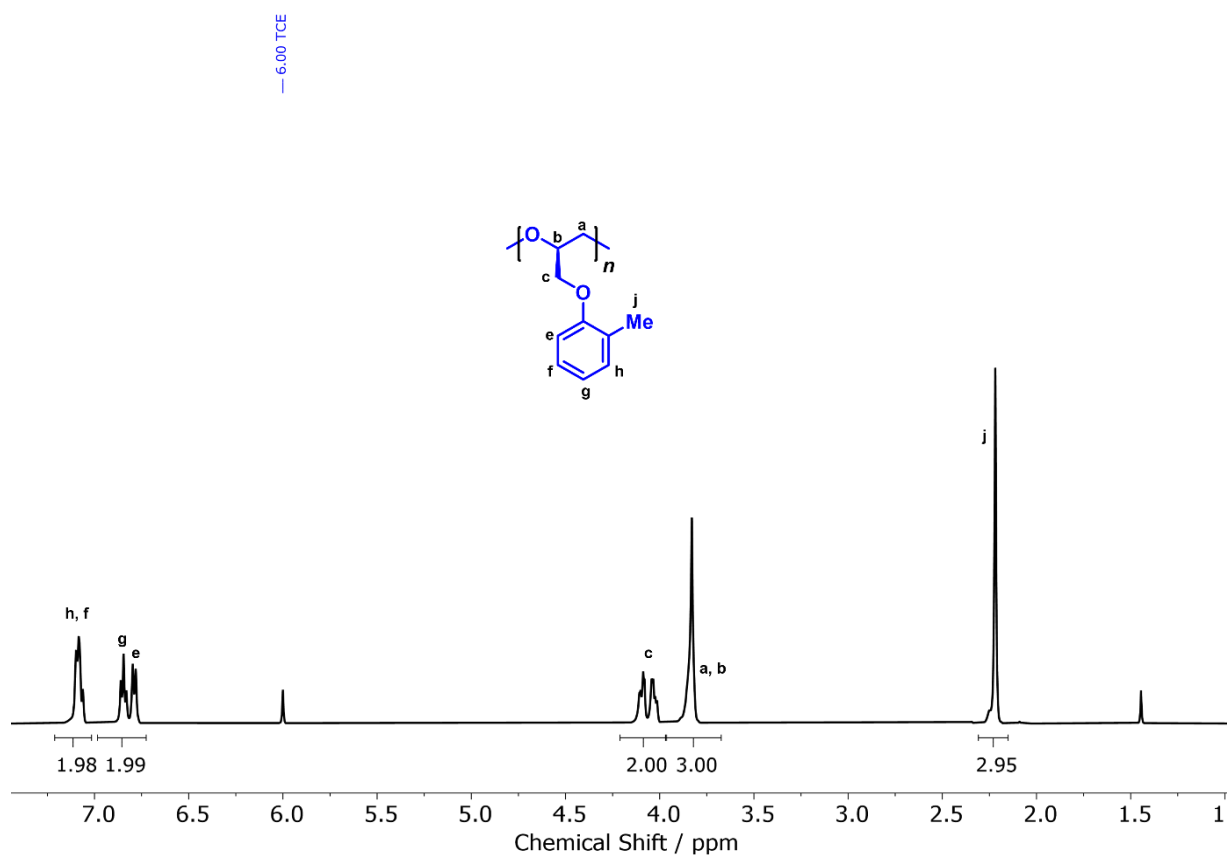


Figure S 11: ^1H NMR spectrum (500 MHz, $\text{TCE-}d_2$, 130 $^\circ\text{C}$) of enantiomeric $i\text{P}((S)\text{-}o\text{-MePhGE})$, synthesized via enantioselective polymerization.

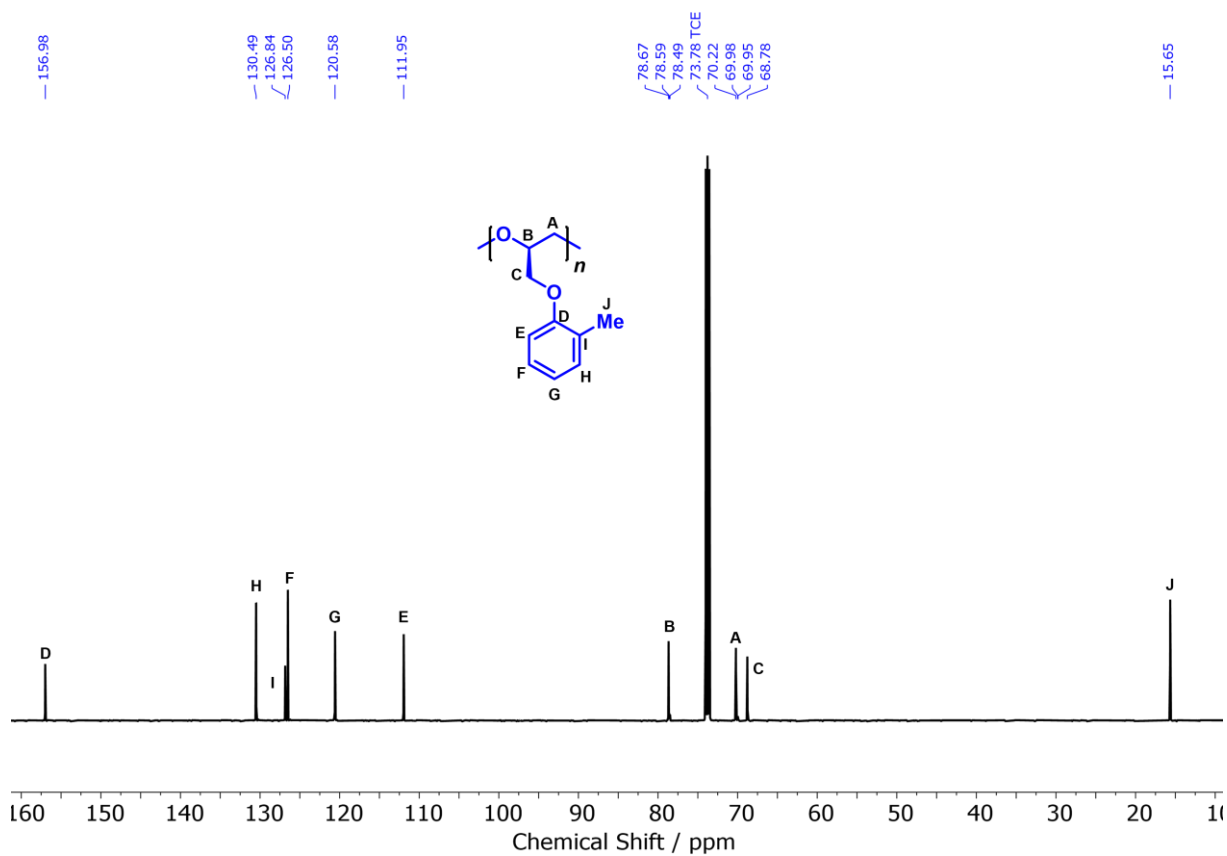


Figure S 12: ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 $^\circ\text{C}$) of enantiomeric $i\text{P}((S)\text{-}o\text{-MePhGE})$, synthesized via enantioselective polymerization.

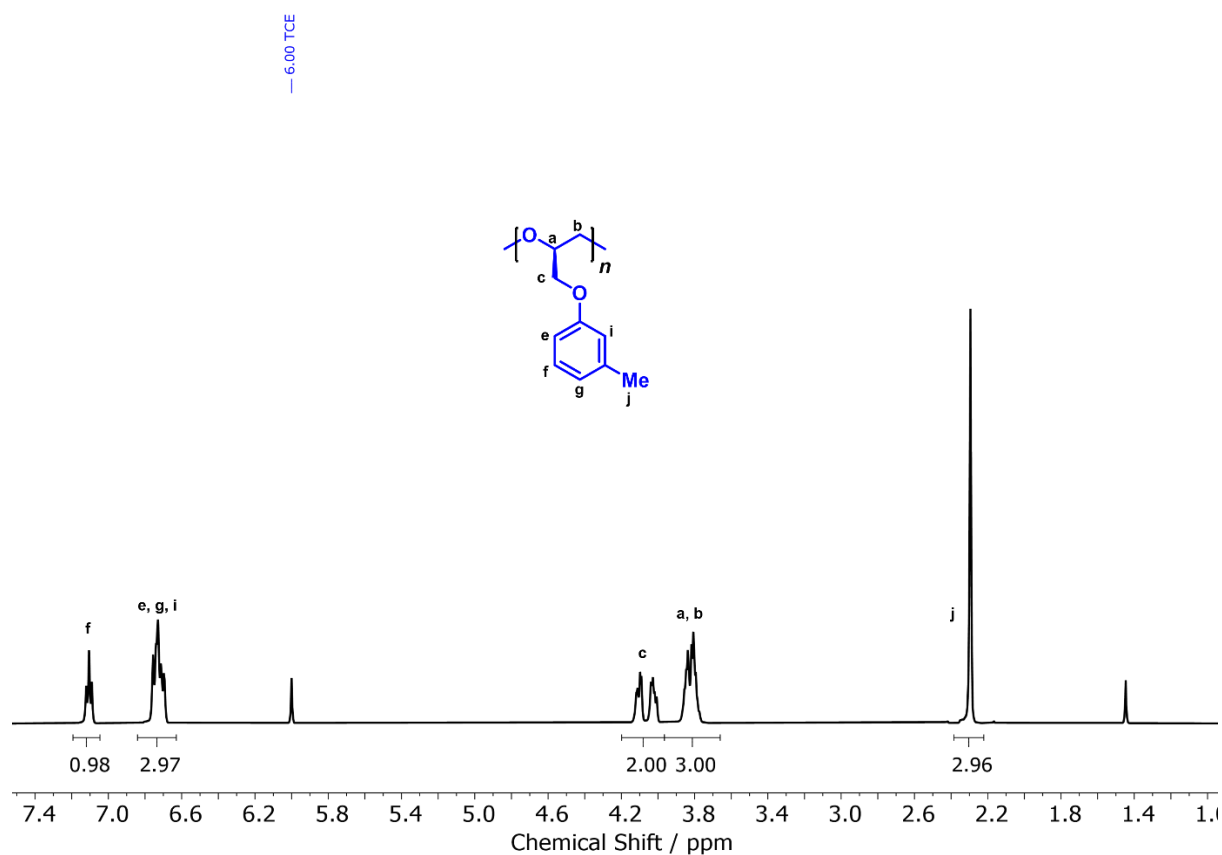


Figure S 13: ^1H NMR spectrum (500 MHz, TCE- d_2 , 130 $^\circ\text{C}$) of enantiomeric $iP((S)\text{-}m\text{-MePhGE})$, synthesized via enantioselective polymerization.

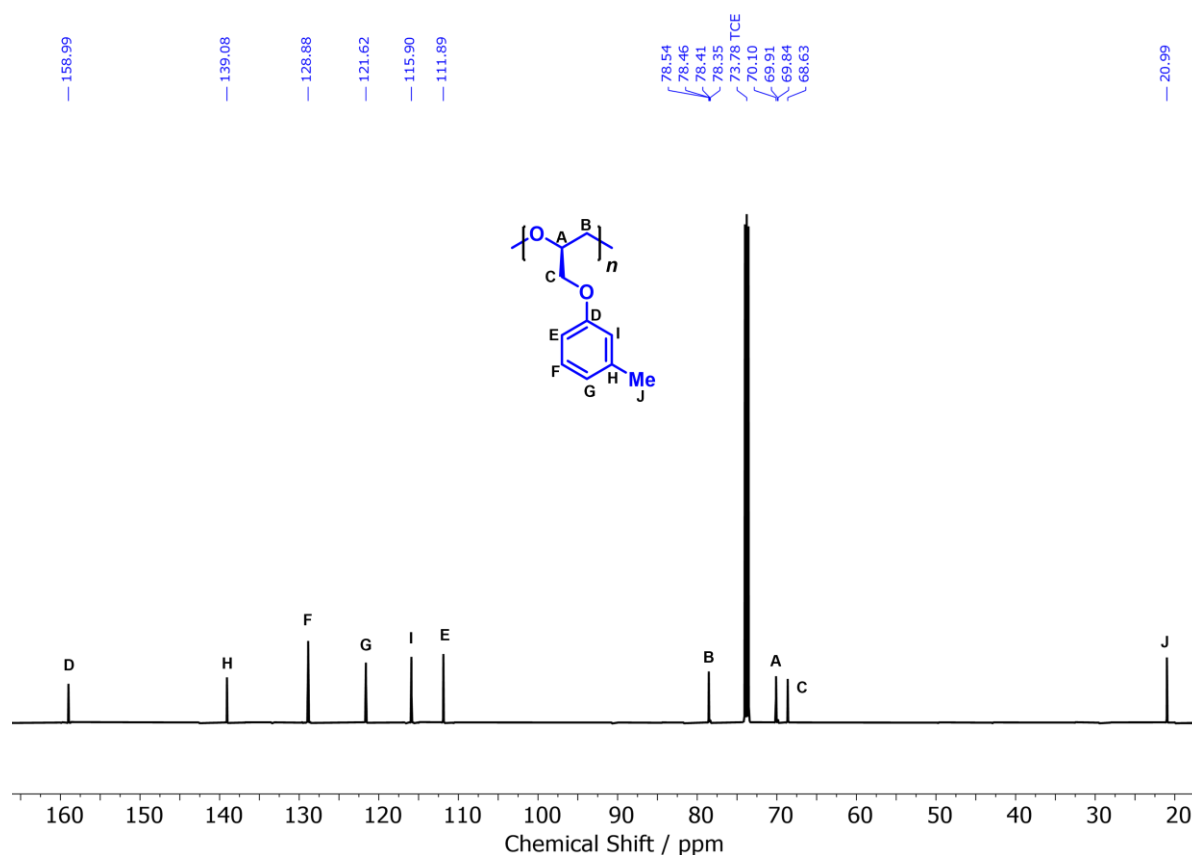


Figure S 14: ^{13}C NMR spectrum (125 MHz, TCE- d_2 , 130 $^\circ\text{C}$) of enantiomeric $iP((S)\text{-}m\text{-MePhGE})$, synthesized via enantioselective polymerization.

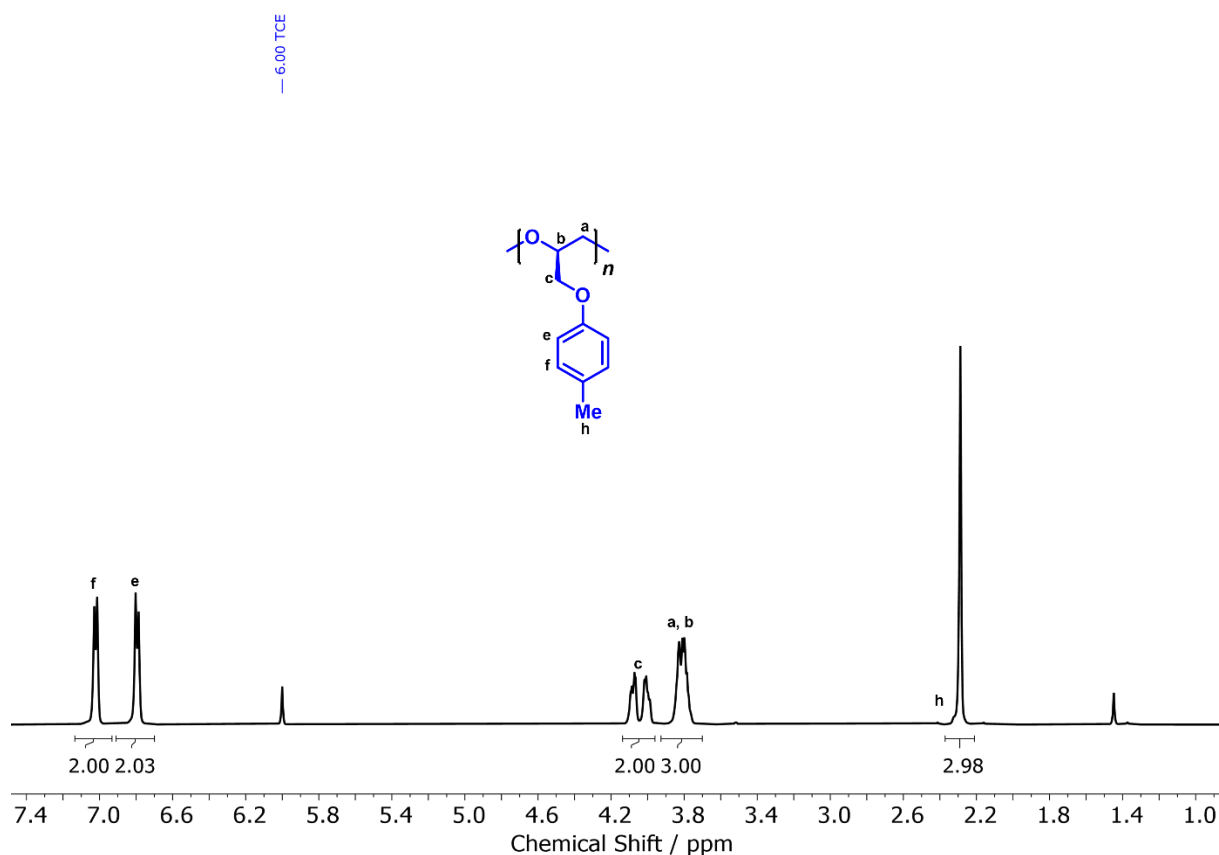


Figure S 15: ^1H NMR spectrum (500 MHz, TCE- d_2 , 130 °C) of isotactic $iP((S)\text{-}p\text{-MePhGE})$, synthesized via enantioselective polymerization.

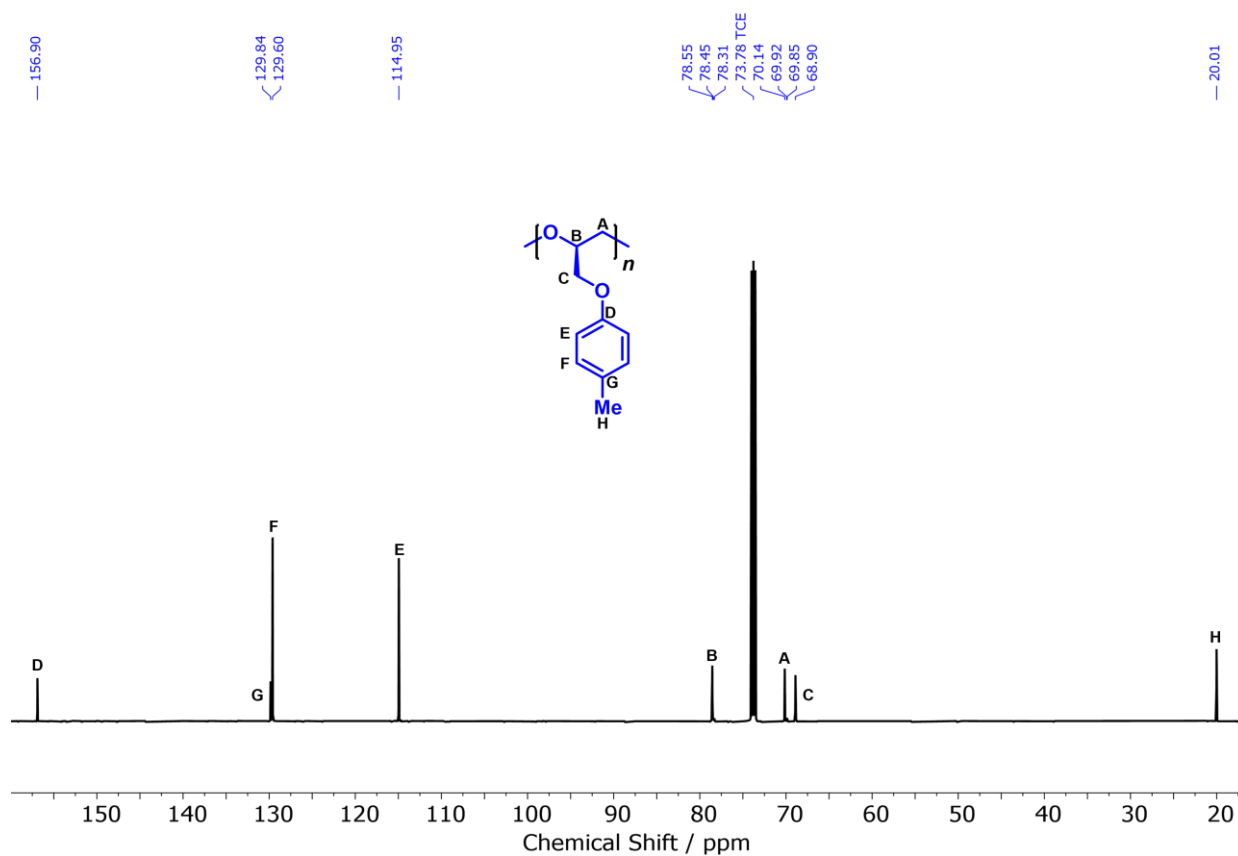


Figure S 16: ^{13}C NMR spectrum (125 MHz, TCE- d_2 , 130 °C) of enantiomeric $iP((S)\text{-}p\text{-MePhGE})$, synthesized via enantioselective polymerization.

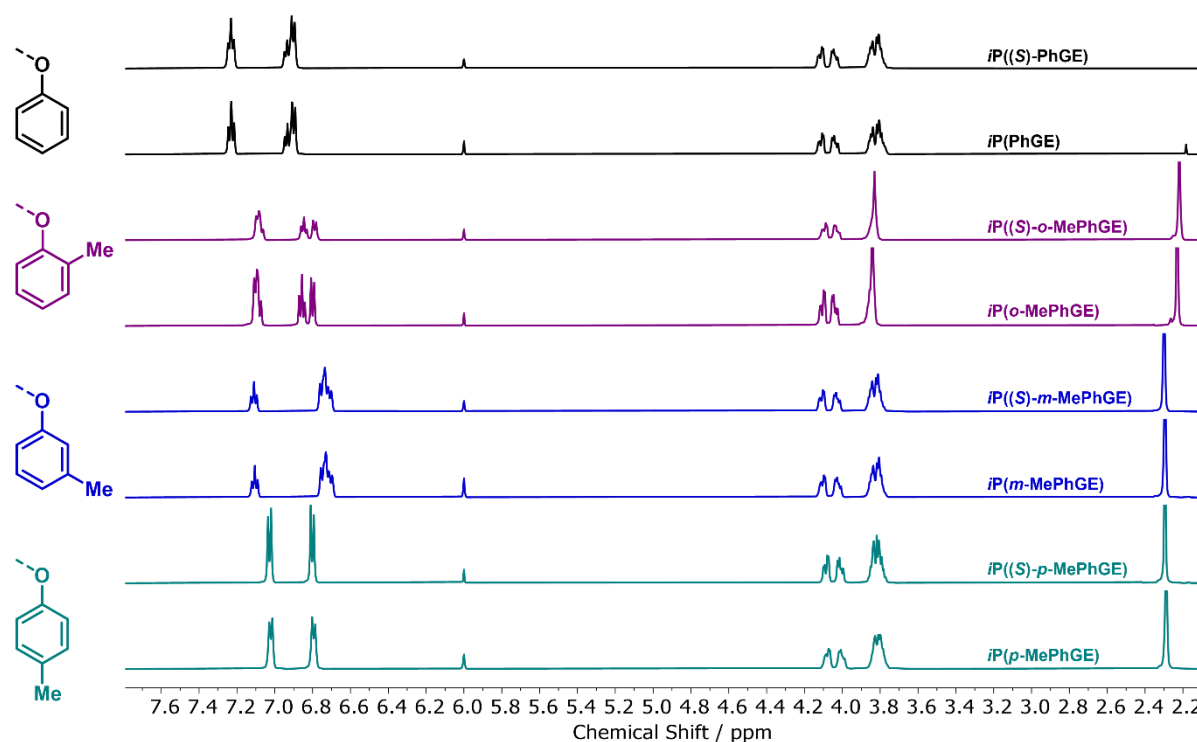


Figure S 17: Overlay of ¹H NMR spectra (500 MHz, TCE-*d*₂, 130 °C) of enantiomeric and racemic, stereoregular *iP*(RPhGE) of varying substitution pattern of the phenyl pendant group.

NMR Quantification of Polymer Tacticity and Selectivity Factors

^{13}C NMR analysis is a common method to determine the type of polymer tacticity and the degree of stereoregularity of a polymer sample. The shifts of various main chain carbon nuclei are sensitive to adjacent stereogenic centers, leading to a distinct fine carbon resonance structure.^[5] In the case of the synthesized isotactic poly(phenyl glycidyl ether)s (*i*P(PhGE)s), the ^{13}C NMR spectra feature various distinct carbon resonances in the ^{13}C NMR spectra as a consequence of stereochemical defects in the polymer main chain. Figure S 18 mirrors the potential triads observed in the absence and presence of stereodefects within the isotactic polyether chain.

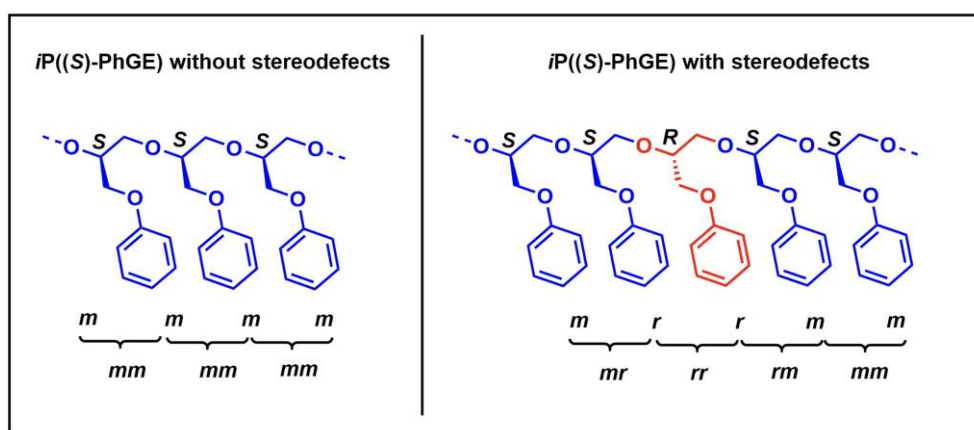


Figure S 18: Possible *i*P(PhGE) tacticities, stereoerrors and respective triad assignment according to the Bovey formalism.

Determination of Polyether Tacticity

The degree of isotacticity is generally reported as $[mm]$. If applicable, the ^{13}C satellite signals of the mm triad are omitted due to their low signal-to-noise ratio. Consequentially, the mm integral is smaller and, in turn, this analysis provides more conservative $[mm]$ values and selectivity factors (*s*-factors). In consideration of the triad stereosequence, every rr triad is accompanied by a mr and rm triad, as visualized on the right in Figure S 18 (due to enantiomorphous-site control).^[6] In conclusion, the following equations apply:

$$[mm] + [rm] + [mr] + [rr] = 1 \quad \text{Eq. 1}$$

$$[rr] = [mr] = [rm] \quad \text{Eq. 2}$$

$$[mm] = 1 - 3[rr] \quad \text{Eq. 3}$$

Triad Analysis and Determination of *s*-factor

Quantitative ^{13}C NMR analysis of all isotactic poly(phenyl glycidyl ether) samples leads to a sufficient triad resolution of the methine carbon of the polyether main chain (ca. 79 ppm), allowing for the triad quantification and the calculation of $[mm]$ as previously reported.^[1,2,5] Since the two heterotactic stereosequences mr and rm are not resolved and additionally overlap with the upfield ^{13}C satellite signals (where applicable) of the mm triad, the distinct rr triad signal is instrumental in precisely calculating $([mr] + [rm])$ for highly isotactic polyethers. As the triads have not previously been assigned for the *i*P(MePhGE) polyethers, the stereoerror furthest from the mm triad was assumed to be the rr triad. After the integration of the mm (Eq. 4) and rr (Eq. 5) triad, the value allows for the calculation of mr and rm triad value (Eq. 2 and Eq. 6) as a result of enantiomorphous-site control statistics.^[6] The $[mm]$ is accessible by the quotient of mm and the total integration value of all methine carbon resonances (mm, mr, rm, rr) (Eq. 7).

$$mm = \int (mm) \quad \text{Eq. 4}$$

$$rr = \int rr \quad \text{Eq. 5}$$

$$(mr + rm) = 2 \int rr \quad \text{Eq. 6}$$

$$[mm] = \frac{mm}{mm + (mr + rm) + rr} \quad \text{Eq. 7}$$

$$[mr] + [rm] = \frac{2 rr}{mm + (mr + rm) + rr} \quad \text{Eq. 8}$$

$[mr]$ and $[rm]$ are given by Eq. 8. Subsequently, the resulting values of the triad analysis were used to calculate the *s*-factor:^[1,2,7]

$$s - \text{factor} = \frac{\ln[1 - \text{conv.} (1 + (2[mm] + ([mr] + [rm]) - 1)^{1/2})]}{\ln[1 - \text{conv.} (1 - (2[mm] + ([mr] + [rm]) - 1)^{1/2})]} \quad \text{Eq. 9}$$

For the integration, the Mestrenova line-fitting tool was employed. Due to the asymmetry of some peaks, triad integrals are composed of more than one peak integration if required. For clarity, the peak fits are omitted, however, the sum function is displayed. Here, the green line corresponds to the sum of the respective peak integrals and matches the experimental peak areas (compare Figures S 19 – 26). Additionally, the red line corresponds with the fitting residues and reflects the difference of the experimental and the integrated peak area (identical to the baseline for an ideal fit).

Exemplarily calculation for *iP*((*S*)-PhGE) (Table 1, entry 1):

$$mm = 109899 + 164861 = 274760$$

$$rr = 21413$$

$$(mr + rm) = 42827$$

$$[mm] = \frac{274760}{274760 + 42827 + 21413} = 0.81$$

$$[mr] + [rm] = \frac{42827}{274760 + 42827 + 21413} = 0.13$$

$$s - \text{factor}_{\text{PhGE}} = \frac{\ln \left[1 - 0.52 \left(1 + (2(0.81) + 0.13 - 1)^{\frac{1}{2}} \right) \right]}{\ln \left[1 - 0.52 \left(1 - (2(0.81) + 0.13 - 1)^{\frac{1}{2}} \right) \right]} = 48$$

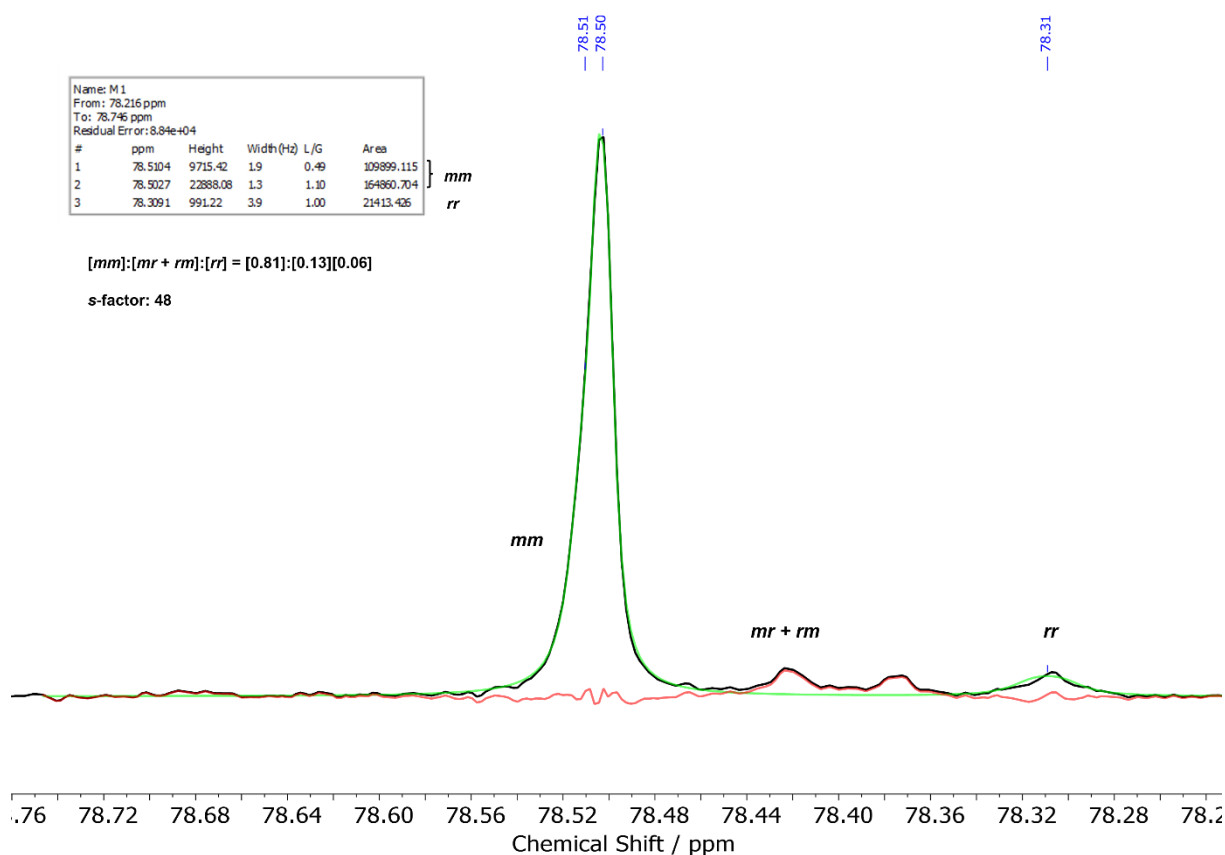


Figure S 19: Methine region of the ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 °C) of enantiomeric *iP*((*S*)-PhGE), synthesized via enantioselective polymerization.

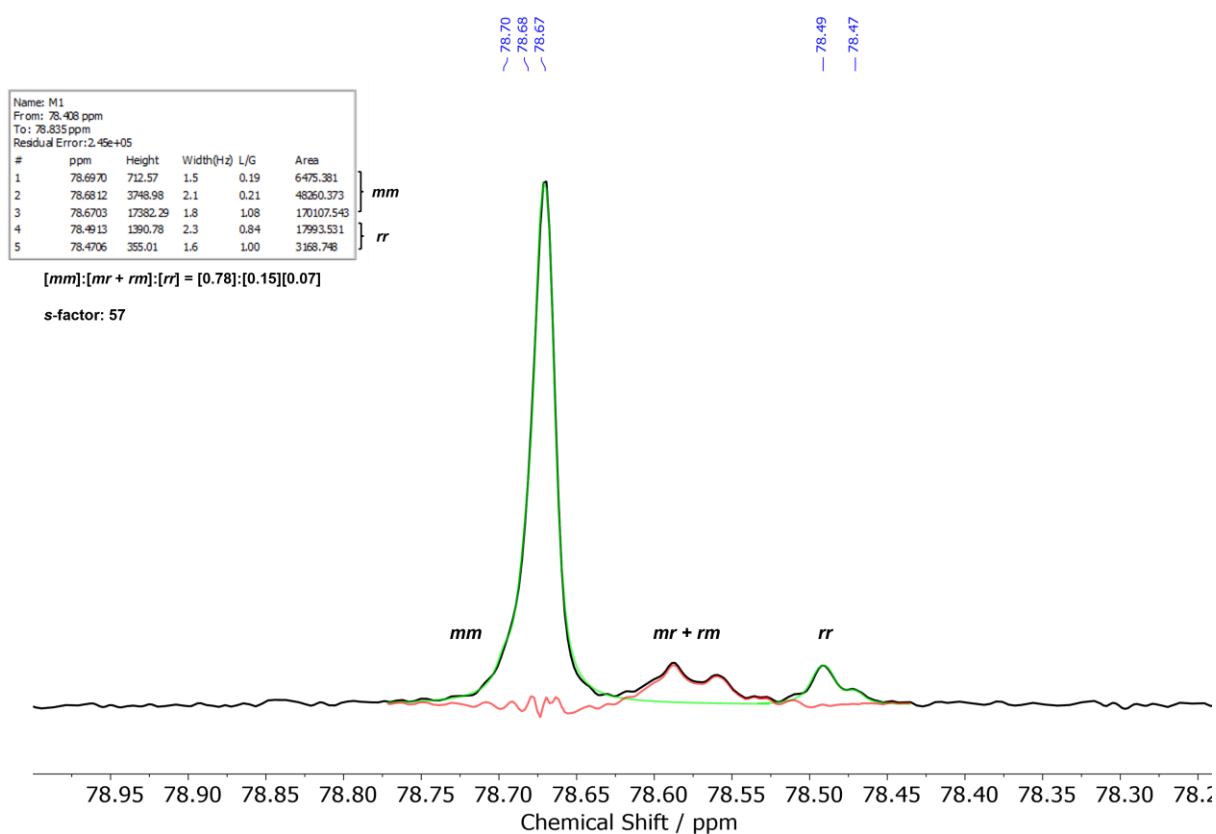


Figure S 20: Methine region of the ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 °C) of enantiomeric $iP((S)\text{-}o\text{-MePhGE})$, synthesized via enantioselective polymerization.

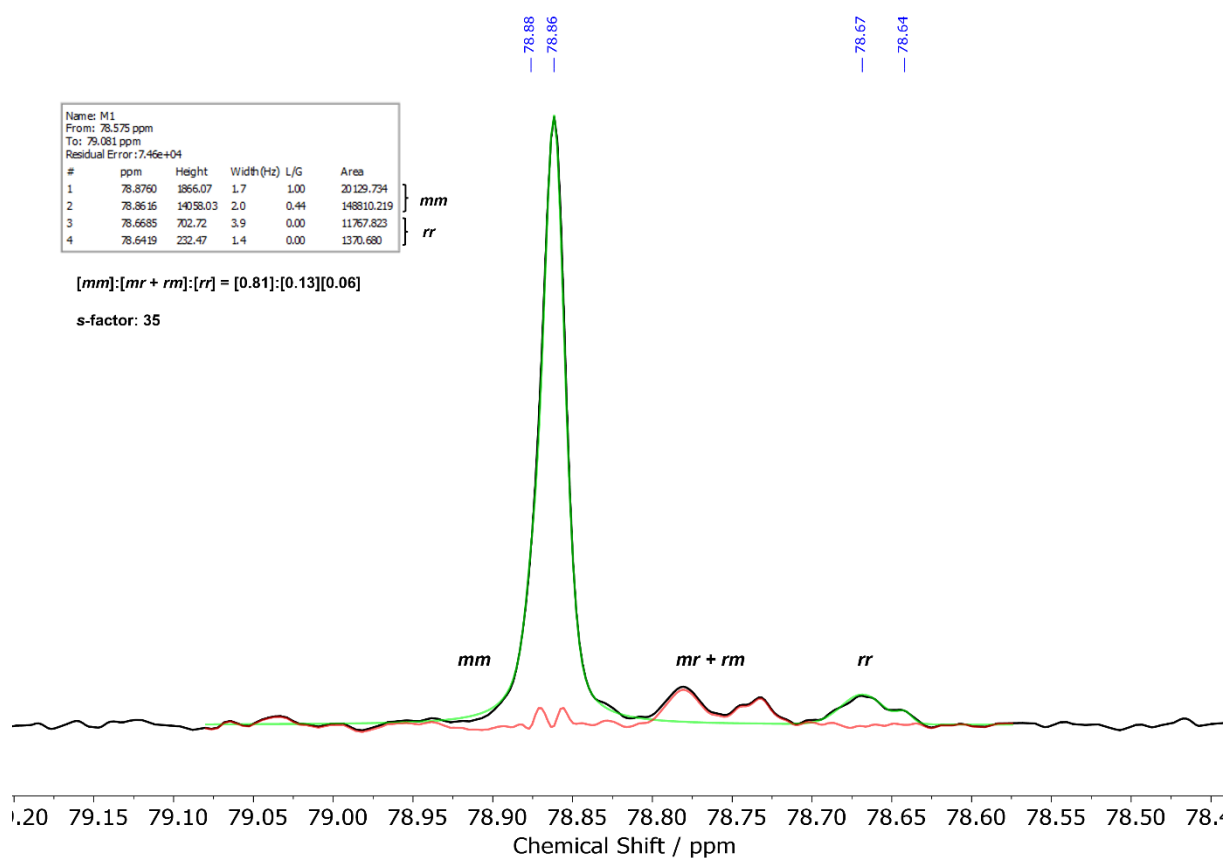


Figure S 21: Methine region of the ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 °C) of enantiomeric $iP((S)\text{-}m\text{-MePhGE})$, synthesized via enantioselective polymerization.

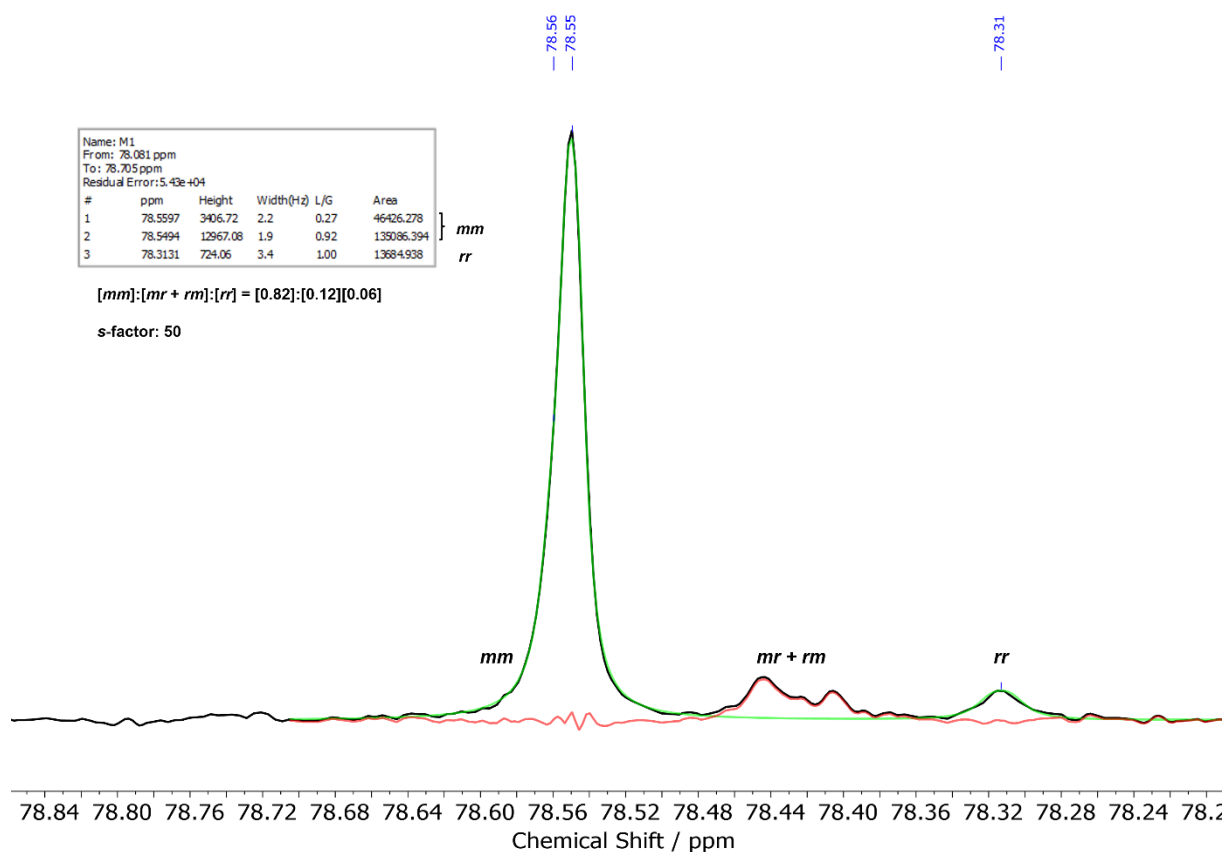


Figure S 22: Methine region of the ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 °C) of enantiomeric $iP((S)\text{-}p\text{-MePhGE})$, synthesized via enantioselective polymerization.

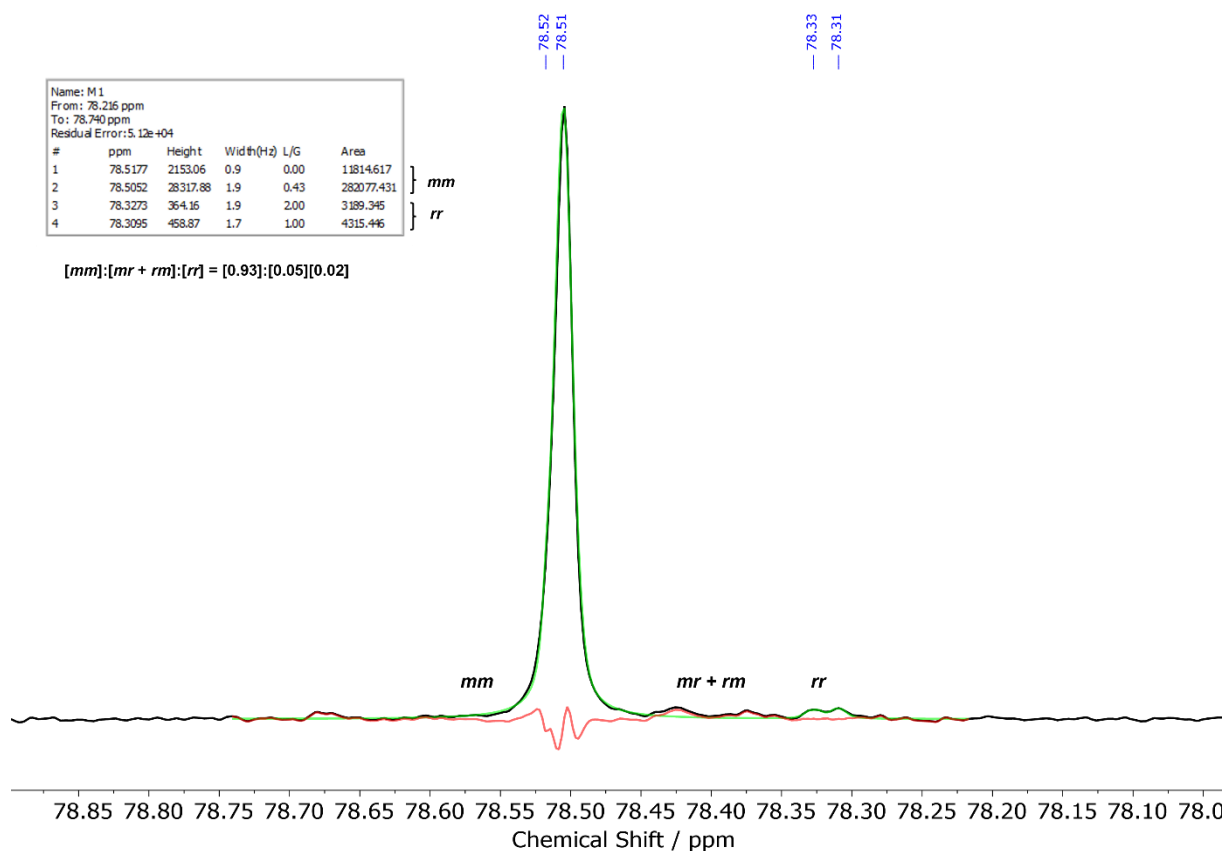


Figure S 23: Methine region of the ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 °C) of racemic $iP(\text{PhGE})$, synthesized via isoselective polymerization.

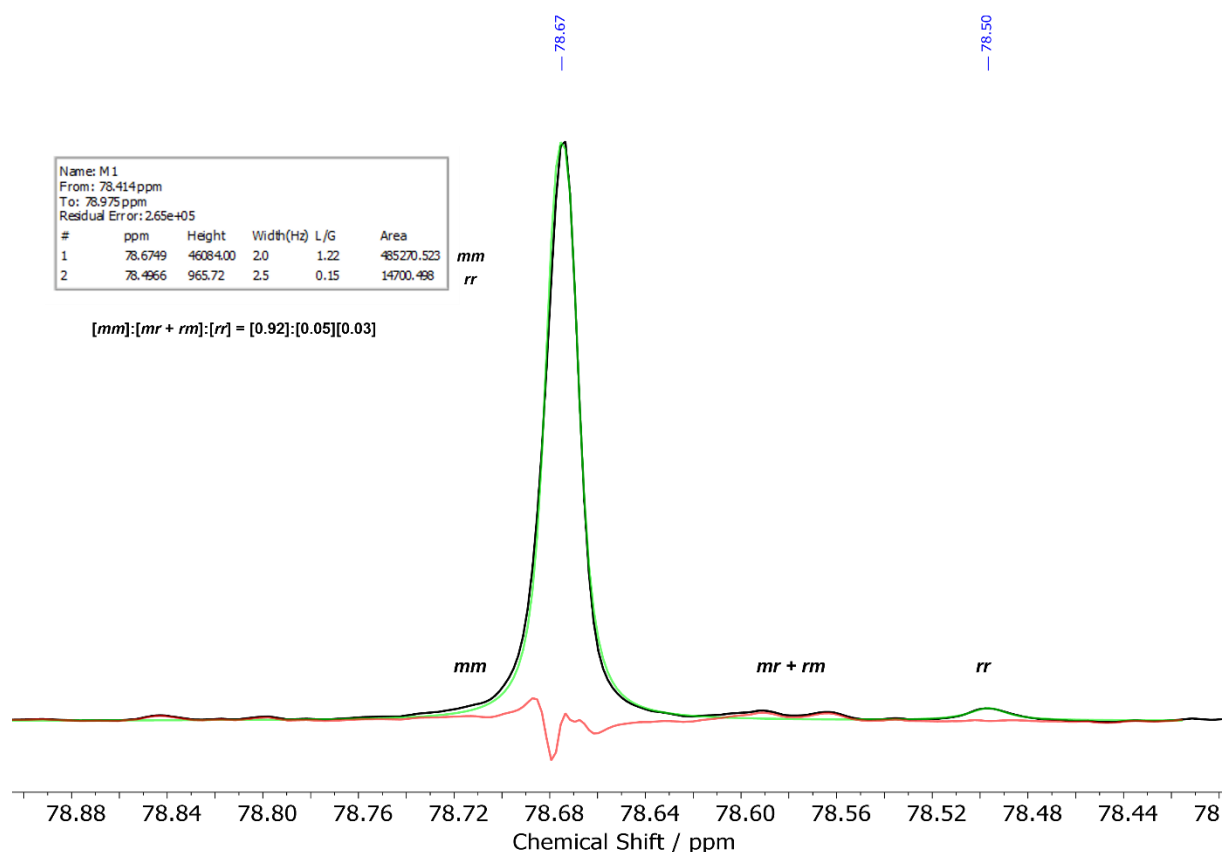


Figure S 24: Methine region of the ^{13}C NMR spectrum (125 MHz, TCE- d_2 , 130 °C) of racemic *iP(o-MePhGE)*, synthesized via isoselective polymerization.

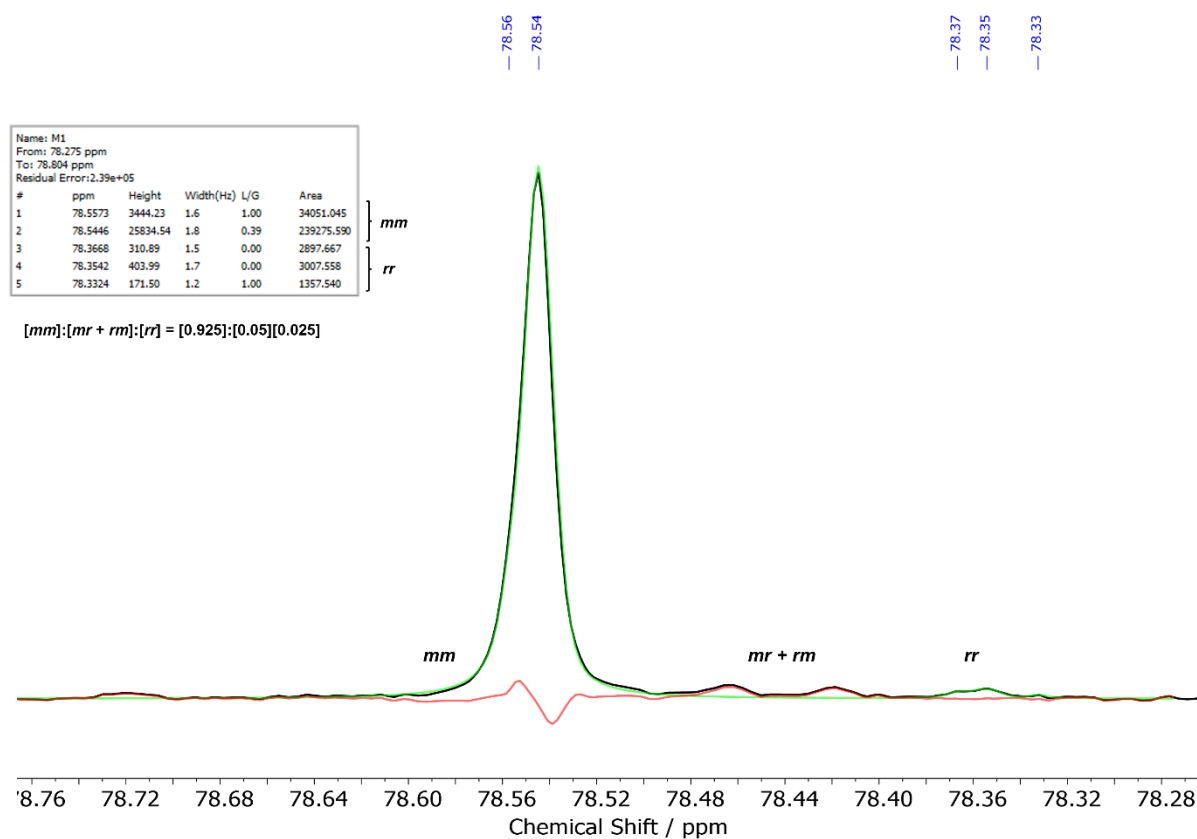


Figure S 25: Methine region of the ^{13}C NMR spectrum (125 MHz, TCE- d_2 , 130 °C) of racemic *iP(m-MePhGE)*, synthesized via isoselective polymerization.

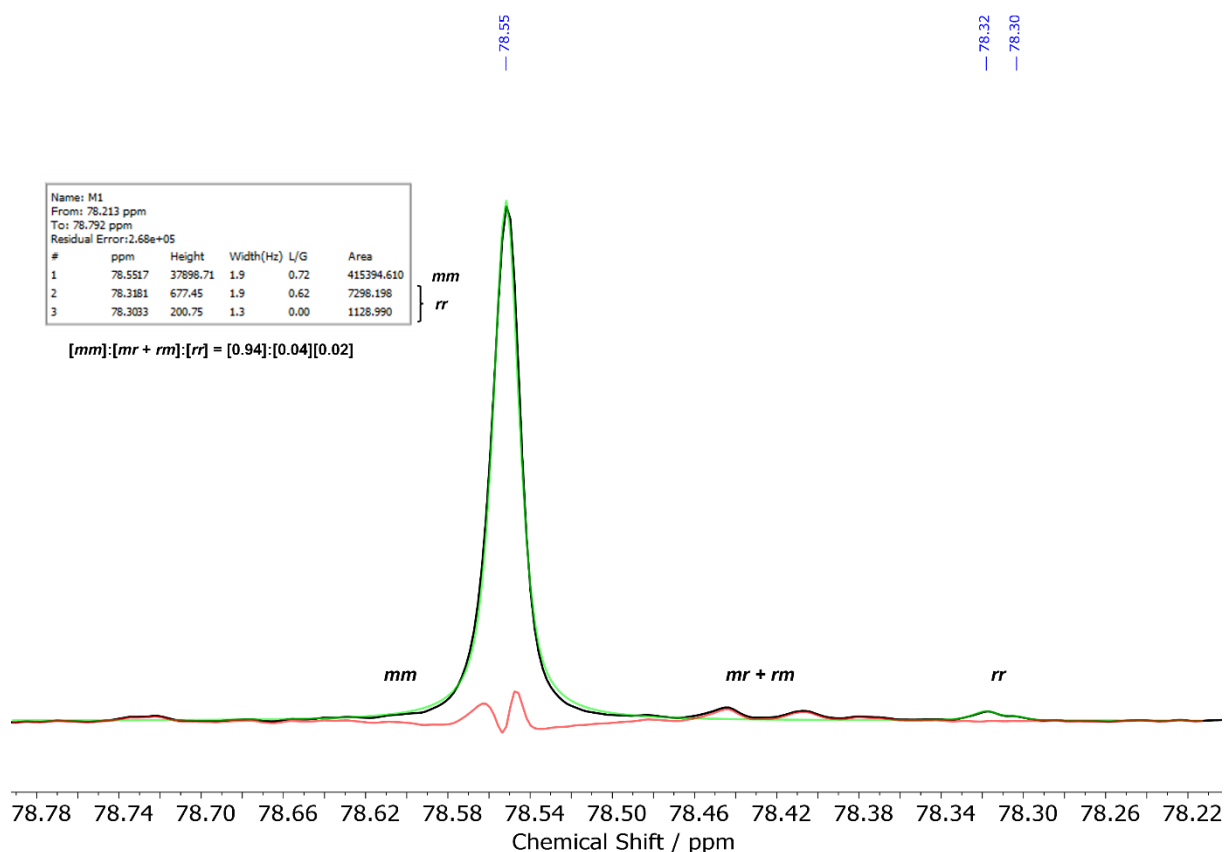


Figure S 26: Methine region of the ^{13}C NMR spectrum (125 MHz, $\text{TCE-}d_2$, 130 $^{\circ}\text{C}$) of racemic $iP(p\text{-MePhGE})$, synthesized via isoselective polymerization.

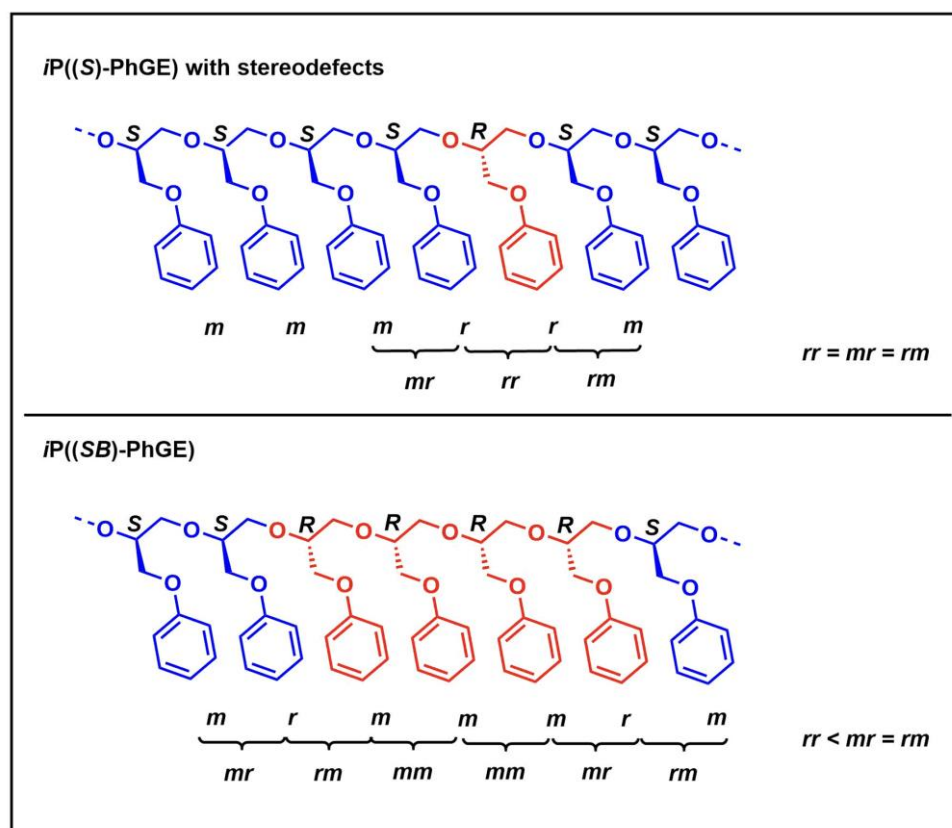


Figure S 27: Comparison of stereoerrors revealed by the triad sequence of enantiopure $iP((S)\text{-PhGE})$ with stereodefects (top) and the respective stereoblock $iP((SB)\text{-PhGE})$ (bottom).^[8]

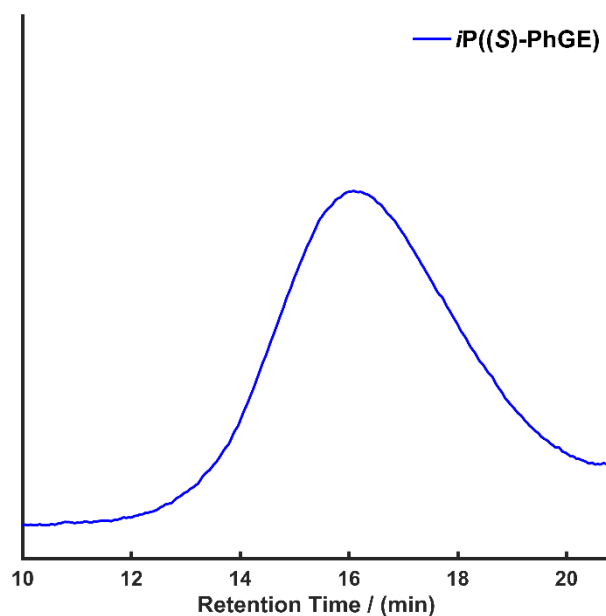
GPC Chromatograms of *iP*((*S*)-RPhGE), *iP*((*R*)-RPhGE) and *iP*(RPhGE)

Figure S 28: GPC chromatogram of enantiomeric *iP*((*S*)-PhGE), synthesized via enantioselective polymerization (Table 1, entry 1).

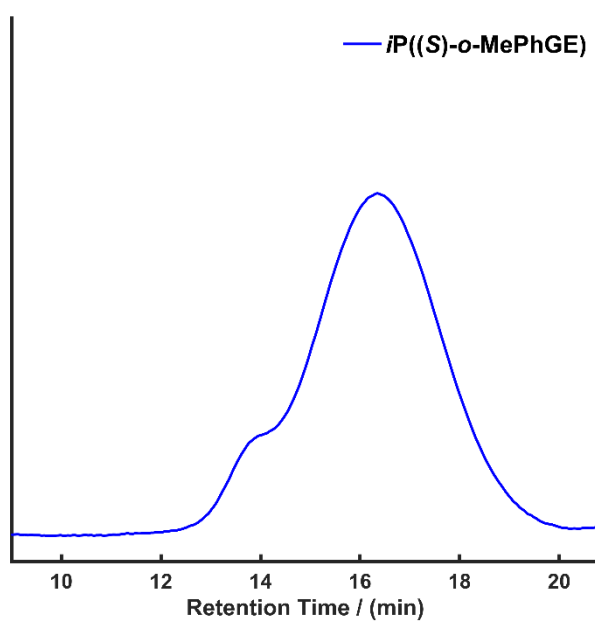


Figure S 29: GPC chromatogram of enantiomeric *iP*((*S*)-*o*-MePhGE), synthesized via enantioselective polymerization (Table 1, entry 2).

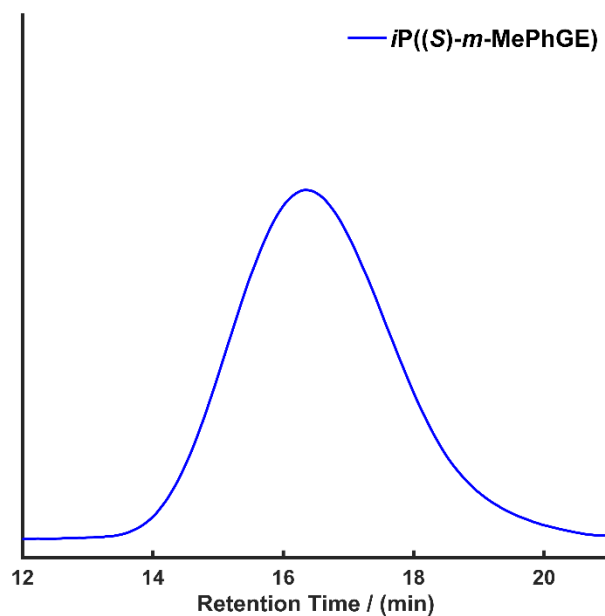


Figure S 30: GPC chromatogram of enantiomeric *iP*((*S*)-*m*-MePhGE), synthesized via enantioselective polymerization (Table 1, entry 3).

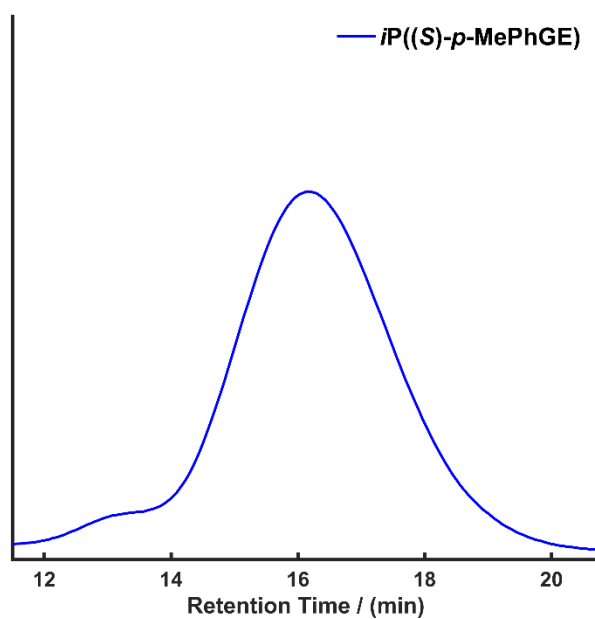


Figure S 31: GPC chromatogram of enantiomeric *iP*((*S*)-*p*-MePhGE), synthesized via enantioselective polymerization (Table 1, entry 4).

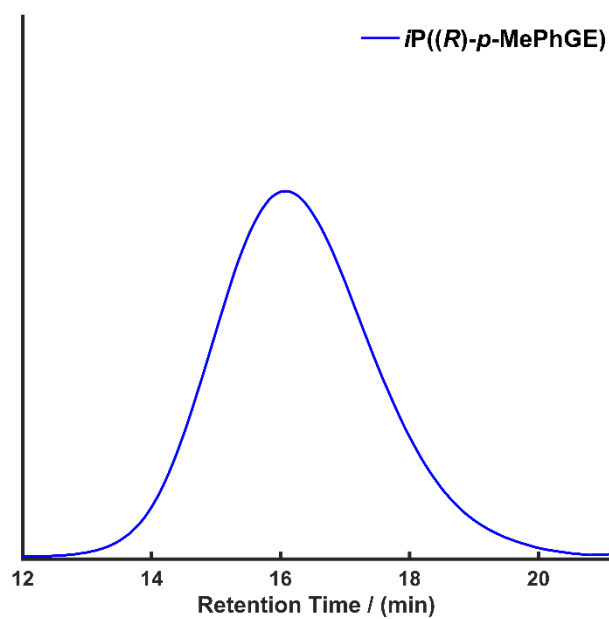


Figure S 32: GPC chromatogram of enantiomeric *iP*((*R*)-*p*-MePhGE), synthesized via enantioselective polymerization, Table S 1, entry 2).

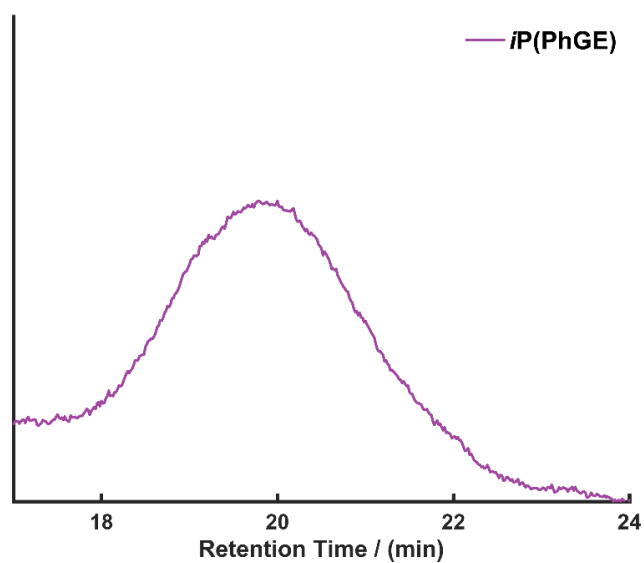


Figure S 33: GPC chromatogram of racemic *iP*(PhGE), synthesized via isoselective polymerization (Table 1, entry 6).

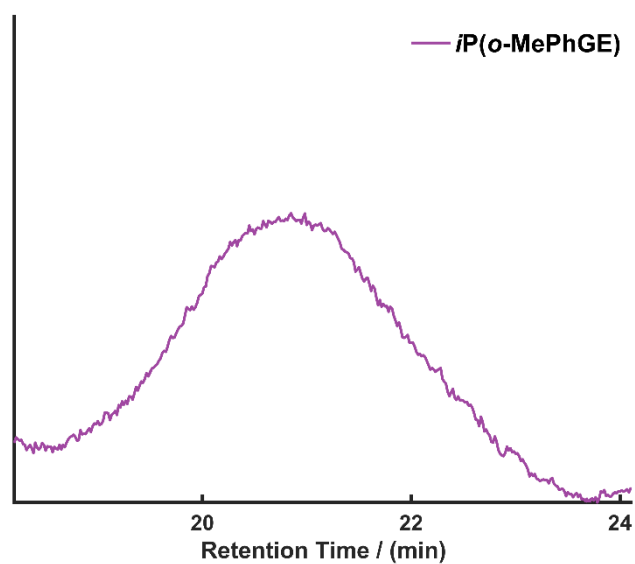


Figure S 34: GPC chromatogram of racemic *iP*(*o*-MePhGE), synthesized via isoselective polymerization (Table 1, entry 6).

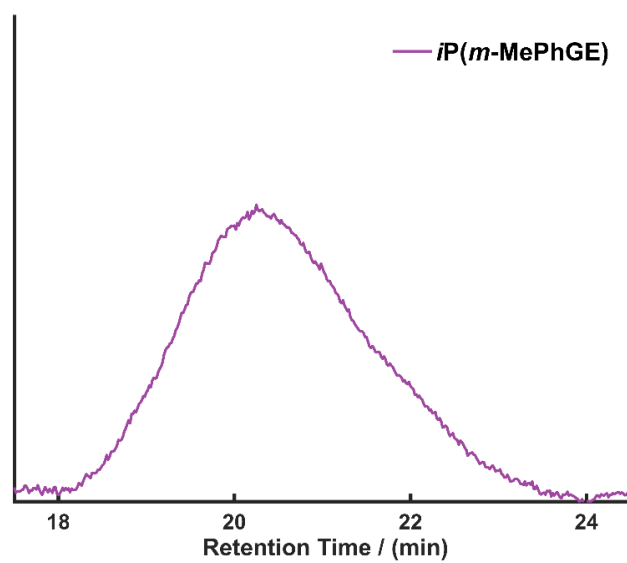


Figure S 35: GPC chromatogram of racemic *iP(m-MePhGE)*, synthesized via isoselective polymerization (Table 1, entry 7).

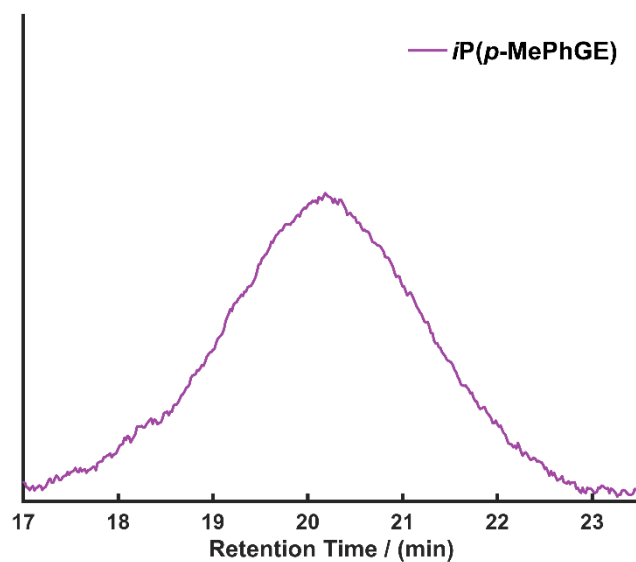


Figure S 36: GPC chromatogram of racemic *iP(p-MePhGE)*, synthesized via isoselective polymerization (Table 1, entry 8).

Thermal Characterization of *iP*((*S*)-RPhGE), *iP*((*R*)-RPhGE) and *iP*(RPhGE)

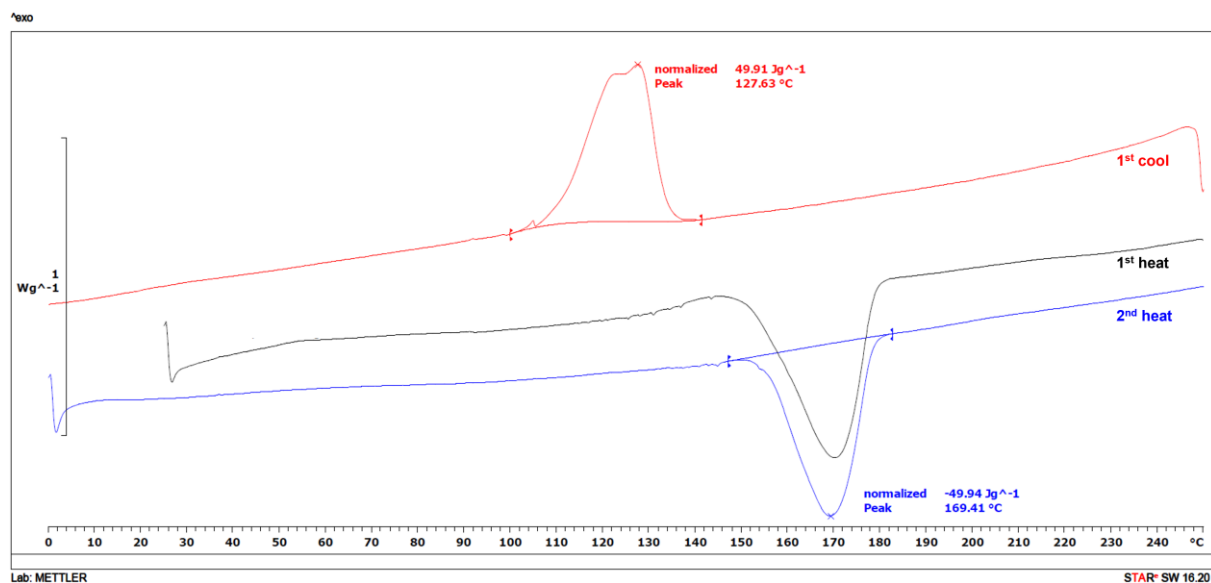


Figure S 37: DSC thermogram of enantiomeric *iP*((*S*)-PhGE), synthesized via enantioselective polymerization (Table 1, entry 1).

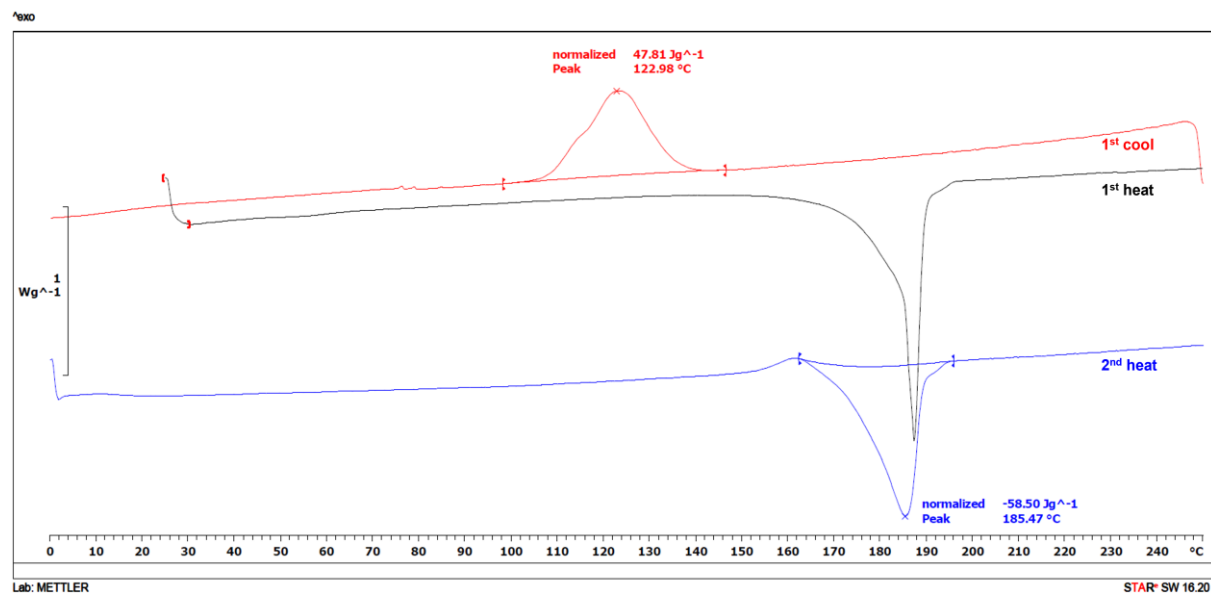


Figure S 38: DSC thermogram of enantiomeric *iP*((*S*)-*o*-MePhGE), synthesized via enantioselective polymerization (Table 1, entry 2).

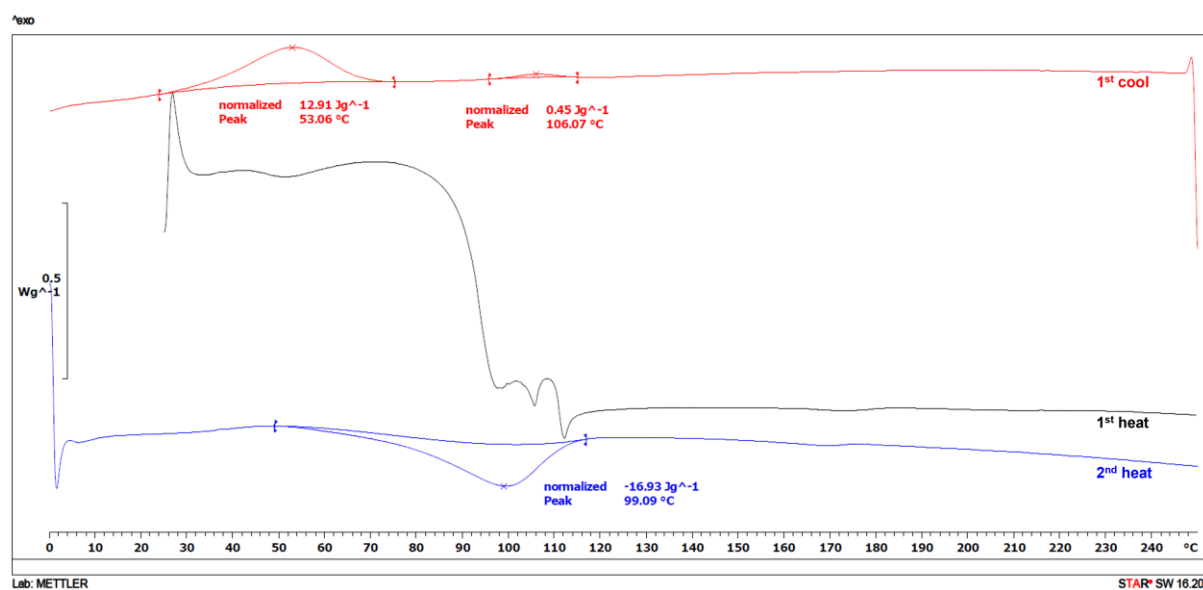


Figure S 39: DSC thermogram of enantiomeric *iP*((*S*)-*m*-MePhGE), synthesized via enantioselective polymerization (Table 1, entry 3).

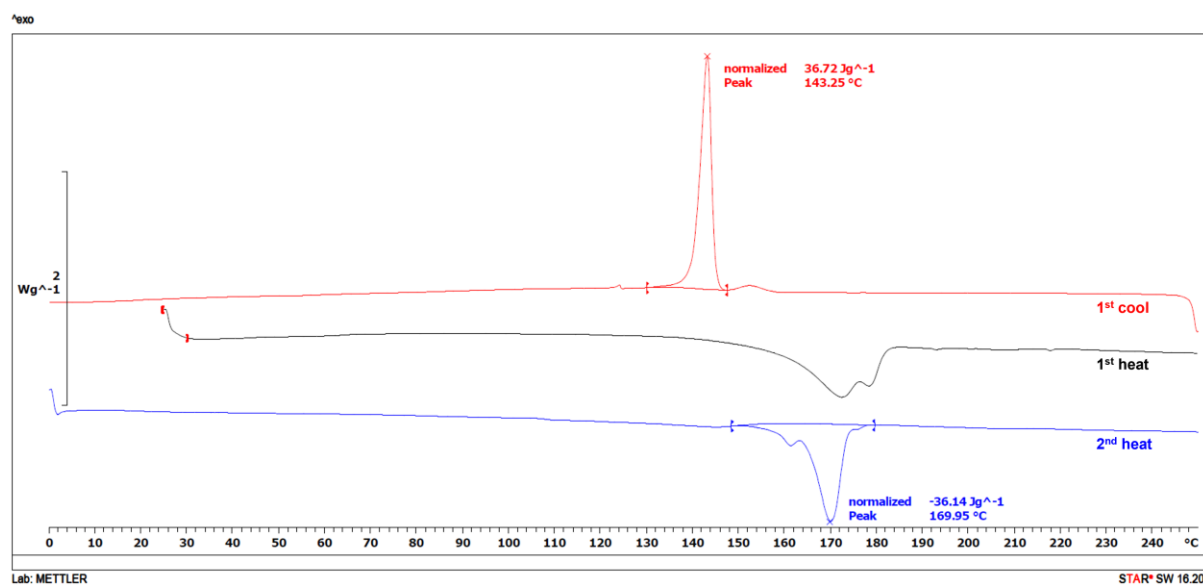


Figure S 40: DSC thermogram of enantiomeric *iP*((*S*)-*p*-MePhGE), synthesized via enantioselective polymerization (Table 1, entry 4).

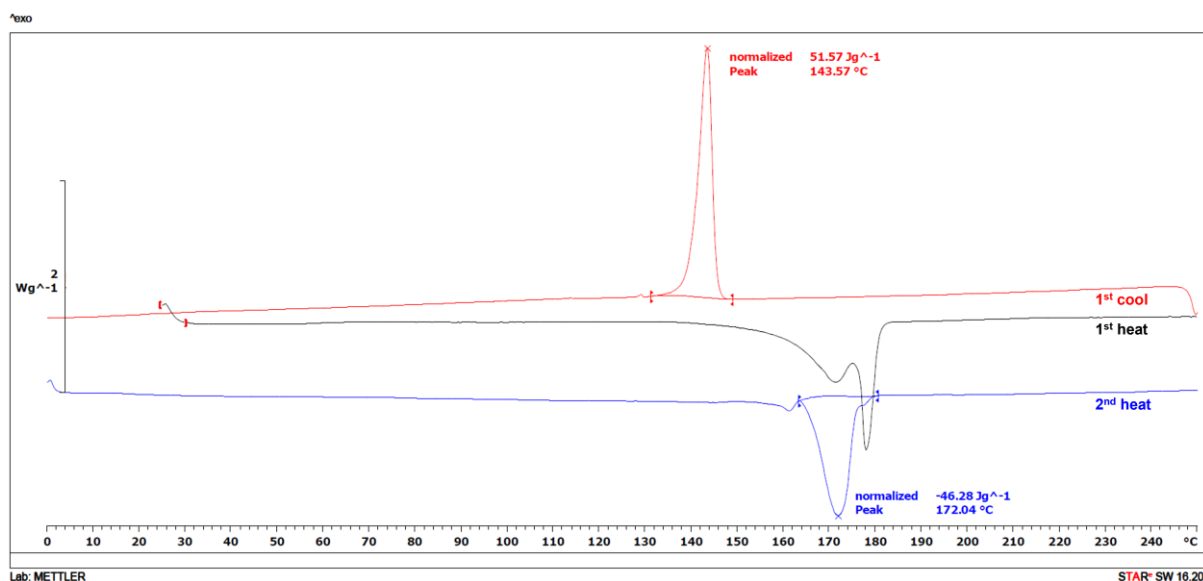


Figure S 41: DSC thermogram of enantiomeric *iP*((*R*)-*p*-MePhGE), synthesized via enantioselective polymerization, (Table S 1, entry 2).

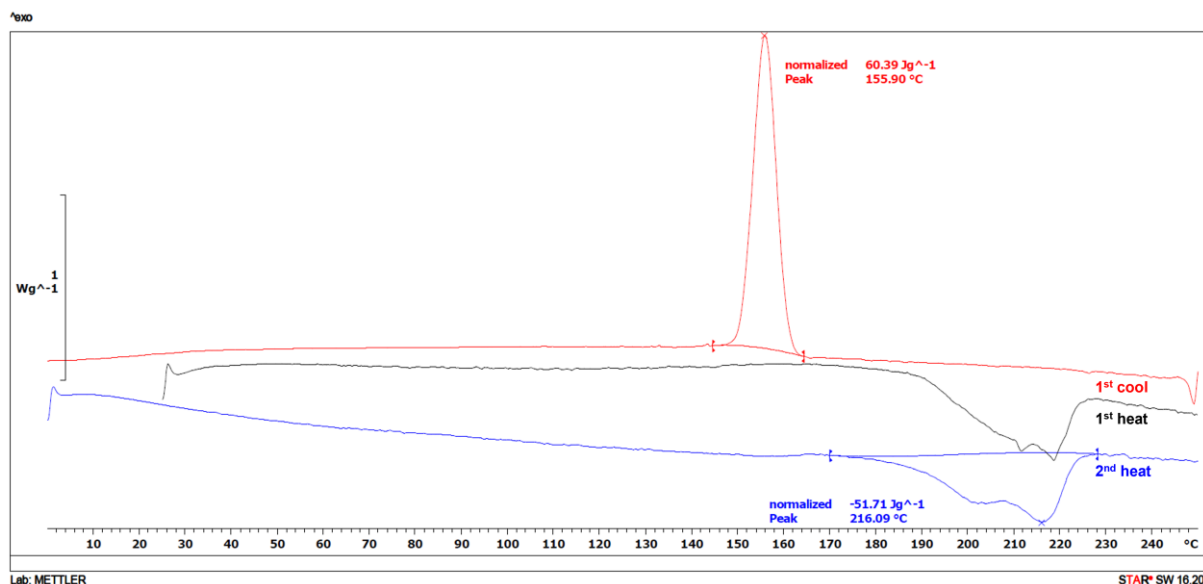


Figure S 42: DSC thermogram of stereocomplexed, racemic *iP*(PhGE), synthesized via isoselective polymerization (Table 1, entry 5).

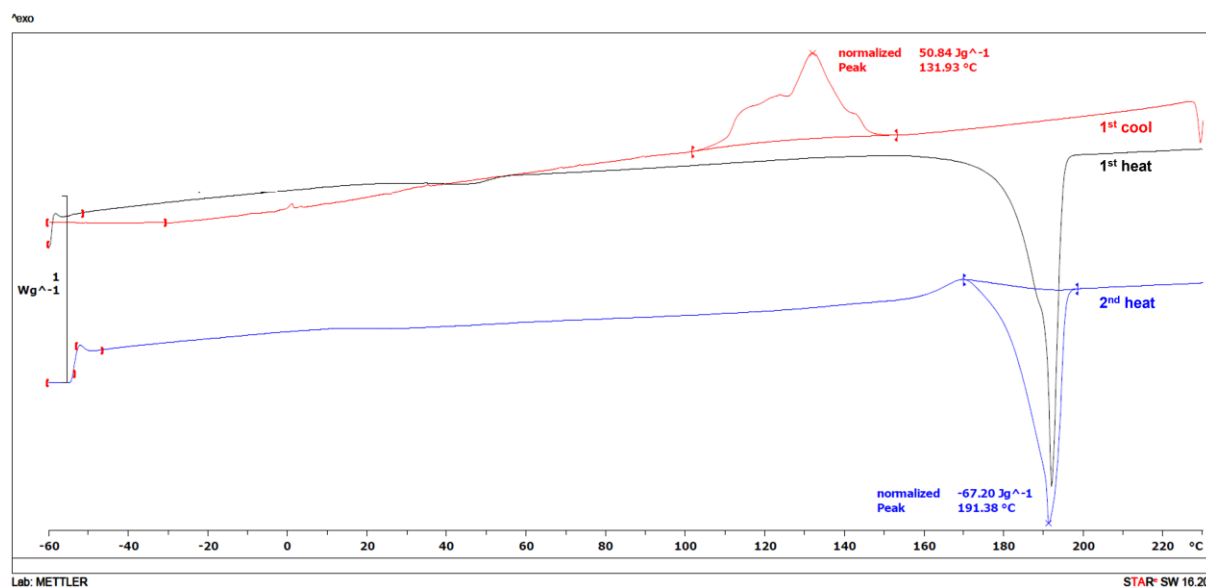


Figure S 43: DSC thermogram of stereocomplexed, racemic *iP(o-MePhGE)*, synthesized via isoselective polymerization (Table 1, entry 6).

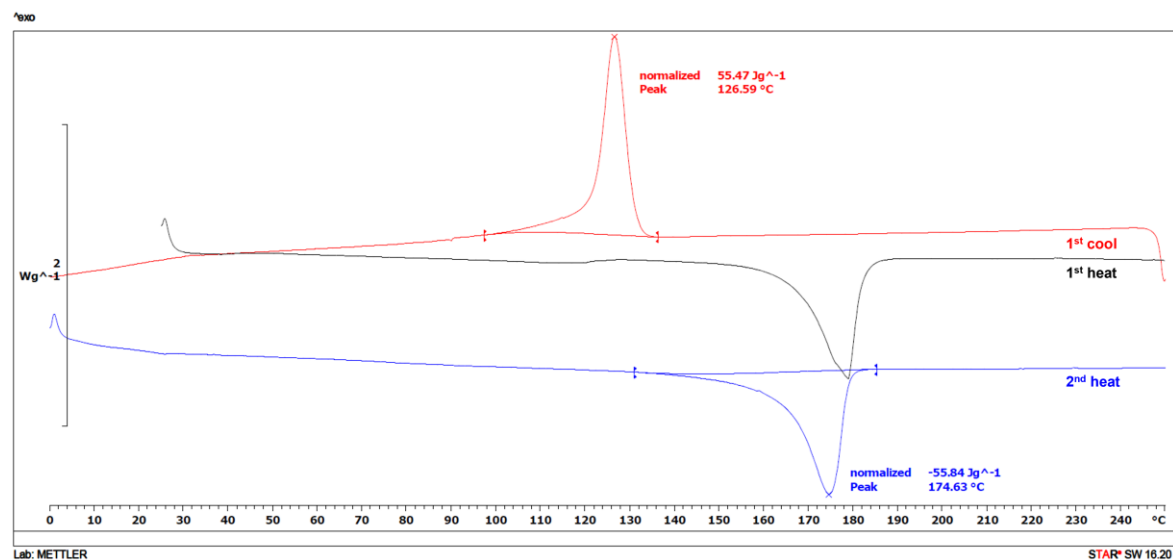


Figure S 44: DSC thermogram of stereocomplexed, racemic *iP(m-MePhGE)*, synthesized via isoselective polymerization (Table 1, entry 7).

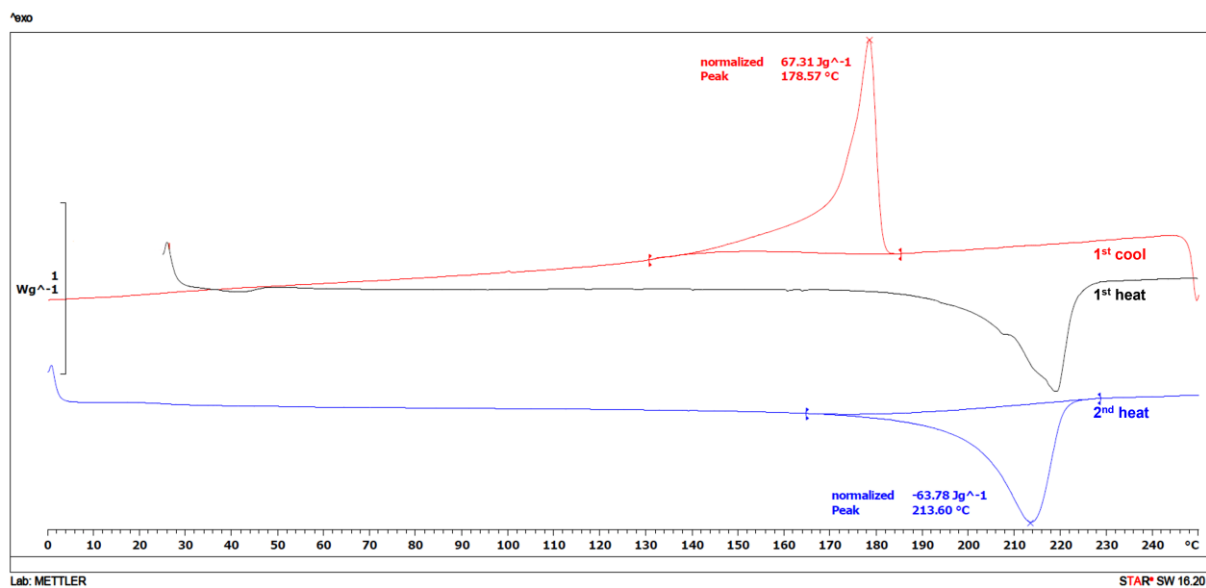


Figure S 45: DSC thermogram of stereocomplexed, racemic *iP*(*p*-MePhGE), synthesized via isoselective polymerization (Table 1, entry 8).

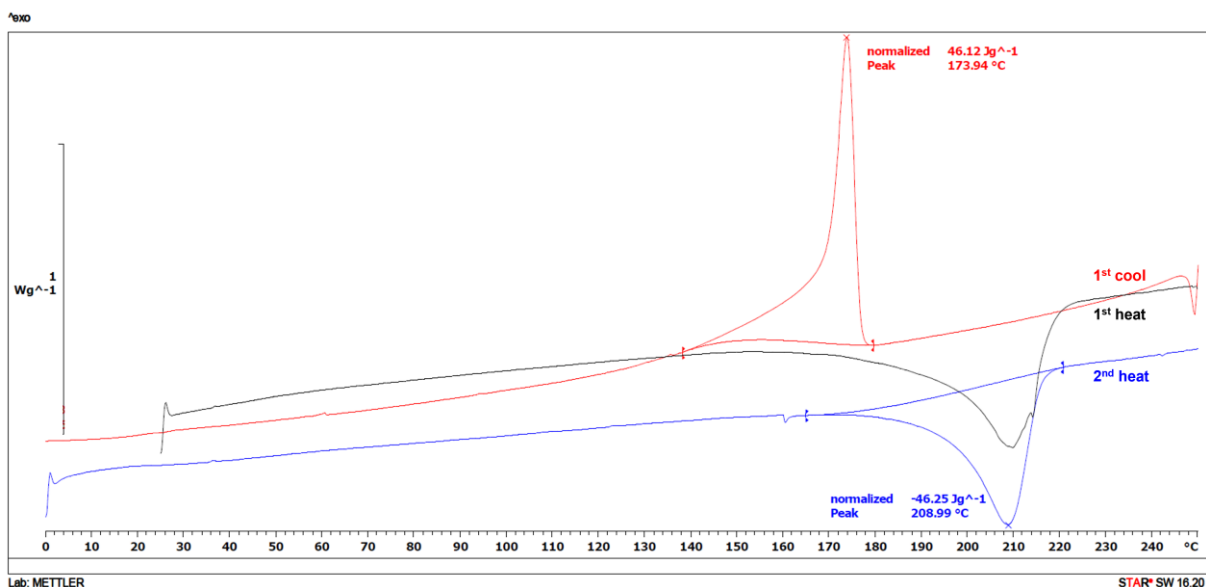


Figure S 46: DSC thermogram of the *iP*(*p*-MePhGE) stereocomplex (Table S 1, entry 4), produced by a 1:1 solution blend of *iP*((*S*)-*p*-MePhGE) (Table S 1, entry 1) and *iP*((*R*)-MePhGE) (Table S 1, entry 2).

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5 Appendix

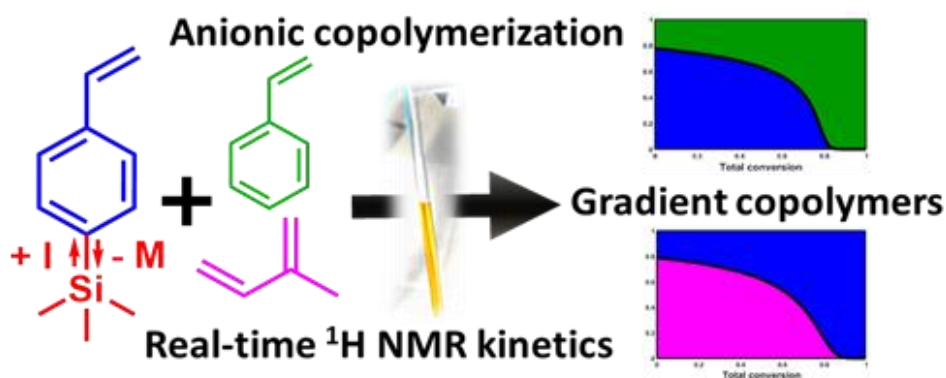
5.1 Anionic Copolymerization of 4-Trimethylsilylstyrene: From Kinetics to Gradient and Block Copolymers

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Anionic Copolymerization of 4-Trimethylsilylstyrene: From Kinetics to Gradient and Block Copolymers

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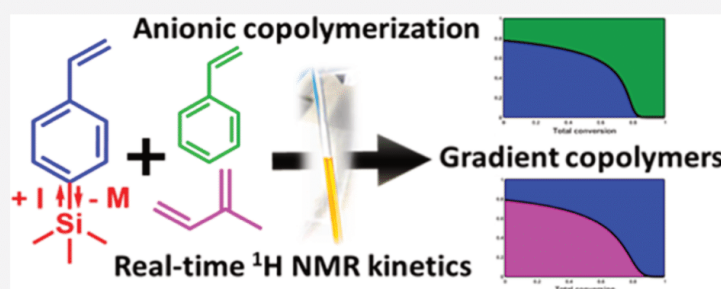
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ABSTRACT: Synthesis and real-time ^1H NMR kinetic studies on the living anionic copolymerization of 4-trimethylsilylstyrene (4TMSS), an electronically intricate monomer, are reported. Statistical copolymers of 4TMSS with styrene (S) and isoprene (I) with M_n up to 50 kg mol^{-1} were synthesized and analyzed with respect to dispersity, comonomer composition, and glass-transition temperatures, T_g . Access to well-defined di- and triblock copolymers ensured comprehensive synthetic control. Real-time ^1H NMR kinetic measurements unraveled an enthralling gradient microstructure ($r_{4\text{TMSS}} = 2.76$; $r_S = 0.087$ and $r_I = 3.28$; $r_{4\text{TMSS}} = 0.15$) in the copolymers. The sequence distribution provided by a tandem MALDI-MS² study validated an enhanced reactivity of 4TMSS in comparison to styrene in cyclohexane at room temperature. Furthermore, the kinetics of 4TMSS homopolymerization revealed detailed mechanistic insights. The possibility to tailor T_g and hydrophobicity of the copolymers by varying the 4TMSS content provides a promising approach to design copolymer-based materials for high-end applications, for example, in gas separation membranes.

INTRODUCTION

Since the development of living anionic polymerization, the method has occupied an eminent status for the synthesis of well-defined polymers with controlled molecular weights and dispersity.^{1,2} Despite significant advances in the field of reversible deactivation radical polymerization techniques in the recent past,^{3–5} living anionic polymerization is still the preferred technique for the commercial synthesis of a variety of high-value functional polymers and thermoplastic elastomers (TPEs).^{2,6,7} Styrene and its derivatives^{8–11} are amenable to living anionic polymerization leading to a wide range of macromolecular architectures such as star, graft, hyperbranched, multiblock, and so forth.¹² Functionalized styrene monomers are of particular interest as polymers therefrom can be further employed for post-polymerization modification or serve as precursors for the synthesis of graft copolymers.^{13–15} Notably, the nature and position of the substituent at the styrene monomer can drastically modify the reactivity of the substituted styrene monomer in anionic polymerization.^{16–18}

In 2013, our group established real-time monitoring of carbanionic copolymerization by ^1H NMR spectroscopic

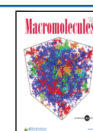
measurements to track monomer consumption and to predict the resulting gradient structure in the copolymers.¹⁹ Since then, this technique has been gaining attention, especially for the elucidation of the gradient microstructure in statistical copolymers prepared by oxyanionic and carbanionic copolymerizations.^{14,16,18,20,21} Knowledge of the shape of the gradient, in turn, is vital to tune material properties, and astonishingly the very same combination of monomers may lead to completely different materials by simply changing the monomer gradient.^{22,23}

Recently, our group investigated the synthesis and kinetics of the statistical copolymerization of isoprene with various ring-substituted styrene monomers,^{16,18} namely, 4-methyl- (4MS), 4-ethyl- (4ES), 4-isopropyl- (4iPS), and 4-(*tert*-butyl)styrene

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(4tBuS). This deliberate manipulation of the monomer substitution pattern and the respective reactivity during statistical copolymerization with isoprene was studied and compared with the well-established isoprene/styrene system ($r_1 = 11.0$ and $r_S = 0.044$).¹⁶ Owing to an increased electron density at the vinyl bond in all studied 4-alkyl-substituted styrene monomers, their statistical copolymerization with isoprene led to an enhanced gradient in the synthesized microstructure. However, the strongest gradient was obtained during copolymerization of isoprene with 4MS ($r_1 = 25.4$ and $r_{4MS} = 0.007$), as the hyperconjugative effect of the 4-alkyl substituent with the phenyl ring is weakened with increasing steric demand of the substituent.

These results of how a judicious change in the electronic nature of the substituent in functionalized styrene monomers can dramatically affect its reactivity and consequently its copolymerization behavior in anionic polymerization prompted us to undertake the current study of a silyl-substituted monomer, that is, 4-trimethylsilylstyrene (4TMSS) (Figure 1).²⁴

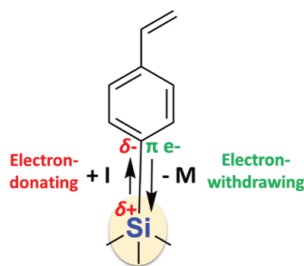


Figure 1. Electronic effects in 4TMSS.

Since the silicon atom is more electropositive when attached to carbon (Pauling electronegativity values; Si: 1.8, C: 2.5), one may expect electron-donating characteristics for the TMS group.²⁵ Even so, the electronic nature of a silyl group (R_3Si-) largely depends on two major factors, namely (i) electronic effect of its alkyl substituents (R) and (ii) nature of the group to which R_3Si- is attached.²⁵ Intrinsically, the trimethyl silyl (TMS) group is electron-donating in nature.²⁶ On the other hand, when the TMS group is directly attached to an aromatic ring, it reveals electron-withdrawing characteristics. This phenomenon is ascribed to the presence of an empty 3d orbital at the silicon atom.²⁷ Since π -electrons of the aromatic ring can delocalize into the empty d-orbitals, silicon is able to interact on a $d_{\pi}-p_{\pi}$ level.²⁸ Altogether, the interaction between silicon atom and the phenyl ring can be described by manifestation of inductive (+I) and mesomeric (−M) effects.^{26,29} An interesting question is which of these effects dominates during anionic polymerization of 4TMSS.

In the case of ring-substituted styrene monomers, the correspondence between the ^{13}C NMR chemical shift of the β -carbon of the vinyl group and its reactivity has been discussed by Hirao and co-workers.⁹ The β -carbon chemical shift correlates with the electronic charge density in the reactive carbon–carbon double bond, which in turn reflects the monomer reactivity in anionic polymerization. The β -carbon chemical shift of 4TMSS ($\delta = 114.14$ ppm, $CDCl_3$) has shifted downfield in comparison to that of styrene ($\delta = 113.36$ ppm, $CDCl_3$) and 4tBuS¹⁸ ($\delta = 113.13$ ppm, $CDCl_3$), suggesting a

higher polarity and, consequently, a higher reactivity of this vinyl bond.

Attaching a TMS group at the styrene scaffold offers promise for several applications. Consequently, 4TMSS has been polymerized by conventional radical polymerization, atom-transfer radical polymerization, nitroxide-mediated polymerization, and also by living anionic polymerization techniques.^{24,30–35} The main application of (co)polymers based on 4TMSS is gas separation membranes,³⁶ which is motivated not only by the high local mobility of the TMS group but also by the steric repulsion on account of its bulky nature.³⁷ A positron annihilation study found the fractional free volume of poly(4TMSS) to be 19.1%, which is 1.4-fold higher than that of polystyrene.³⁶ In addition, silicon shows high etch resistance and hence incorporation of a silicon-containing block in block copolymers with a high Flory–Huggins interaction parameter is known to lead to high etch contrast.^{38–43} This property has rendered such block copolymers promising in fields such as photonics, nanofiltration, lithography, and for microelectronic devices. In this regard, polystyrene-*b*-poly(4TMSS) was studied as a candidate for lithographic applications.^{38,44} One out of the several noteworthy studies regarding the preparation of copolymers from 4TMSS with various comonomers is the investigation of its miscible blend and block copolymers with polyisoprene composed of dominant 1,2- and 3,4-microstructures, wherein their phase behavior was evaluated by small-angle neutron scattering.^{45,46}

Considering these applications and the intricate electronic effects of the TMS group in this work, we employ real-time 1H NMR spectroscopy to monitor the anionic (co)polymerization kinetics in the non-polar solvent cyclohexane to elucidate the reactivity of 4TMSS in copolymerizations with two standard monomers, namely, styrene (S) and isoprene (I). The determined reactivity ratios of these comonomer pairs are used to predict the monomer gradient in the synthesized statistical copolymers. The copolymers are characterized with regard to their molecular weight, dispersity, glass-transition temperature, T_g , and contact angle. To establish access to various polymer architectures based on these results, di- and triblock copolymers with isoprene were synthesized and characterized.

EXPERIMENTAL SECTION

Reagents, synthesis of monomer, and details of instrumentation are given in the Supporting Information Section 1.

Synthesis Procedures for Homopolymerization, Statistical Polymerization, and Block Copolymerization ($M_n^{th} = 5$ kg mol^{-1}). Polymerization reactions were performed in cyclohexane at room temperature in an argon-filled glovebox (MBraun UNILAB, <0.1 ppm of O_2 and <0.1 ppm of H_2O) in 40 mL glass vials equipped with a magnetic stir bar, screw cap, and septum. For homopolymerization and statistical copolymerization, a 2.2 M monomer/solvent (20 wt %) mixture was initiated by addition of 0.1 mL of *sec*-butyllithium (1.3 M in cyclohexane/hexane 92/8) via 1 mL syringe. The solution was stirred for 2.5 h for homopolymerization and copolymerization with styrene and for 6 h for copolymerization with isoprene to ensure complete monomer conversion, which was confirmed by 1H NMR. For preparation of sequential block copolymers, the first block (10 wt % solution in cyclohexane) was initiated by addition of 0.1 mL of *sec*-butyllithium (1.3 M in cyclohexane/hexane 92/8). At full monomer conversion, (usually after 5 h for isoprene and 2 h for each styrene and 4TMSS) the second monomer feed was added via syringe. Typical isolated polymer yields were 90–95% for statistical copolymers of 4TMSS with styrene and 85–90% for statistical copolymers with isoprene.

Table 1. Summary of P(4TMSS) Homopolymers Prepared with Molecular weights in the Range of 5–50 kg mol⁻¹^a

entry	M_n^{th} , kg mol ⁻¹	M_n^{NMR} , kg mol ⁻¹	$M_n^{\text{SEC,UV}}$, kg mol ⁻¹	$\bar{D}$ (UV)	$M_n^{\text{SEC,MALS}}$, kg mol ⁻¹	$\bar{D}$ (MALS)	T_g , °C
1	5	4.7	4.7	1.11	5	1.15	113.6
2	10	10.3	8.7	1.11	10	1.11	123.3
3	25	^b	18	1.13	21.7	1.09	129.9
4	50	^b	52	1.18	63.5	1.11	132.2

^a M_n^{th} is calculated from the formula $\bar{D}\bar{P}_n = \frac{[M]_0}{[I]_0}$, where $[M]_0$ and $[I]_0$ are monomer and initiator concentrations, $M_n^{\text{SEC,UV}}$ is determined by SEC measurements in THF (PS standards), UV signals. $M_n^{\text{SEC,MALS}}$ is determined by SEC measurements in THF, MALS signals. M_n^{NMR} is obtained from ¹H NMR spectroscopy in CD₂Cl₂ by referencing to methyl protons of the initiator. ^bNot evaluated due to increasing inaccuracy at high molecular weights.

Procedures for homopolymerization and copolymerization up to $M_n^{\text{th}} = 50$ kg mol⁻¹ and block copolymer synthesis are given in the Supporting Information, Section 1.

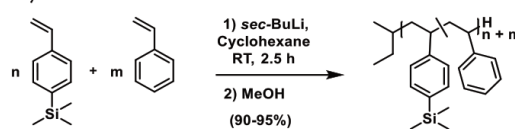
Sample Preparation for Real-Time ¹H NMR Kinetic Studies. Monomers and the deuterated solvent (cyclohexane-*d*₁₂) were stirred over CaH₂ overnight, degassed by three freeze–pump–thaw cycles, and vacuum distilled prior to use. Sample preparation was carried out in an argon-filled glovebox (MBraun UNILAB, <0.1 ppm of O₂ and <0.1 ppm of H₂O). The monomer/solvent stock solutions (20 wt % in cyclohexane-*d*₁₂) were prepared in 20 mL glass vials equipped with a magnetic stir bar, screw cap, and septum. Essentially, 0.65 mL of the 2.2 M monomer stock solution was filled into standard NMR tubes and tightly sealed with a rubber septum. A ¹H NMR spectrum of the solution was recorded prior to the initiation step. Initiation was carried out by addition of 0.01 mL of *sec*-butyllithium (1.3 M in cyclohexane/hexane 92/8 v/v) via a syringe through the septum fitted to the NMR tube. The tube was vigorously shaken to homogenize the mixture and was placed in an NMR spectrometer. However, a time delay of 1–2 min before the first scan should be noted. For the entire time span of measurements, the temperature was maintained at 23 °C and sample rotation was turned off. The chosen timeframe of measurement was 1 h for homopolymerization kinetics, 2 and 8 h, for copolymerization kinetics with styrene and isoprene. A single spectrum with one scan was recorded every 30 s throughout the experiment. After completion of real-time measurements, samples were terminated with degassed methanol and SEC traces of the obtained homopolymers and copolymers were recorded.

RESULTS AND DISCUSSION

Homopolymerization of 4TMSS with *sec*-BuLi in Cyclohexane. First, a series of homopolymers was synthesized and analyzed to understand the polymerization behavior of 4TMSS under respective conditions. *sec*-BuLi-initiated homopolymerizations were carried out at room temperature in cyclohexane (details in Experimental Section). All synthesized homopolymers were analyzed via SEC, ¹H NMR spectroscopy, and DSC. Table 1 summarizes the details of the synthesized homopolymers with molecular weights in the range of 5–50 kg mol⁻¹ (entries 1–4). The SEC curves shown in Figure S5 show that well-defined homopolymers with molecular weights with low to moderate dispersity ($\bar{D}$ (UV): 1.11–1.18) were accessible under the employed reaction conditions. The molecular weights of P(4TMSS) synthesized by ATRP have been reported to be underestimated by ca. 10–15% relative to polystyrene (PS) standards in comparison with static light scattering data.³⁵ Hence, absolute molecular weights were determined by SEC-MALS, and a comparable underestimation was observed for the synthesized P(4TMSS) when using PS standards (Table 1). The ¹H NMR spectrum of P(4TMSS) is shown in Figure S6. The MALDI-TOF mass spectrum of the P(4TMSS) sample with 5 kg mol⁻¹ (Figure S7) indicates a low dispersity of 1.08.

The glass transition temperature, T_g , of the P(4TMSS) homopolymer, extrapolated to infinite M_n , was observed at 134.6 °C (Figures S8 and S9), in accordance with the literature reported value.^{32,40} This value is much higher than that of PS ($T_g = 106$ °C).⁴⁷ This is attributed to reduced flexibility in the polymer chains due to restricted rotation of the bulky TMS group and to d_{π} – p_{π} interactions between the silicon atom and the aromatic ring.^{28,32}

Statistical Copolymerization of 4TMSS with Styrene. Statistical copolymers of 4TMSS with styrene were synthesized in cyclohexane at room temperature (Scheme 1). In addition

Scheme 1. Statistical Copolymerization of 4TMSS with Styrene

to insights into the polymerization behavior of this comonomer pair, there was particular interest to study the material properties of these new statistical copolymers.

The concentration of the polymerization solution (20 wt %) was kept constant for the entire series (details in the Experimental Section). Table 2 summarizes the details of the synthesized copolymers.

SEC traces of the copolymers are shown in Figures 2 and S10. Absolute molecular weights were determined by SEC-MALS and were found to be comparable to SEC values calibrated to PS standards. Well-defined copolymers with low dispersity values ($\bar{D}$: 1.05–1.09) were obtained, independent of the 4TMSS content. Using a molar comonomer fraction of 50%, P(4TMSS_{0.5}-co-S_{0.5}) up to $M_n^{\text{th}} = 50$ kg mol⁻¹ was synthesized to demonstrate that higher molecular weight copolymers are accessible (entries 8–10). Typical ¹H NMR, ²⁹Si, and ²⁹Si-¹H HMBC NMR spectra of the synthesized copolymers are shown in Figures S11–S13 and the DOSY NMR spectrum in Figure S14.

The T_g values of the copolymers are shown in Table 2. DSC curves are shown in Figures S15 and S16. Although the copolymers exhibit a significant gradient (see Figure 4B below), they only show a single T_g even at highest M_n , intermediate of the homopolymers. The T_g values increase with increasing content of 4TMSS and molecular weight (Figure S17). Since phase separation was observed in PS-*b*-P(4TMSS) block copolymers,⁵⁰ this seems to indicate that the gradient is not steep enough to impart phase segregation in statistical copolymers.

Table 2. Statistical Copolymers of 4TMSS and Styrene (S) at Various 4TMSS Mole Fractions (x_{feed}^a)

entry	polymer composition	x_{feed}	x_{NMR}	w_{NMR}	M_n^{th} kg mol ⁻¹	M_n^{NMR} kg mol ⁻¹	$M_n^{\text{SEC,UV}}$ kg mol ⁻¹	$\bar{D}$ (UV)	$M_n^{\text{SEC,MALS}}$ kg mol ⁻¹	$\bar{D}$ (MALS)	T_g °C
5	P(4TMSS ₇ -co-S ₂₁)	0.25	0.25	0.36	5	3.4	3.5	1.05	3.7	1.08	80.5
6	P(4TMSS ₁₉ -co-S ₂₀)	0.5	0.47	0.62	5	5.2	4.6	1.10	5.2	1.1	90.1
7	P(4TMSS ₁₆ -co-S ₇)	0.75	0.7	0.79	5	3.5	3.8	1.09	4.2	1.11	83.9
8	P(4TMSS ₂₄ -co-S ₂₅)	0.5	0.49	0.61	10	6.9	7.1	1.06	7.7	1.06	101
9	P(4TMSS-co-S)	0.5	0.51	^b	25	^b	24.6	1.12	29.1	1.02	119
10	P(4TMSS-co-S)	0.5	0.55	^b	50	^b	42.3	1.14	48.3	1.04	124

^a M_n^{th} is calculated from the formula $\overline{DP}_n = \frac{[M]_0}{[I]_0}$, where $[M]_0$ and $[I]_0$ are monomer and initiator concentrations, $M_n^{\text{SEC,UV}}$ is determined by SEC measurements in THF (PS standards), UV signals. $M_n^{\text{SEC,MALS}}$ is determined by SEC measurements in THF, MALS signals. M_n^{NMR} is obtained from ¹H NMR spectroscopy in CD₂Cl₂ by referencing to methyl protons of the initiator. ^bNot evaluated due to increasing inaccuracy at high molecular weights.

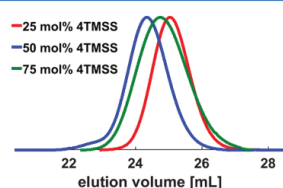


Figure 2. SEC traces of the synthesized P(4TMSS-co-S) ($M_n^{\text{th}} = 5$ kg mol⁻¹) with varying molar fractions of 4TMSS (UV signals, eluent: THF).

Real-Time ¹H NMR Kinetics of 4TMSS with Styrene.

Real-time ¹H NMR spectroscopy was used to track the consumption of 4TMSS and S during statistical copolymerization. Since in a classical anionic living polymerization, termination and transfer reactions are absent; monitoring of integrals characteristic to each individual monomer peak in the ¹H NMR spectra not only reflects comonomer consumption but also their relative position along the growing polymer chains.^{17,19} Thus, the determined reactivity ratios allow us to determine the compositional gradient.

In cyclohexane-*d*₁₂, the doublet vinyl signals in the region 5.73–5.66 ppm for 4TMSS and at 5.70–5.63 ppm for S overlap partially, and hence, one-half of each doublet peak was tracked and integrated to follow the individual monomer conversions. Three different monomer ratios, $[4\text{TMSS}]_0/[S]_0 = 0.25, 1$, and 2.2 , were studied. SEC traces for the obtained copolymers are shown in Figure S18. The stacked ¹H NMR spectra are given in Figures 3, S19, and S20.

Comonomer concentrations plotted as a function of time (Figure S21) and of total conversion (Figure 4A) demonstrate a more rapid consumption of 4TMSS than of styrene. Upon initiation, 4TMSS polymerizes preferentially and is therefore prevalent at the initiator end of the polymer chain. Over the course of polymerization, styrene incorporation increases and at >80% total conversion, a pure polystyrene block is formed. The enhanced reactivity of 4TMSS in comparison to styrene in a non-polar solvent explicitly demonstrates the impact of the TMS group at the para position of the styrene monomer. It confirms predictions made from the ¹³C NMR β -carbon shifts, which suggested an increased polarity at the vinyl bond.

The data collected was used to determine reactivity ratios, $r_{4\text{TMSS}}$ and r_S , which define the relative rates of homopolymerization versus copolymerization (i.e. crossover). Reactivity ratios were determined using the Meyer-Lowry fit for a terminal copolymerization model.⁴⁸ (Figure S22). The values, $r_{4\text{TMSS}} = 2.76$ and $r_S = 0.087$ ($r_{4\text{TMSS}}r_S = 0.24$), are utilized to

generate a plot of comonomer distribution, which shows a pronounced gradient microstructure in P(4TMSS-co-S), as shown in Figure 4B. Analogous results were obtained for the other two comonomer ratios $[4\text{TMSS}]/[S] = 0.25$ and 2.2 , respectively (Figures S23, S24 and Table S1). Evaluation of data according to the non-terminal model via the Jaacks fit (Figure S25) resulted a distinctly non-linear curve that excludes the non-terminal model for our system.

The kinetics of this copolymerization system resemble that of isoprene/styrene ($r_I = 11.0$; $r_S = 0.044$),¹⁶ where the gradient is steeper. Here, it was concluded that the crossover from isoprene to styrene is extremely fast, preventing longer sequences of styrene in the copolymer before isoprene is completely consumed.

In order to obtain a complete understanding of the kinetics of this copolymerization, we determined the homopolymerization rate constant of TMSS at 23 °C using real-time ¹H NMR kinetics. Details are given in the Supporting Information, Section 6 (Figures S26–S29). The alkyllithium-initiated anionic polymerization in hydrocarbon solvents involves the presence of aggregates (initiator, polymer, and initiator polymer), which determines the related reactivity ratios.^{49–51} It is known that polystyryl-Li chains form dimeric aggregates in cyclohexane. Our kinetic measurements in the initiator concentration range from 0.44 to 17.2 mmol L⁻¹ in fact provided a reaction order of 0.5, which translates to an association number of 2.0. The results shown in Table 3 clearly show that the rate constant of 4TMSS is 4.4 times higher than that of styrene, confirming the increased reactivity of 4TMSS relative to styrene as predicted from the ¹³C β -carbon shifts. The inverse reactivity ratio $1/r_S = k_{S,4\text{TMSS}}/k_{SS} = 11.5$ indicates that this increase is mainly due to the increased reactivity of the 4TMSS monomer. On the other hand, the ratio $k_{4\text{TMSS,S}}/k_{SS} = 1.59$ indicates that both types of living chain ends, PTMSS-Li and PS-Li, have similar reactivity toward styrene. Taking into account that the -I effect of the TMS group stabilizes the PTMSS-Li anion, this is surprising. We tentatively explain this by assuming that the degree of association of the chain end is lower, forming a higher number of active unimers.

According to the definition of the reactivity ratios and using the homopolymerization rate constants of 4TMSS and styrene, the cross-propagation rate constants were calculated and compared to the I/S system. Similar to the I/S system it turns out that the cross-over rate constant from PS-Li to 4TMSS, $k_{S,4\text{TMSS}} = 73.4$ (L/mol)^{1/2} s⁻¹, is 3 orders of magnitude higher than that of TMSS homopolymerization, $k_{4\text{TMSS,4TMSS}} = 28 \times 10^{-3}$ (L/mol)^{1/2} s⁻¹, preventing the

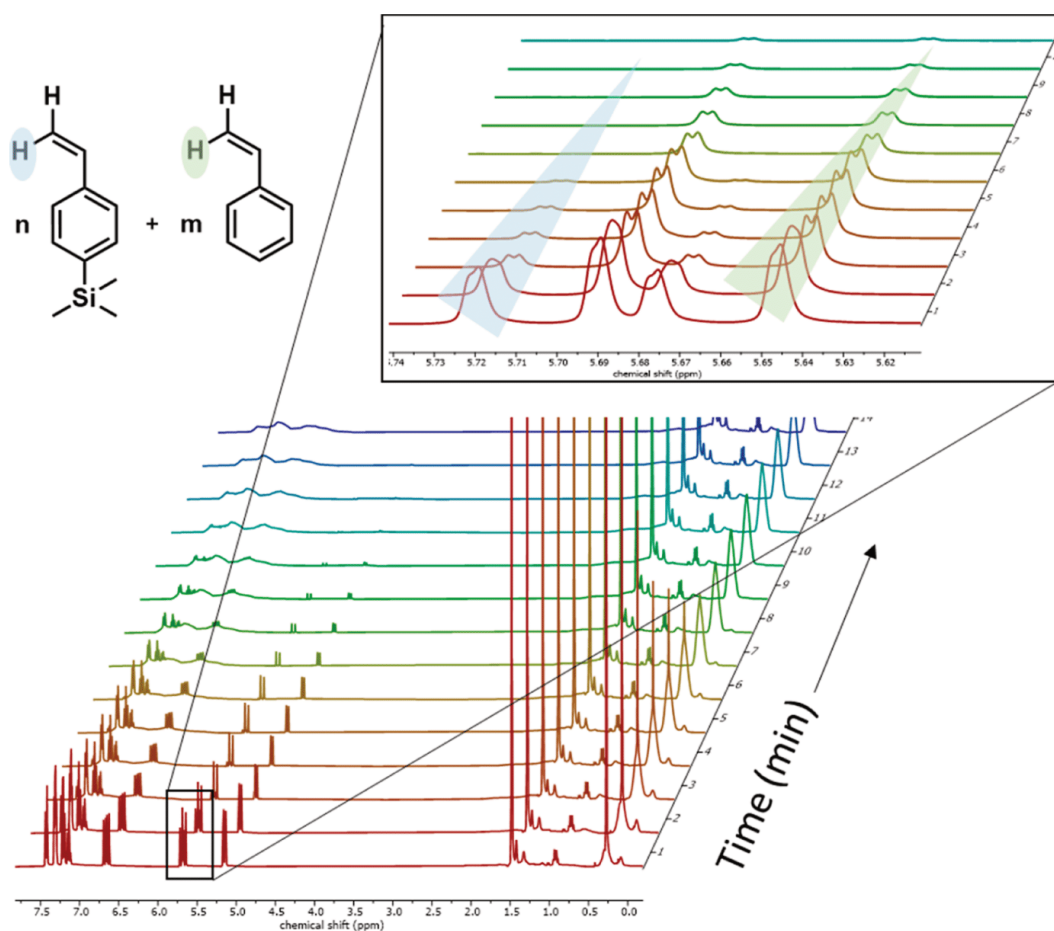


Figure 3. Stacked ^1H NMR spectra (400 MHz, C_6D_{12}) as a function of time ($[\text{4TMSS}]_0/[\text{S}]_0 = 1$). The zoomed-in region was used for tracking individual comonomer consumption.

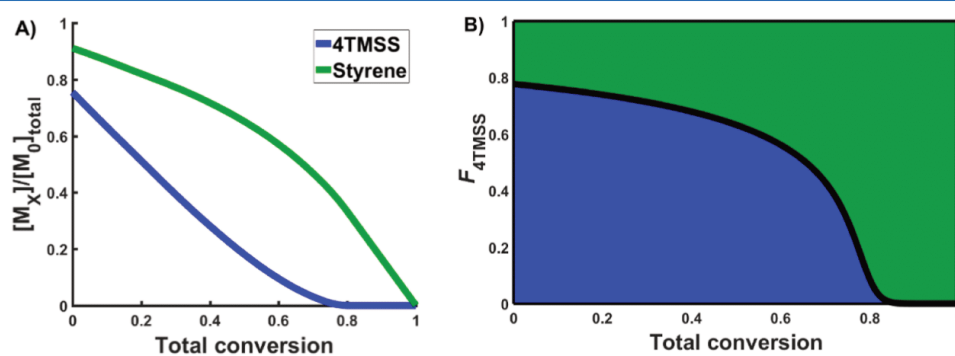
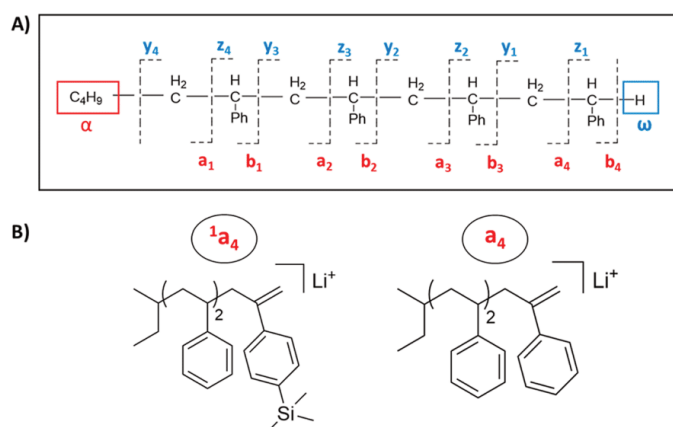
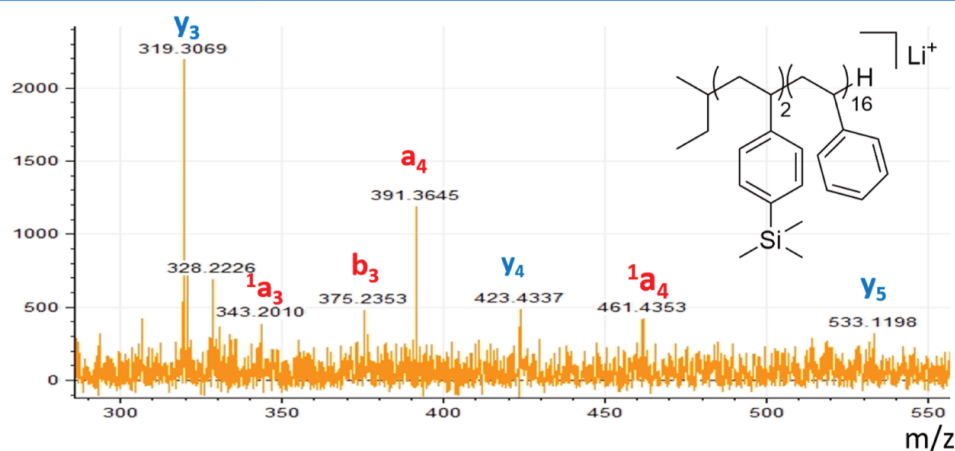


Figure 4. (A) Monomer concentration versus total conversion in C_6D_{12} at $23\text{ }^\circ\text{C}$ in the statistical copolymerization of 4TMSS with styrene, $[\text{4TMSS}]_0/[\text{S}]_0 = 1$. (B) Simulation of the instantaneous molar comonomer composition, F , at a given conversion; blue: 4TMSS, green: styrene monomer units.

Table 3. Computed Rate Constants Obtained from Real-Time ^1H NMR Kinetics of Homopolymerization and Copolymerization of 4TMSS and Isoprene with Styrene

system	$r_{4\text{TMSS}}$	r_{S}	$10^3 k_{4\text{TMSS},4\text{TMSS}}$ (L/mol) $^{1/2}$ s $^{-1}$	$10^3 k_{\text{SS}}$ (L/mol) $^{1/2}$ s $^{-1}$	$k_{\text{S},4\text{TMSS}}$ (L/mol) $^{1/2}$ s $^{-1}$	$10^3 k_{4\text{TMSS},\text{S}}$ (L/mol) $^{1/2}$ s $^{-1}$
4TMSS/S	2.76	0.087	28.2	6.39	73.4	10.2
system	r_{I}	r_{S}	$10^3 k_{\text{II}}$ (L/mol) $^{1/4}$ s $^{-1}$	$10^3 k_{\text{SS}}$ (L/mol) $^{1/2}$ s $^{-1}$	k_{SI} (L/mol) $^{1/2}$ s $^{-1}$	$10^3 k_{\text{IS}}$ (L/mol) $^{1/4}$ s $^{-1}$
I/S 16	11.0	0.044	0.612	6.39	145	0.056

**Figure 5.** (A) Fragment ion notation for MS^2 products from polystyrenes. The subscripts give the overall number of complete or partial repeat units and the superscripts denote the number of 4TMSS comonomer units. 52 Copyright 2014. Modified with permission, American Chemical Society. (B) Structures of the ions in Figure 6.**Figure 6.** MALDI- MS^2 mass spectrum of $[\text{M} + \text{Li}]^+$ ions in the mid mass of $\text{P}(4\text{TMSS}_2\text{-co-S}_{16})$.

formation of long sequences of styrene units as long as TMSS is present. In contrast, the cross-over rate constant from $\text{P}(4\text{TMSS})\text{-Li}$ to styrene, $k_{4\text{TMSS},\text{S}} = 10.2 \times 10^{-3}$ (L/mol) $^{1/2}$ s $^{-1}$, is comparable to that of styrene homopolymerization, $k_{\text{SS}} = 6.39 \times 10^{-3}$ (L/mol) $^{1/2}$ s $^{-1}$, which is necessary for a narrow molecular weight distribution. The I/S system is similar but more pronounced. In particular, the cross-over from PI-Li to styrene is 260 times slower than styrene homopolymerization, which has been shown to increase the polydispersity of $\text{PI-}b\text{-PS}$ block copolymers. 16

Sequence Analysis of $\text{P}(4\text{TMSS-co-S})$ by MALDI-TOF and MS^2 Tandem Mass Spectrometry. To further corroborate the results of the microstructure obtained from the kinetics study of the statistical copolymerization of 4TMSS with styrene, MALDI-TOF MS along with tandem mass spectrometry (MS^2) via collision-induced dissociation (CID) were used to evaluate the sequence distribution. MALDI-TOF MS gives insights into comonomer composition, while analysis of the MS^2 fragmentation patterns provides evidence for the specific comonomer location along the polymer chain. 52 From the kinetic study, it was concluded that during the statistical

copolymerization, 4TMSS is incorporated preferentially at the beginning of polymerization, giving rise to a gradient microstructure. Thus, 4TMSS is incorporated near the initiator end of the copolymer chain. MALDI-TOF MS was combined with MS² to give conclusive insights into the sequence produced during statistical copolymerization.

Two P(4TMSS-*co*-styrene) oligomers, with an average of 1 and 2 repeating units of 4TMSS, respectively, were synthesized in an analogous manner as described for the copolymer synthesis procedure in the Experimental Section. M_n of P(4TMSS₁-*co*-styrene₁₆) was 1820 g mol⁻¹ and that of P(4TMSS₂-*co*-styrene₁₄) was 1770 g mol⁻¹. The SEC traces of the two copolymers, as shown in Figure S30, show monomodal distributions with low dispersity. The MALDI-TOF mass spectrum of P(4TMSS₁-*co*-styrene₁₆) is shown in Figure S31. A peak-to-peak mass increment of 104.15 g mol⁻¹ corresponding to styrene repeat units and 176 g mol⁻¹ for that of 4TMSS could be assigned, confirming incorporation of both comonomers in the synthesized copolymers.

To determine the sequence distribution in copolymers, a parent ion was chosen from the MALDI-TOF MS spectrum, which was further analyzed via CID. Figures 5 and S32 show MS² fragmentation pathways for linear polystyrenes and a previously established nomenclature for the fragmentation pattern to expedite the understanding of observations from the analysis.⁵²

As represented in Figure 5, the fragments thus formed may either retain the α -initiating or the ω -terminating end group. From MALDI-TOF MS analysis, an intense parent ion at 1707 g mol⁻¹ was further treated via CID, and the low-mass, mid-mass, and high-mass regions of the MALDI-TOF/TOF CID spectra of both the copolymers were analyzed. It is noteworthy that both analyzed copolymers on average contain only 1 and 2 repeating units of 4TMSS, respectively, as compared to 14 and 16 repeating units of styrene. Hence, in the fragmentation spectra, the majority of detected ions contained styrene repeating units. However, by studying fragments with α - and ω -end groups, information regarding favorability of 4TMSS incorporation in these oligomers can be derived. Figure 6 shows the MALDI-TOF/TOF CID spectrum of $[M + Li]^+$ ions in the mid-mass region of P(4TMSS₂-*co*-S₁₆). The CID spectrum of P(4TMSS₁-*co*-S₁₇) is shown in Figure S33. A short discussion along with low-mass region CID spectra of P(4TMSS₁-*co*-S₁₇) and P(4TMSS₂-*co*-S₁₆) is shown in Figure S34.

In the spectrum, a-type ions (i.e., α -fragments) containing one 4TMSS and three S units, $1a_4$, could be observed along with homopolymer ions with four styrene units, a_4 . The peak height ratio $1a_4/a_4$ is 350/1150 = 0.33, whereas the stoichiometric ratio is 2/16 = 0.125. Thus, the incorporation of TMSS is 2.6-fold more pronounced. This supports our observations from the kinetic study, which demonstrates the preferential incorporation of 4TMSS near the initiator end: $F_{TMSS}/F_S = 78/22 = 3.55$ (see Figure 4).

Statistical Copolymerization of 4TMSS with Isoprene.

The statistical copolymerization of isoprene with styrene and certain styrene derivatives has been intensely investigated.^{16,18,53,54} In non-polar media, these monomer pairs exhibit disparate reactivity ratios, leading to tapered copolymers with a strong gradient microstructure, consequently leading to different material properties in comparison to conventional block copolymers.^{16,18,55} The enhanced reactivity of 4TMSS observed in our kinetic investigation of the

copolymerization of 4TMSS with styrene motivated a study of the copolymerization of 4TMSS with isoprene in cyclohexane at room temperature (Scheme 2).

Scheme 2. Statistical Copolymerization of 4TMSS with Isoprene

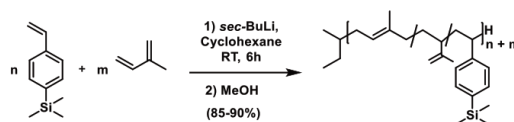


Table 4 summarizes details of the resulting P(I-*co*-4TMSS) copolymers. For the entire series the same concentration of the polymerization solution (20 wt %) was maintained, and the reactions were carried out at room temperature. Details are given in the Experimental Section. Examples of typical ¹H NMR and ²⁹Si and ²⁹Si-¹H HMBC NMR spectra of the synthesized copolymers are shown in Figures S35–S37 and DOSY NMR spectrum in Figure S38.

The molecular weights obtained by SEC and ¹H NMR spectroscopy along with the comonomer incorporation were found to be in accordance with the target. Absolute molecular weights determined by SEC-MALS suggested an overestimation of 15–20% in comparison to PS standards. As seen in Figure 7A, all copolymers with $M_n^{th} = 5$ kg mol⁻¹

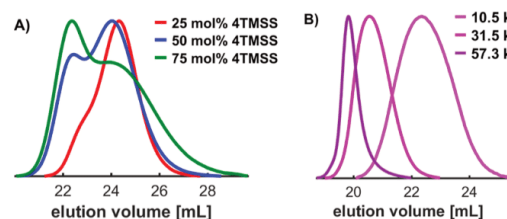


Figure 7. SEC traces of the P(I-*co*-4TMSS). (A): $M_n^{th} = 5$ kg mol⁻¹ with varying 4TMSS feed, x_{4TMSS} . (B): $x_{4TMSS} = 0.5$, with increasing molecular weight. (UV signals, eluent: THF).

exhibit a shoulder or bimodal molecular weight distribution, and the dispersities increased with the 4TMSS feed. In contrast, when creating polymers with increasing molecular weights at a fixed 4TMSS ratio (Figure 7B), the curves are monomodal and the dispersity decreases. This behavior is known from the copolymerization of isoprene with styrene as well as the recently studied 4-alkyl-substituted styrenes.^{16,18} The marked reactivity difference between isoprene and 4-alkylstyrenes results from a low crossover rate from the PI-Li chain end to the (substituted) styrene. Hence, this living copolymerization, despite the absence of termination or chain transfer, suffers from slow initiation, which leads to broad or even bimodal distributions. While the bimodal distributions of P(I-*co*-4TMSS) vanish at $M_n \geq 10$ kg mol⁻¹, in the statistical copolymerization of isoprene with 4-*t*BS, well-defined copolymers were only achieved for $M_n \geq 50$ kg mol⁻¹.

The development of T_g values for the statistical copolymers of 4TMSS with isoprene (Table 4), follows the same trend as for copolymers with styrene. DSC curves are shown in Figures S39 and S41. Polyisoprene synthesized in a nonpolar solvent has a dominant 1,4 microstructure, showing $T_g \approx -68$ °C.⁵⁶

Table 4. Statistical Copolymers of 4TMSS and Isoprene (I) at Various 4TMSS Mole Fractions, x_{feed}^a

entry	polymer composition	x_{feed}	x_{NMR}	w_{NMR}	M_n^{th} kg mol ⁻¹	M_n^{NMR} kg mol ⁻¹	$M_n^{\text{SEC,UV}}$ kg mol ⁻¹	$\bar{D}$ (UV)	$M_n^{\text{SEC,MALS}}$ kg mol ⁻¹	$\bar{D}$ (MALS)	T_g (°C)
11	P(I ₂₁ -co-4TMSS ₁₃)	0.25	0.38	0.61	5	3.7	4.9	1.17	^c	^c	-22.7
12	P(I ₁₅ -co-4TMSS ₂₁)	0.5	0.57	0.79	5	4.5	5.8	1.37	5.1	1.49	18.4
13	P(I ₆ -co-4TMSS ₃₀)	0.75	0.76	0.90	5	3.9	4.9	1.67	4.7	1.92	46.8
14	P(I ₂₆ -co-4TMSS ₃₀)	0.5	0.53	0.75	10	7.1	10.5	1.22	8.3	1.33	19.4
15	P(I-co-4TMSS)	0.5	0.47	^b	25	^b	31.4	1.18	26.3	1.1	20.4
16	P(I-co-4TMSS)	0.5	0.51	^b	50	^b	57.3	1.12	49.1	1.07	21.9

^a M_n^{th} is calculated from the formula $\overline{DP}_n = \frac{[M]_0}{[I]_0}$, where $[M]_0$ and $[I]_0$ are monomer and initiator concentrations, $M_n^{\text{SEC,UV}}$ is determined by SEC measurements in THF (PS standards), UV signals. $M_n^{\text{SEC,MALS}}$ is determined by SEC measurements in THF, MALS signals. M_n^{NMR} is obtained from ¹H NMR spectroscopy in THF-*d*₈ by referencing to methyl protons of the initiator. ^bNot evaluated due to increasing inaccuracy at high molecular weights. ^cNot evaluated as the sample eluted partially outside the lower limits of the calibration curve.

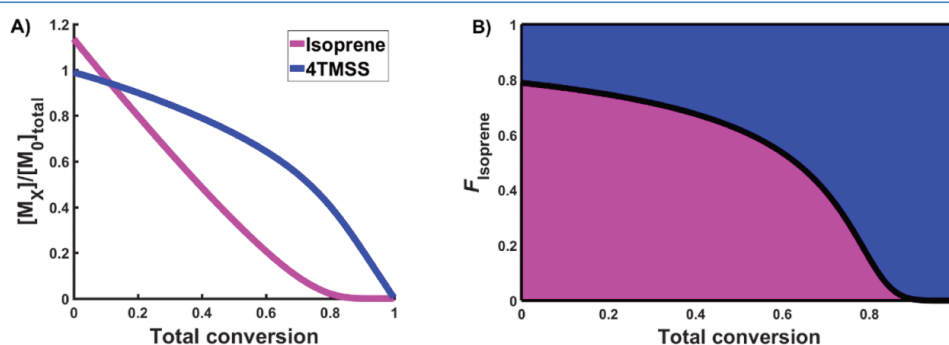


Figure 8. (A) Comonomer concentrations vs total conversion in C₆D₁₂ at 23 °C for the statistical copolymerization of 4TMSS with isoprene. (B) Simulation of the instantaneous molar comonomer composition, *F*, at a given conversion; pink area: isoprene.

Table 5. Computed Rate Constants of Homopolymerization and Copolymerization of Isoprene with Styrene and Para-Substituted Styrenes^a

comonomer "S"	r_I	r_S	$10^3 k_{II}$ (L/mol) ^{1/4} s ⁻¹	$10^3 k_{SS}$ (L/mol) ^{1/2} s ⁻¹	k_{SI} (L/mol) ^{1/2} s ⁻¹	$10^3 k_{IS}$ (L/mol) ^{1/4} s ⁻¹
4TMSS	3.28	0.152	0.612	28.2	184	0.186
S ¹⁶	11.0	0.053	0.612	6.39	145	0.024
4BS ¹⁸	19.8	0.022	0.612	5.44	247	0.031
4MS ¹⁶	25.4	0.007	0.612	1.26	180	0.024

^aThe index S stands for all styrene derivatives.

The T_g also increased linearly with increasing 4TMSS content (Figures S40) and increasing molecular weight (Figures S42). Although the copolymers exhibit a significant gradient, again only a single T_g is observed even at high M_n (entries 14–16), which is in between the corresponding homopolymer T_g values. As already mentioned in the introduction, P(4TMSS) is miscible with poly(3,4-isoprene), and the block copolymer shows an LCST in bulk between 150 °C and 200 °C.⁴⁵ Thus, in addition to the gradient, possibly being not steep enough, the Flory–Huggins interaction parameter of P(4TMSS) with poly(1,4-isoprene) may not be sufficient to induce phase segregation. For further discussion, see the section on 4TMSS/I sequential block copolymers below.

Real-Time ¹H NMR Kinetics of Copolymerization of 4TMSS with Isoprene. In analogy to the 4TMSS/S system, the statistical copolymerization of 4TMSS with isoprene was carried out in an NMR tube and tracked in real time to follow individual monomer consumption (see details in the Experimental Section). The stacked NMR spectra as a function of time are shown in Figure S43; the SEC trace of the

copolymer obtained during the kinetics experiment is shown in Figure S44. From the acquired real-time data, comonomer concentrations were plotted against total conversion (Figure 8A) and against time (Figure S45). In analogy to previously studied isoprene and substituted styrene systems,^{16,18} at the start of polymerization, isoprene polymerizes preferentially and incorporation of 4TMSS increases with time. Since a Jaacks fit for the non-terminal model is not linear (Figure S47), the Meyer–Lowry fit (Figure S46) for a terminal copolymerization model was used to evaluate reactivity ratios. These along with the previously studied I/S, I/4tBS, and I/4MS systems^{16,18} are summarized in Table 5 for a direct comparison. These values indicate a strikingly increased reactivity of 4TMSS in comparison to the copolymerization with styrene, 4tBS (the carbon analogue of 4TMSS), and 4MS. Simulation of the molar copolymer microstructure from the reactivity ratios (Figure 8B) indicate a gradient microstructure in P(I-co-4TMSS), albeit less pronounced than that of tapered P(I-co-S), P(I-co-4tBS), and P(I-co-4MS) copolymers.

Table 6. Sequential Block Copolymers of Isoprene and 4TMSS with Targeted $M_n = 5 \text{ kg mol}^{-1}$ (Entry 17 and 18) and Targeted $M_n = 80 \text{ kg mol}^{-1}$ (Entry 19) with Equal Comonomer Mole Fractions^a

entry	polymer	M_n^{th} , kg mol^{-1}	$M_n^{\text{SEC (UV)}}$, kg mol^{-1}	$\bar{D}$ (UV)	$\bar{D}$ (RI)	$M_n^{\text{SEC,MALS}}$, kg mol^{-1}	$\bar{D}$ (MALS)
17	P(4TMSS)- <i>b</i> -PI	5	5.4	1.09	1.09	3.9	1.25
18	PI- <i>b</i> -P(4TMSS)	5	7.3	1.12	1.26	6.3	1.24
19	PI- <i>b</i> -P(4TMSS)	80	82	1.08	1.08	84.2	1.14
20	P(4TMSS)- <i>b</i> -PI- <i>b</i> -P(4TMSS)	35	33.5	1.19	1.19	33.3	1.07

^a M_n^{th} is calculated from the formula $\bar{D}\bar{P}_n = \frac{[M]_0}{[I]_0}$, where $[M]_0$ and $[I]_0$ are monomer and initiator concentrations, $M_n^{\text{SEC,UV}}$ is determined by SEC measurements in THF (PS standards), UV signals. $M_n^{\text{SEC,MALS}}$ is determined by SEC measurements in THF, MALS signals.

In the same way as for the copolymerization of 4TMSS and styrene described above, the cross-propagation rate constants for the copolymerization of isoprene with 4TMSS were calculated and compared to styrene and other para-substituted styrenes. In all cases, isoprene is the more reactive comonomer, although its homopolymerization is slower than that of all styrenes. 4TMSS has the highest homopolymerization rate constant of all styrenes, again confirming the negative inductive effect of the TMS group.

The crossover rate constant from P(4TMSS)-Li, $k_{\text{SI}} = 184 \text{ (L/mol)}^{1/2} \text{ s}^{-1}$, is 2 orders of magnitude higher than that of the isoprene homopolymerization, $k_{\text{II}} = 0.61 \times 10^{-3} \text{ (L/mol)}^{1/4} \text{ s}^{-1}$, preventing long sequences of 4TMSS units as long as isoprene is present. In contrast, the crossover from PI-Li to 4TMSS, $k_{\text{IS}} = 0.19 \times 10^{-3} \text{ (L/mol)}^{1/4} \text{ s}^{-1}$, is 2 orders of magnitude slower than that of 4TMSS homopolymerization, $k_{\text{SS}} = 28 \times 10^{-3} \text{ (L/mol)}^{1/2} \text{ s}^{-1}$. As seen in Figure 7, this slow initiation leads to broadening of the molecular weight distribution of the copolymers P(4TMSS-*co*-I). Copolymerizations of isoprene with styrene and the para-substituted styrenes are similar but more pronounced.

Synthesis of Block Copolymers of 4TMSS and Isoprene by Sequential Polymerization. Based on the crossover rate constants for the 4TMSS/I system (Table 5), it was predicted that the order 4TMSS, followed by isoprene to generate sequential diblock copolymers, is advantageous for low dispersity since the rate of crossover characterized by k_{SI} is fast, in comparison to the inverse order (k_{IS}). Consequently, the inverse order should lead to higher dispersity. The results shown in Table 6 and Figure 9 confirm these predictions, for instance when comparing entries 17 and 18. This underlines

the significance of our kinetic data even for conventional, sequential block copolymer synthesis.

When P(4TMSS)-Li was used as a macroinitiator, a well-defined diblock copolymer with a low dispersity of 1.09, in the UV signal, was obtained. This illustrates the smooth crossover from P(4TMSS)-Li to the polyisoprene block. However, using PI-Li as the macroinitiator for 4TMSS leads to a higher dispersity of 1.26 (UV signal). The RI-signal shows a low molecular weight shoulder, which is not observed in the UV signal, where PI is not visible. This peak corresponds to unreacted PI.

A high molecular weight PI-*b*-P(4TMSS) block copolymer with a target molecular weight of 80 kg mol^{-1} shows a well-defined molecular weight distribution with low dispersity of 1.08 (UV signal). As calculated by Gold,⁵⁷ the effect of slow initiation on dispersity decreases with increasing M_n . From ¹H NMR analysis (Figure S48), the PI block in the diblock copolymer shows 94% of 1,4- and 6% of 3,4- microstructure.

Thriving on this understanding, a symmetric triblock copolymer with equal comonomer mole fractions and intermediate molecular weight was synthesized by two sequential monomer additions (Table 6, Figure S49). The second addition of 4TMSS resulted in a certain broadening of the distribution. Since only one quarter of all comonomers was added to a P(4TMSS)-*b*-PI block copolymer, the narrow distribution of that precursor prevented stronger broadening of the triblock. A single diffusion trace in the DOSY NMR spectrum (Figure S50) evidences the successful synthesis of the triblock copolymer. As calculated from ¹H NMR shown in Figure S51, the PI block in the triblock copolymer also consists of 94% of 1,4- and 6% 3,4- microstructure. Thus, in such a manner, we could demonstrate successful synthesis of an ABA-type structure based on 4TMSS and isoprene in analogy to the industrially relevant SIS thermoplastic elastomer.

For the sequential block copolymer PI-*b*-P(4TMSS) with $M_n = 80 \text{ kg mol}^{-1}$ (entry 19) (Figure S52), DSC shows two distinct T_g values at -49.9 and 53.8 °C, indicating phase separation. This is surprising since P4TMSS and 3,4-PI have been reported to be miscible, with the Flory–Huggins interaction parameter, $\chi_{4\text{TMSS}/3,4\text{-PI}}$, being close to zero at room temperature.⁴⁵ However, the PI microstructure is likely to play a pivotal role in miscibility since the interaction parameters of PS with 1,4-PI and 3,4-PI differ considerably: $\chi_{\text{S}/1,4\text{-PI}} = -0.0419$; $\chi_{\text{S}/3,4\text{-PI}} = -0.0937$.⁵⁸ Since $\chi_{4\text{TMSS}/1,4\text{-PI}}$ is not known, we performed a rough estimation based on Hildebrand solubility parameters⁵⁹ (see Supporting Information, Section 12). This indicates that $\chi_{4\text{TMSS}/1,4\text{-PI}} \approx 0.01$. Since phase separation requires $\chi N \geq 10.5$,^{60,61} this should be achieved above $M_n \approx 13 \text{ kg mol}^{-1}$. A lower T_g value of the P(4TMSS) block hints toward partial mixing of the two blocks. Similarly, for the triblock copolymer, P(4TMSS_{0.25})-*b*-P(I_{0.5})-

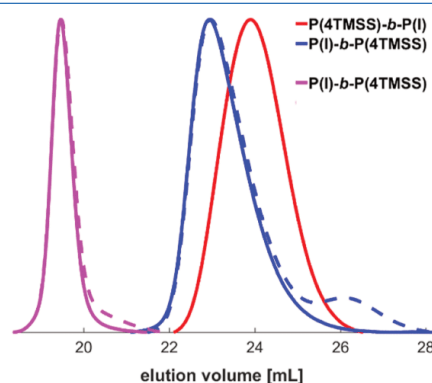


Figure 9. SEC traces of isoprene and 4TMSS diblock copolymers, UV signal (solid lines), and RI signal (dashed line); eluent: THF.

b-P(4TMSS_{0.25}) (entry 20) (Figure S53), two marked T_g s at -35.1 °C and at 48.7 °C could be assigned. Morphology and tensile properties are being evaluated to elucidate the effect of the introduction of the TMS group in the “hard” block of this thermoplastic elastomer.

Contact Angle Measurements. An important property of the TMS group embodiment is the increased hydrophobicity of the corresponding copolymers.⁶² In order to study the effect of the TMS group in the synthesized copolymers, contact angle measurements for ultrapure water were performed on thin polymer films on a glass substrate (Figure 10). The

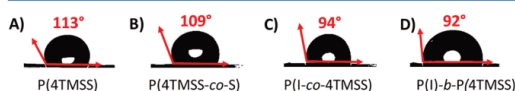


Figure 10. Contact angles of ultrapure water on (A) P(4TMSS) (entry 2), (B) 4TMSS/S gradient (entry 8), and (C) 4TMSS/I gradient (entry 14) and (D) 4TMSS/I diblock (entry 19) copolymers with equimolar TMSS content.

homopolymer P(4TMSS) showed a contact angle as high as 113° , and thus clearly displayed increased hydrophobicity as compared to polystyrene (Figure S54A), which has a contact angle of 88° .

The P(4TMSS_{0.5}-co-S_{0.5}) gradient copolymer, (Figure 10B), exhibited a contact angle of 109° . This demonstrates a considerable effect due to the introduction of 50 mol % of 4TMSS in polystyrene. As expected, the contact angle of the gradient copolymer P(I_{0.5}-co-4TMSS_{0.5}) increased to 94° as compared to 86° for P(I_{0.5}-co-S_{0.5}) (Figure S54B), owing to the TMS group. Similarly, the diblock copolymer PI-*b*-P(4TMSS) showed a contact angle of 92° . This, in turn, demonstrated an increased hydrophobicity in the synthesized gradient and block copolymers based on 4TMSS.

CONCLUSIONS

We have presented a detailed synthetic and kinetic study of the reactivity of 4-trimethylsilylstyrene (4TMSS) under living anionic polymerization conditions in the non-polar solvent cyclohexane. The 4TMSS monomer was statistically copolymerized with styrene and isoprene, respectively. The kinetics of the copolymerizations, studied via real-time ^1H NMR measurements, follows the terminal copolymerization model. The calculated reactivity ratios indicate an enhanced reactivity of 4TMSS in comparison to styrene ($r_{4\text{TMSS}} = 2.760$ and $r_S = 0.087$), resulting in copolymers with a moderate gradient microstructure. These results reflect the lowered electron density at the vinyl bond of 4TMSS, owing to electron-withdrawing characteristics of the TMS group, thus increasing its reactivity in comparison to styrene. Similarly, statistical copolymerization of 4TMSS with isoprene led to copolymers with a gradient microstructure ($r_I = 3.276$; $r_{4\text{TMSS}} = 0.152$). Statistical copolymers with molecular weights as high as 50 kg mol^{-1} were accessible with varying fractions of 4TMSS. The presence of a single T_g in the DSC curves suggests that the statistical copolymers of 4TMSS with styrene and isoprene with M_n up to 50 kg mol^{-1} do not phase segregate. Contact angle measurements showed increased hydrophobicity of 4TMSS copolymers.

The knowledge gained from the kinetic data was further used for the synthesis of block copolymers based on 4TMSS and isoprene. By using the determined rate constants of

crossover, a reactivity direction could be predicted, which can render access to well-defined block copolymers. Well-defined di- and triblock copolymers of potential industrial relevance could be synthesized, illustrating both the synthesis potential and rapid access to macromolecular architectures based on this monomer. We believe that this combined fundamental and synthetic study opens up opportunities for the synthesis of gradient and sequential block copolymers based on 4TMSS, with specific applications in photolithography or gas permeation membranes, capitalizing on the TMS group. The fundamental insights both motivate and enable further investigation of morphology and mechanical properties of tapered and sequential copolymers and more complex architectures based on 4TMSS.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at <https://pubs.acs.org/doi/10.1021/acs.macromol.2c00570>.

Detailed synthesis description for the 4TMSS monomer and copolymers, ^1H and ^{13}C NMR spectra, DSC curves, real-time ^1H NMR characterization data, and additional characterization data for the resulting copolymers (PDF)

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Author Contributions

S.P.W.—performed and evaluated experiments and wrote the paper. S.S.—support for real-time ^1H NMR measurements. E.B.-N.—MALDI-MS² measurements. H.F and A.H.E.M.—conceptualized and supervised the project, reviewed, and edited the paper.

Notes

The authors declare no competing financial interest.

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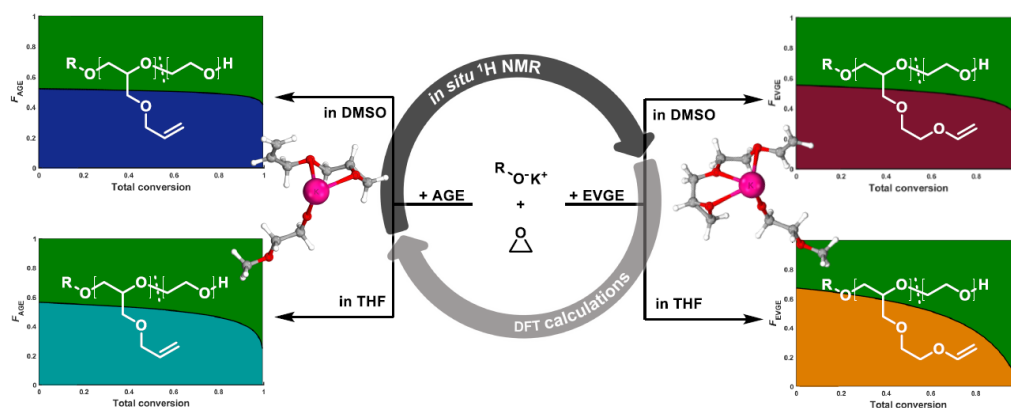
5.2 In Situ Kinetics Reveal the Influence of Solvents and Monomer Structure on the Anionic Ring-Opening Copolymerization of Epoxides.

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RESEARCH ARTICLE



In Situ Kinetics Reveal the Influence of Solvents and Monomer Structure on the Anionic Ring-Opening Copolymerization of Epoxides

Philip Dreier, Rebecca Matthes, Ramona D. Barent, Sandra Schüttner, Axel H. E. Müller,* and Holger Frey*

Dedicated to Brigitte Voit on the occasion of her 60th birthday

In-depth understanding of copolymerization kinetics and the resulting polymer microstructure is crucial for the design of materials with well-defined properties. Further, insights regarding the impact of solvents on copolymerization kinetics allows for precisely tuned materials. In this regard, in situ ^1H NMR spectroscopy enables precise monitoring of the living anionic ring-opening copolymerization (AROP) of ethylene oxide (EO) with the glycidyl ethers allyl glycidyl ether (AGE) and ethoxy vinyl glycidyl ether (EVGE), respectively. Determination of reactivity ratios reveals slightly higher reactivity of both glycidyl ethers compared to EO, emphasizing a pronounced counterion chelation effect by glycidyl ethers in AROP. Implementation of density functional theory (DFT) calculations further illustrates the complexation capability of ether-containing side groups in glycidyl ethers, in analogy to crown ethers ("crown ether effect"). Investigation of the copolymerization in i) THF- d_6 and ii) DMSO- d_6 shows an increasing disparity of reactivity ratios for both glycidyl ethers compared to EO, clearly related to decreasing solvent polarity.

chain end is feasible. Besides controlled radical polymerization, living anionic polymerization (LAP) remains the most efficient method for the synthesis of well-defined copolymers with narrow molecular weight distributions and controlled monomer gradients. Detailed understanding of the compositional profile of the comonomers along the polymer chains is of key importance in gradient or tapered copolymers to adjust the thermal properties in bulk^[1–6] and consequently to control the morphology^[1,4,7] and properties of the resulting materials.

To date, common methods for the evaluation of reactivity ratios and the corresponding comonomer gradient in the copolymer chains formed have relied on the determination of the comonomer content at different stages of copolymerization. After termination at different stages of the reaction,^[8,9] samples were analyzed by gas chromatography to determine residual monomer

1. Introduction

In depth kinetic studies of the statistical copolymerization of different monomers have received renewed interest in recent years, particularly for living polymerization techniques. In this case, reactivity ratios mirror the monomer gradients along the chain and thus "mapping" of the chain composition from initiator to

content.^[10] These monitoring techniques are time-consuming, often rather difficult to implement and may hold uncertainties due to missing reproducibility, since the data are obtained from different polymerization experiments. In comparison, triad analysis via ^{13}C inverse gated (IG) spectroscopy^[11,12] is a reliable method for the determination of the global microstructure, but a large variety of samples must be synthesized for correct assignment and evaluation of the corresponding triads. In addition, it is not possible to derive the gradient structure. More recently, in situ monitoring via near infrared (NIR) spectroscopy^[7,13,14] was established as a feasible analytical tool to directly correlate the polymerization kinetics with the copolymer microstructure for carbanionic copolymerization. The in situ methods advantageously permit to follow the mean composition over the whole conversion range, that is, at all given chain positions, resulting in a full compositional profile of the copolymers.^[7,15] For instance, the influence of temperature^[7] and polar additives^[13,14] on the compositional drift and steepness of the gradient in isoprene/styrene-based tapered block copolymers, synthesized via carbanionic copolymerization, was recently investigated in great detail via NIR spectroscopy.

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The rather slow polymerization kinetics of the anionic ring-opening polymerization (AROP) in polar aprotic solvents facilitates NMR spectroscopic monitoring at room temperature. This has been exploited to follow the monomer consumption of epoxides^[16–22,12,23] as well as activated aziridines^[24–27] via in situ ¹H NMR spectroscopy. Depending on the comonomer employed, the copolymerization of EO with monosubstituted epoxides may result in rather different polymer microstructures. For instance, preferred addition of EO over alkylene oxides^[19] and glycidyl amines^[16] to the active chain end has been observed. In anionic copolymerization with EO, both propylene oxide ($r_{EO} = 2.8$, $r_{PO} = 0.25$)^[11] and butylene oxide ($r_{EO} = 6.46$, $r_{BO} = 0.148$) exhibit significantly lower reactivities compared to EO.^[22] In contrast, the copolymerization of EO with various glycidyl ethers (GE) generally revealed an almost ideally random distribution of the comonomer units along the polyether backbone.^[17,20,28,21] Considering the underlying reactivity ratios, r , and rate constants, k ($r_{EO} = k_{EO,EO}/k_{EO,GE}$, $r_{EO} = k_{GE,GE}/k_{GE,EO}$), this copolymerization behavior necessitates $k_{EO,EO} = k_{GE,EO}$ as well as $k_{GE,GE} = k_{EO,GE}$ and thus the product $r_{EO} \cdot r_{GE}$ equals unity. Consequently, non-terminal models, for example, the Jaacks method^[29] can be employed to investigate the underlying copolymerization kinetics in AROP.^[28,23,17]

In addition to the chemical nature of the monomers, the polarity of the solvent and its potential interaction with the counterion affects the kinetics of AROP copolymerization. EO or substituted epoxides have been investigated with regard to polymerization kinetics in different aprotic polar solvents ranging from linear and cyclic ethers^[30–33] to polar solvents like dimethyl sulfoxide (DMSO)^[34–38] and hexamethylphosphoramide (HMPA).^[36,39] Depending on the polarity of the solvents, ion pairs were observed as reactive species in ethers,^[33,31] whereas free ions were found to be present in the case of the more polar DMSO^[40] and HMPA.^[39] Nevertheless, although the homopolymerization kinetics in these solvents is well understood, the influence of the solvent on the copolymerization kinetics of EO with monosubstituted epoxides remains largely unexplored.

In 2011, our group investigated the microstructure of copolymers consisting of ethoxy vinyl glycidyl ether (EVGE) and EO copolymerized with cesium alkoxides in THF via ¹³C NMR triad analysis. The post-polymerization analysis revealed a random distribution of EVGE units along the polymer backbone while no specific reactivity ratios were calculated.^[41] One year later, Lynd, Hawker and coworkers reported a novel initiator-based method for the calculation of the reactivity ratios based on post-polymerization ¹H NMR spectroscopy. Here, the AROP copolymerization of EO and monosubstituted epoxides, namely EVGE and allyl glycidyl ether (AGE), was investigated in THF with potassium alkoxides as active chain ends.^[42]

To the best of our knowledge, merely the variation of the reactivity ratios in the presence of electron donors has been investigated in detail for the copolymerization of epoxides to date.^[10] Further, online monitoring of the comonomer consumption during copolymerization of EO with EVGE/AGE has not been compared in-depth regarding the influence of substituents as well as solvent variation.

In the current work we utilize in situ ¹H NMR kinetics to evaluate and compare the reactivity ratios of the copolymerization of EO with EVGE and AGE, respectively, both in tetrahydrofuran-

d_8 (THF- d_8) and DMSO- d_6 as solvents (Scheme 1). DFT calculations were employed, leading to an in-depth understanding of the copolymerization kinetics.

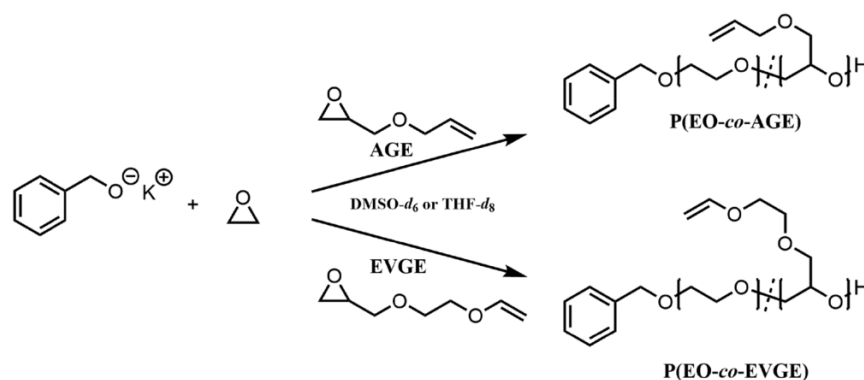
2. Results and Discussion

2.1. Impact of Solvents on Copolymerization Kinetics of EO and Glycidyl Ethers

The anionic ring-opening polymerization (AROP) of epoxides is often performed in polar solvents to achieve ion pair separation and consequently accelerate the polymerization. DMSO with a dipole moment of 3.96 D is the solvent with the highest polarity that can be utilized in AROP, besides the carcinogenic HMPA, which was not used in this study for safety reasons. Thus, DMSO can be considered as the ideal polar system with a high extent of ion dissociation and free ions as the active species.^[40] On the contrary, THF exhibits a lower dipole moment of 1.63 D and accordingly is a less polar solvent implemented in AROP, permitting only partial dissociation of alkali metal alkoxides.^[43] The reactive species of the alkoxide chain ends in THF can be characterized as ion pairs. These ion pairs are in equilibrium with unreactive aggregates,^[31] and polymerization in THF most likely mimics the behavior in bulk polymerizations of epoxides. Therefore, DMSO and THF represent a strongly polar and a comparably nonpolar example to perform AROP of epoxides. Although several studies targeting the copolymerization of EO with various substituted epoxides have been conducted in either THF, DMSO, or mixtures of both, their influence on the copolymerization kinetics has not been compared in a detailed manner to date. Based on this lack of data, we elucidated the impact of solvent polarity on the incorporation of different epoxides in the polyether during the copolymerization of EO with monosubstituted epoxides via in situ ¹H NMR kinetics. To this end, model copolymerization reactions of EO with the two typical glycidyl ethers AGE and EVGE, respectively were performed, initiated by potassium benzyl alkoxide at 45°C in DMSO- d_6 and THF- d_8 , respectively. Potassium benzyl alkoxide was selected as initiator as a commonly employed example in AROP.^[44,42] By recording one spectrum every 30 s, the monomer consumption was monitored over time (Figure 1, top),

As shown in Figure S1, Supporting Information, in DMSO, the copolymerization of EO with AGE and EVGE exhibits high propagation rates, with a half-life (50% conversion) of the respective glycidyl ether of 13 (AGE) and 20 min (EVGE), respectively. A plot of comonomer consumption versus total conversion, as shown in Figure 1 (bottom), shows that in both cases the glycidyl ether is incorporated slightly faster than EO.

Implementation of the Jaacks equation^[29] enabled the calculation of reactivity ratios for both copolymerizations with a coefficient of determination (R^2) of 0.9995 (AGE) and 0.998 (EVGE), respectively (Figure S2, Supporting Information). The Jaacks model is a non-terminal, integrated model for ideal copolymerizations that originates in the simplification $r_1 = r_2^{-1}$ and relies on the linearization of the Meyer–Lowry equation. The latter is applicable, if the rate of monomer incorporation does not show a strong dependence on the identity of the terminal unit, but on the nature of the reacting monomers. Its strength lies in the reduction of potential errors caused by overfitting. The implementation of the non-terminal model is further justified by DFT cal-



Scheme 1. Copolymerization for P(EO-co-AGE) and P(EO-co-EVGE), initiated by potassium benzyl alkoxide in DMSO- d_6 and THF- d_8 .

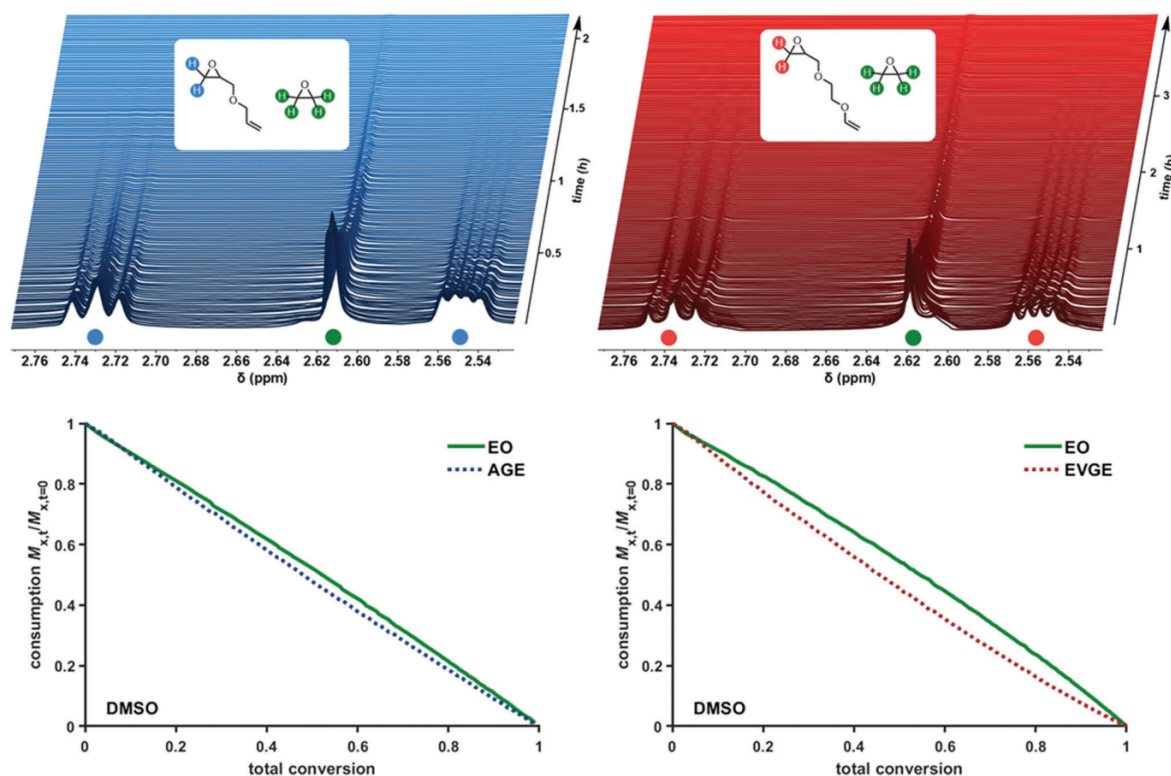


Figure 1. Top: in situ ^1H NMR kinetics of the anionic copolymerization of EO with AGE in DMSO- d_6 (left) and with EVGE (right), initiated by potassium benzyl alkoxide at 45°C ; bottom: conversion of both comonomers versus total conversion.

culations, as discussed in a later section. Note that reactivity ratios are defined as $r_1 = k_{1,1}/k_{1,2}$ and $r_2 = k_{2,2}/k_{2,1}$ with index 1 representing EO and 2 the respective glycidyl ether. Both glycidyl ethers demonstrate rate constants of $k_{\text{AGE,AGE}} > k_{\text{AGE,EO}}$ and $k_{\text{EVGE,EVGE}} > k_{\text{EVGE,EO}}$, resulting in the preferential incorporation of AGE and EVGE in the early stages of the copolymerization. The herein performed in situ kinetic experiments in DMSO con-

sequently revealed reactivity ratios of $r_{\text{EO}}^{\text{DMSO}} = 0.92 \pm 0.002$ and $r_{\text{AGE}}^{\text{DMSO}} = 1.08 \pm 0.002$ as well as $r_{\text{EO}}^{\text{DMSO}} = 0.81 \pm 0.001$ and $r_{\text{EVGE}}^{\text{DMSO}} = 1.23 \pm 0.002$. Collectively, the copolymerization of EO and AGE in DMSO shows nearly ideally random character, whereas the copolymerization with EVGE results in a very slight gradient microstructure. Based on the obtained reactivity ratios, the molar composition diagrams F_{GE} versus total conversion il-

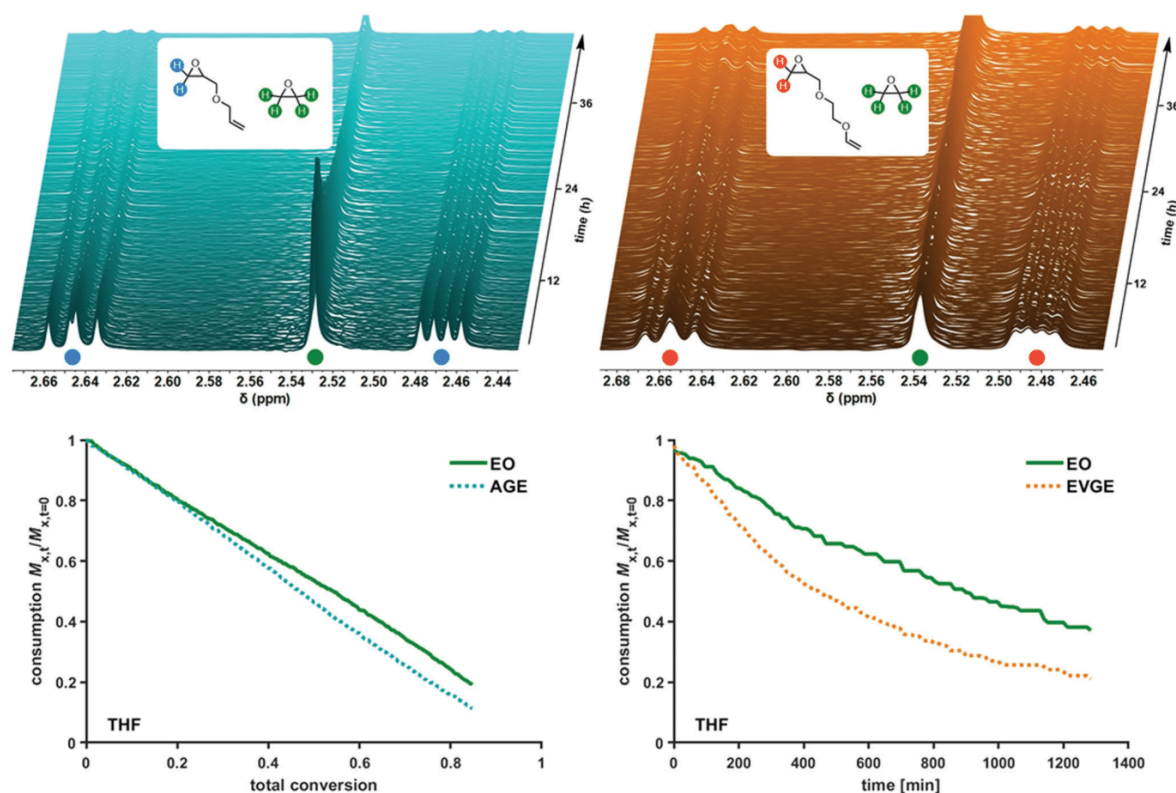


Figure 2. Top: in situ ^1H NMR kinetics in THF- d_8 of the anionic copolymerization of EO/AGE (left) and EO/EVGE (right), initiated by potassium benzyl alkoxide at 45°C ; bottom: consumption $M_{x,t}/M_{x,t=0}$ versus total conversion for P(EO-co-AGE) (left) and for P(EO-co-EVGE) (right).

illustrate the close to random (AGE) and slight gradient (EVGE) microstructure (Figure S3, Supporting Information).

Subsequently, analogous in situ ^1H NMR kinetic experiments were performed in THF to determine the polymerization kinetics of ion pairs in equilibrium with unreactive aggregates. As expected, in THF both copolymerizations revealed significantly decreased propagation rates compared to DMSO, leading to half-lives of 17.3 h (AGE) and 7.6 h (EVGE), respectively (Figures 2 and Figure S4, Supporting Information). The experiment was not carried out to full conversion due to limited measurement time. Nevertheless, the amount of data points reaching >70 % conversion ensures a reliable evaluation of reactivity ratios by the Jaacks equation (R^2 of 0.997 (AGE) and 0.992 (EVGE)) (Figure S5, Supporting Information).

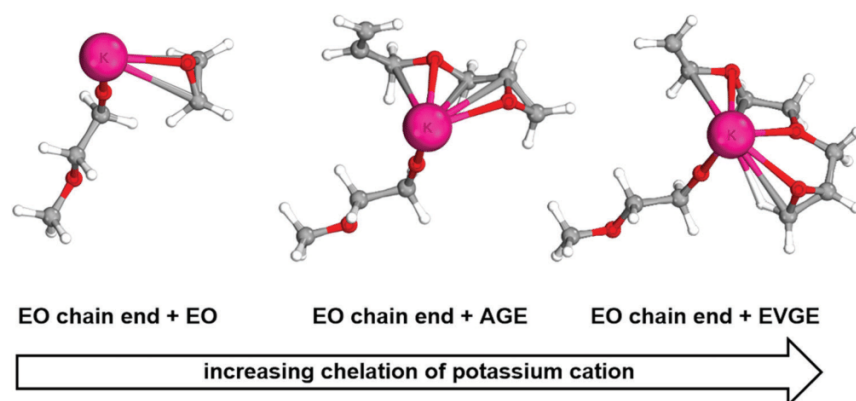
The differences in reactivity between EO and both glycidyl ethers are notably more pronounced in THF in comparison to the polar DMSO system, albeit without changing the overall trend. Accordingly, reactivity ratios were determined as $r_{\text{EO}}^{\text{THF}} = 0.78 \pm 0.001$ and $r_{\text{AGE}}^{\text{THF}} = 1.29 \pm 0.002$ as well as $r_{\text{EO}}^{\text{THF}} = 0.48 \pm 0.004$ and $r_{\text{EVGE}}^{\text{THF}} = 2.05 \pm 0.015$. In THF, both copolymerizations exhibit soft gradient microstructures, illustrated in the molar composition diagrams (Figure S6, Supporting Information). In the case of P(EO-co-EVGE), the gradient determines the nature of the terminal units, consisting almost exclusively of EO repeating units, which can be important for further trans-

formation of the chain end. The investigated polymerizations in DMSO as well as THF resulted in polymers of low to moderate dispersities ($\bar{D} < 1.19$) (see Figure S7, Supporting Information).

A summary of the evaluated reactivity ratios compared to the values reported by Lynd, Hawker and coworkers^[42] based on a different method, that is, the end-group dyad (EGD) method as well as the current results of our group evaluated by ^{13}C NMR triad analysis (for EVGE)^[41] is given in Table 1. The reactivity ratios evaluated for the copolymerization of EO and AGE in THF are in good agreement for both methods (in situ and EGD), while the error is decreased for in situ kinetics due to the large amount of data points. However, the copolymerization of EO and EVGE shows a pronounced discrepancy when comparing the different methods. The EGD analysis yielded a more pronounced reactivity of EVGE compared to the established in situ method as well as the ^{13}C NMR triad analysis. Analysis via EGD enables facile and quick first access to reactivity ratios subsequent to several polymerization experiments via ^1H NMR spectroscopy, but it relies on the first monomer addition steps at the initiator. In contrast, in situ experiments reveal online results with a multitude of data points over minutes up to hours reaction time, however necessitating a demanding reaction set-up within the NMR spectrometer. Nevertheless, the calculated reactivity ratios are independent of the nature of the utilized initiator and enable precise results with low error values, notably up to full monomer conversion.

Table 1. Reactivity ratios evaluated by in situ ^1H NMR experiments using the Jaacks method,^[29] by EGD^[42] and ^{13}C triad analysis.^[41]

Monomer	Method	Solvent	r_{EO}	$r_{\text{EO}}^{\text{eff}}$	r_{GE}	$r_{\text{GE}}^{\text{eff}}$	$r_{\text{EO}} \times r_{\text{GE}}$	R^2
AGE	Jaacks	DMSO	0.92	0.002	1.08	0.002	1.00	0.9995
	Jaacks	THF	0.78	0.001	1.29	0.002	1.00	0.997
	EGD	THF	0.54	0.03	1.31	0.26	0.71	-
EVGE	Jaacks	DMSO	0.81	0.001	1.23	0.002	1.00	0.998
	Jaacks	THF	0.48	0.004	2.05	0.015	1.00	0.992
	EGD	THF	0.32	0.10	3.50	0.90	1.12	-
	triad analysis	THF	$r_{\text{EO}} \approx r_{\text{GE}} \approx 1$					

**Figure 3.** Complexation of potassium by EO chain end with EO, AGE, and EVGE calculated by DFT.

2.2. Impact of Transition State on Monomer Reactivity

The described results demonstrate that the influence of cation complexation on monomer reactivities during the polymerization is more pronounced in THF rather than DMSO. Following these findings, we postulate a transient “crown ether-effect” of the investigated glycidyl ethers, causing the enhanced reactivity of both glycidyl ethers compared to EO in THF, as also mentioned by Lynd, Hawker et al.^[42] It is a known phenomenon that the addition of 18-crown-6, a cyclic oligo(ethylene glycol) consisting of six EO repeating units, strongly complexes potassium cations in THF.^[45] The distance of two methylene units between the oxygens of 18-crown-6 is similarly found for the three oxygens in EVGE. Based on this rationale, a preferential combined complexation of the potassium cation with EVGE monomer and the alkoxide of the propagating chain via chelation can be hypothesized and investigated by quantum chemistry methods, namely density functional theory (DFT) (Figure 3, right). In contrast, EO exhibits only one coordination site per monomer and therefore a lower complex coordination constant with potassium cations. Consequently, this results in a higher probability to find EVGE rather than EO in the chain segments close to the initiator, explaining the preferential incorporation of EVGE ($r_{\text{EVGE}} > r_{\text{EO}}$) during chain propagation. The chelation of potassium cations is less pronounced for AGE, as only two possible coordination sites are present in each AGE monomer (Figure 3, center). Therefore, the stability constant of AGE complexes is lower than that of EVGE,

but still somewhat higher than for EO, resulting in a merely slightly preferred addition of AGE to the chain end in THF ($r_{\text{AGE}} > r_{\text{EO}}$).

The propagating chain ends of the three investigated monomers were simulated using DFT calculations. As visualized in Figure S8, Supporting Information, the presence of a glycidyl ether, namely AGE or EVGE, as an ultimate or penultimate repeating unit of the growing chain allows for a complexation by not merely the backbone oxygens of the former epoxide moiety, but also by the glycidyl ether's side chain. In the case of AGE, the number of oxygens potentially coordinating to the potassium counterion equals the number of coordinating atoms when the backbone aligns with the counterion. On the contrary, with the two oxygen atoms of the side chain of EVGE, the propagation chain end with (pen)ultimate EVGE units further saturates the complexation sites of the potassium counter ion. As discussed, the coordination capability of the monomers to be added follows the trend $\text{EO} < \text{AGE} < \text{EVGE}$ (Figure 3).

The enhanced coordination of the potassium counterion by the monomer going from EO and AGE to EVGE was observed as a local energy minimum. Hence, the inherent entropic benefit is a determining factor for the preferred chelation of the potassium cation. Furthermore, we compared the electron densities of the electrophilic methylene groups of the epoxides calculated by DFT, which are attacked by the alkoxide during polymerization. Since the bond angles of the different epoxides and hence the ring strain of the monomers are comparable, the electron density is

Table 2. Partial charges of the unsubstituted methylene carbon of the epoxide moiety of the monomers ethylene oxide (EO), allyl glycidyl ether (AGE), and ethoxy vinyl glycidyl ether (EVGE) calculated by DFT without taking solvation into account or rather in THF and DMSO using CPCM.

System	EO	AGE	EVGE
Vacuum	−0.285 e	−0.251 e	−0.251 e
THF	−0.275 e	−0.242 e	−0.249 e
DMSO	−0.273 e	−0.240 e	−0.243 e

the pivotal parameter for the monomer reactivity. In Table 2, the partial charges of the three monomers simulated in vacuum as well as in THF and DMSO are given, using the implicit solvation model CPCM.

Both investigated glycidyl ethers exhibit lower electron density at their electrophilic carbon relative to EO. The trend is further decreased for all epoxides with increasing dipole moment of the respective solvent. Consequently, the partial charges give a first indication for preferential incorporation of the glycidyl ethers at the chain end compared to EO. The observed trend in monomer reactivity is further verified by evaluating the electron densities of the electrophilic epoxide methylene groups once coordinated to the propagating chain end, (see Table S1, Supporting Information).

This is in accordance with the observed trend from the in situ ^1H NMR kinetic experiments. Surprisingly, the unsubstituted methylene carbon of AGE exhibits a higher electrophilicity than the respective carbon of EVGE in all solvents. Considering the afore described reactivity ratios, the potassium complexation of glycidyl ethers appears to be the major contributing factor to the copolymerization kinetics in THF, rather than the electrophilicity itself. These findings suggest that the monomer, but not the respective chain, primarily affects the incorporation with its specific complexation behavior. This further supports the implementation of the non-terminal model for the determination of reactivity ratios by in situ ^1H NMR measurements.

Additional considerations are required to understand the impact of solvent polarity on the differences of the reactivity ratios in THF and DMSO ($r_{\text{GE}}^{\text{DMSO}}$ and $r_{\text{GE}}^{\text{THF}}$). Compared to THF, DMSO is a solvent with a high dipole moment. The resulting high polarity of the solvent allows an excellent dissolution of ions. Therefore, free ions are the primary active species, which mainly contribute to propagation.^[40] The strong solvation effect of DMSO has a documented impact on complexes, for example, it is known to decrease the stability constants of crown ether complexes.^[46] This influence is clearly visible when comparing the reactivity ratios obtained via in situ ^1H NMR measurements in the different solvents. In DMSO, only a slightly preferred incorporation of EVGE over EO is observed. Therefore, the previously proposed crown ether-effect of EVGE in THF (Figure 3) is less pronounced in the case of DMSO. This is additionally confirmed by the increasing r_{EO} values from THF (0.57) to DMSO (0.81) and the increasing similarity of $r_{\text{EVGE}}^{\text{DMSO}}$ (1.23) and $r_{\text{AGE}}^{\text{DMSO}}$ (1.08). The described influence of DMSO is equally observed in the copolymerization of EO with AGE, resulting in an almost ideally random copolymerization with $r_{\text{EO}} \approx r_{\text{AGE}}$. Similar values of the reactivity ratios were previously reported by our group for the

copolymerization of ethoxyethyl glycidyl ether (EEGE) with EO in DMSO under AROP conditions.^[17]

In summary, variation of the chemical structure of a glycidyl ether, for example, the addition of an ethylene glycol spacer at the monomer side chain, has a distinct influence on the behavior of epoxide monomers in the copolymerization with EO and consequently the microstructure of the resulting copolymers. In this context, the choice of solvent thus has a pronounced effect on the copolymerization reaction kinetics.

Further, the choice of a non-polar solvent enables the synthesis of “EO-rich” terminal segments within the polymer microstructure. If post-modification of the ω -terminus is desired, a decreased reactivity of EO in copolymerization leads to an increase of primary hydroxy functionalities in the resulting polyether. Consequently, the reactivity of the polyether copolymers for post-modification reactions is largely enhanced.

3. Conclusion

With this study we aim at a general understanding of the anionic ring-opening copolymerization kinetics of ethylene oxide (EO) with glycidyl ethers (GE), relying on online ^1H NMR monitoring of the reaction. Allyl glycidyl ether (AGE) and ethoxy vinyl glycidyl ether (EVGE) were chosen as typical and synthetically valuable representatives of glycidyl ether monomers, and copolymerization was carried out either in THF or DMSO. Online ^1H NMR kinetics enables in situ monitoring of monomer consumption, leading to precise and reliable determination of reactivity ratios by common non-terminal models. Both investigated glycidyl ethers exhibited slightly higher reactivity ratios than EO in DMSO as well as in THF. However, the reactivity difference increased with reduced solvent polarity. These results further emphasize the crown ether effect and the underlying multidentate cation complexation as the driving force for the enhanced reactivity of glycidyl ethers compared to EO in the anionic copolymerization. The impact of the crown ether-like complexation consequently increased with reduced cation dissociation in less polar media going from DMSO to THF. Supplementary calculations by density functional theory (DFT) support the presented crown ether-effect, showing the stronger complexation with increasing number of oxygen atoms comparing EO with ethylene glycol spacer containing GEs ($\text{EO} < \text{AGE} < \text{EVGE}$).

Overall, the results disclose the underlying effects of the slightly preferred glycidyl ether incorporation over EO. This is crucial for the design of glycidyl ether-based copolymers since the resulting microstructure is tunable to a certain extent by choice of solvent as well as the introduction of ethylene glycol spacers in the monomer structures. The monomer gradient governs the behavior of the resulting materials in bulk or solution. In summary, this study provides in-depth insights in epoxide reactivity with respect to the design of the respective monomers as well as its solvent dependence. The results emphasize the vast value of in situ experiments for the control of chemical properties via precise tuning of polymer microstructures.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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P.D. and R.M. contributed equally to this work. The manuscript was written through contributions of all authors. All authors have given approval to the final version of the manuscript.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Keywords

anionic ring-opening polymerization, copolymerization, epoxide monomers, in situ kinetics, polyethers

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5.3 Glycidyl Cinnamate: Copolymerization with Glycidyl Ethers, in-situ NMR Kinetics and Photocrosslinking

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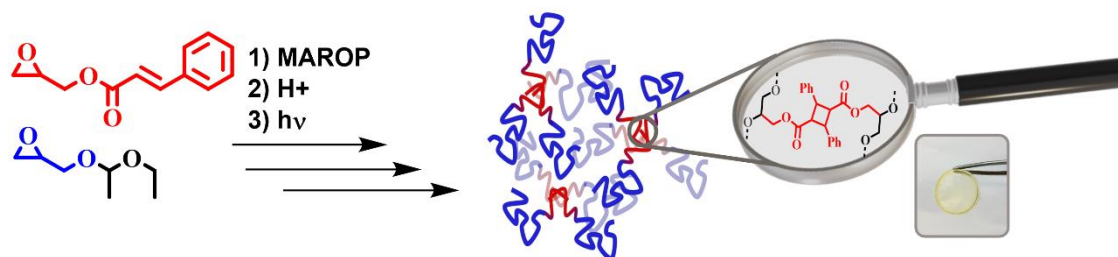
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RESEARCH ARTICLE



Glycidyl Cinnamate: Copolymerization with Glycidyl Ethers, In-Situ NMR Kinetics, and Photocrosslinking

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The copolymerization of glycidyl cinnamate (GC) as a hitherto non-polymerizable, photoreactive epoxide structure to aliphatic polyether copolymers is described, using the monomer-activated epoxide ring-opening polymerization (MAROP). Ethoxyethyl glycidyl ether (EEGE) and GC are copolymerized employing triisobutylaluminum (*i*-Bu₃Al) as a catalyst and tetraoctylammonium bromide (NOctBr₄) as an initiator. The amount of GC varies from 3 mol% to 100 mol%, which results in apparent molecular weights in the range of 2600 to 4600 g mol⁻¹ and dispersities (*Đ*) below 1.34. Studies of the microstructure by in-situ ¹H NMR kinetics indicate a gradient-like distribution of EEGE and GC (reactivity ratios: *r*_{EEGE} = 0.28; *r*_{GC} = 3.6), applying the ideal copolymerization model for evaluation. A tentative explanation relies on differing bond lengths in the respective epoxide rings, as suggested by density functional theory (DFT) calculations. Mild and selective cleavage of the acetal protecting groups of EEGE is achieved using the acidic ionic resin Dowex, leaving the GC ester bonds intact (*M*_n = 1900–3700 g mol⁻¹, *Đ* < 1.34). Thermal properties of the copolymers and the PGC homopolymer are investigated by differential scanning calorimetry (DSC). The crosslinking of P(G-co-GC) copolymers by UV irradiation allows hydrogel formation, which is confirmed by IR spectroscopy.

1. Introduction

Crosslinkable polymer structures for thermosets or composites often rely on acrylates and methacrylates.^[1] In recent work

photoreversible hydrogels were described, derived from coumarin-containing polyacrylates.^[2] However, polyether structures bearing reactive or polymerizable monomer units have only been studied to a very limited extent. In this context, glycidyl esters represent a very interesting platform to generate photocrosslinked polymer networks. Glycidyl esters with a variety of substituents are known.^[3] This class of compounds has hardly been explored to date with respect to ring-opening polymerization due to the harsh, basic conditions of the conventional oxanionic polymerization,^[4] which lead to saponification of the glycidyl esters. Consequently, one has to resort to other polymerization mechanisms, such as the monomer-activated ring-opening polymerization (MAROP), pioneered by Carloti and Deffieux^[5,6,7a–c,8,9] with the polymerization of glycidyl methacrylate (GMA).^[10] In 2020, our group extended the library of ester functional polyethers via MAROP. The copolymerization of ethylene oxide (EO) with the tailor-made ester functional epoxides methyl 4,5-epoxypentenoate (MEP) and *t*-butyl 4,5-epoxypentenoate (*t*BEP) was reported and also provided access to novel carboxylic acid functional poly(ethylene glycol) (PEG) copolymers after cleavage of the ester protective groups.^[11] Further, Kim and coworkers applied a glycidyl ether analogue, *t*-butyl glycidioxy acetate (*t*BGA) in a MAROP. Acidic hydrolysis leads to poly(glycidioxy acetic acid) (PGA), comprising H-bonding donor and acceptor moieties within one monomer repeating unit.^[12] Alternatively, these polymer architectures are also accessible by coordination–insertion polymerization, however, this results in broader molar mass distributions.^[13]

Glycidyl cinnamate (GC) is the glycidyl ester of cinnamic acid and possesses both a reactive double bond and an epoxide function.^[14,15] Cinnamic acid is an intermediate metabolite in the lignin-biosynthesis process and hence represents a biosourced monomer precursor.^[16] As a photocrosslinkable monomer, the glycidyl ester of cinnamic acid is of particular interest, because it represents a bifunctional monomer. GC possesses a polymerizable epoxide moiety and a photosensitive cinnamoyl group. Cinnamic acid derivatives undergo a [2+ 2] photocycloaddition, isomerization or a photo-Fries rearrangement under UV irradiation.^[17a–c,18] Previous access to the cinnamoyl groups in polyethers was achieved by post-polymerization modification, since the harsh conditions of an AROP would cleave the ester

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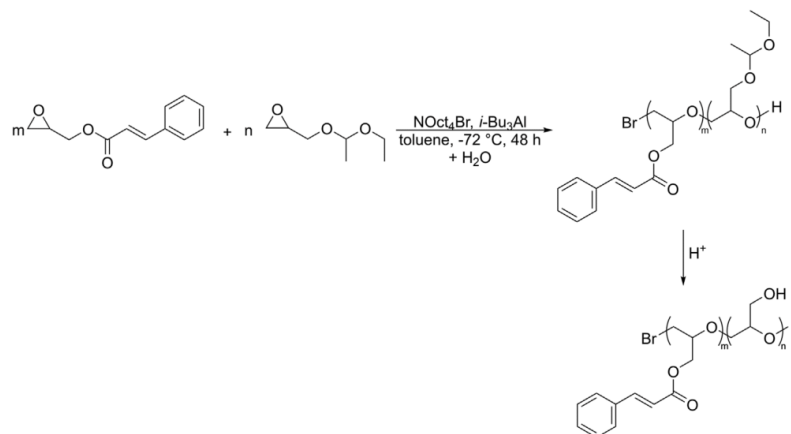
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Scheme 1. Synthesis of P(G-co-GC) via the monomer activation technique by copolymerization of EEGE and GC and subsequent acidic cleavage of the protecting groups.

structure. Trzebicka et al. modified linear poly(ethylene oxide)-*b*-polyglycerol *lin*P(EO-*b*-G) block copolymers using cinnamic acid to nanogels synthesized by UV irradiation.^[19] The photoreactivity of the cinnamic acid moiety was already used in various photoresponsive polymer structures like polyvinyl cinnamic acid ester (PVCm), which was the first synthesized photopolymer to be used as a negative-tone photoresist.^[18,20,21] Application for drug delivery systems was demonstrated by Shi et al. with the synthesis of degradable, photoresponsive nanoparticles. Starting from 3,4-dihydroxycinnamic acid (3,4DHCA), 4-hydroxycinnamic acid (4HCA) and dithiothreitol (DTT), photoresponsive PCA-graft-DTT nanoparticles were prepared, in which protein encapsulation was achieved during nanoparticle formation.^[22] Recently, Zhao et al. synthesized an acrylated, acid-degradable PEG hydrogel with a single cinnamaldehyde acetal unit in the initiator system. However, thiol-ene click reaction was performed under basic conditions to prevent crosslinking by the degradable cinnamaldehyde acetal unit.^[23] Polyglycerol (PG) represents a highly biocompatible and hydrophilic material.^[24] Both linear and branched PG are water-soluble, showing structural similarity to PEG, but possess functional groups at the polyether backbone.^[25] The direct anionic ROP (AROP) of glycidol is not applicable for the synthesis of linear PG (*lin*PG) due to the inimer (initiator–monomer) structure of glycidol, which leads to branching.^[26] The use of suitable protecting groups allows for the formation of linear polyether structures. Ethoxyethyl glycidyl ether (EEGE)^[27] is commonly applied for the synthesis of *lin*PG, capitalizing on the acetal moiety as a base-stable protecting group.^[28] Each hydroxyl group of *lin*PG offers an anchor point for the introduction of various functional groups by post-polymerization modification, which renders the polymer attractive for biomedical application.^[29] Potential applications for *lin*PG include the use for drug delivery systems or bioconjugation with proteins (“PGylation”),^[30] coatings for gold surfaces,^[31] or star-shaped macroinitiators for star block copolymers with core–shell structure.^[25,32]

In this work, we describe the statistical copolymerization of EEGE and GC. To the best of our knowledge, the anionic poly-

merization of GC has not been described to date. Obviously, conventional AROP is not applicable for the polymerization of GC, since cleavage of the ester moiety cannot be avoided under basic reaction conditions. Furthermore, a chain transfer reaction to the monomer caused by the proton abstraction from the methylene proton adjacent to the epoxide ring is a weight limiting side reaction for substituted epoxides.^[33] However, employing the MAROP, *lin*P(G-co-GC) copolymers have been synthesized under mild conditions, circumventing saponification of the ester and proton abstraction.^[5,6,8,9] **Scheme 1** shows the synthetic strategy for the copolymerization of EEGE and GC. The copolymers were characterized taking into account the selective cleavage of the acetal groups of EEGE as well as thermal properties and microstructure of the copolymers. In addition, photocrosslinking of cinnamate-containing P(G-co-GC) copolymers without additives were studied and hydrogels formed.

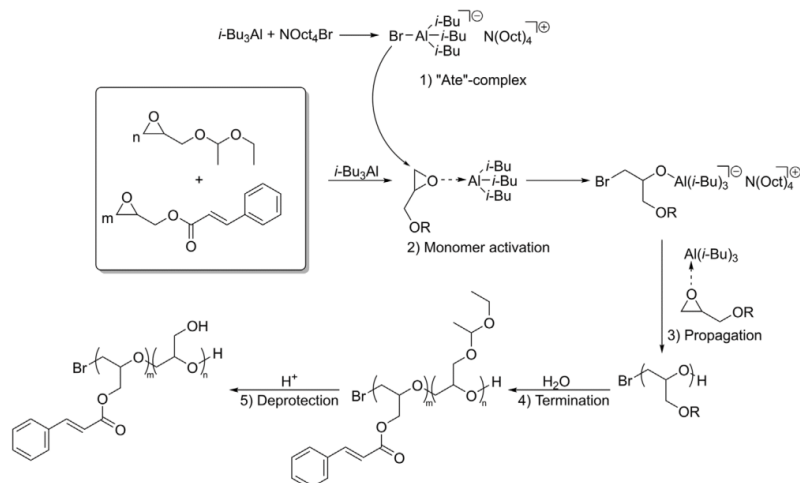
2. Results and Discussion

2.1. Synthesis of the GC Monomer

The preparation of glycidyl cinnamate was performed by esterification of epichlorohydrin with cinnamic acid, which was converted into an activated nucleophile with KOH. It should be emphasized that compared to literature, the yield could be increased by $\approx 17\%$, which is due to a higher amount of phase transfer catalyst and longer reaction times.^[14] In general, GC is readily storable in the refrigerator (4 °C) with high storage stability. Temperatures of 150 °C and a pressure of 1×10^{-3} mbar are required for monomer distillation. For the corresponding ¹H NMR, ¹³C NMR, and 2D NMR spectra, see Figures S1–S4, Supporting Information.

2.2. Copolymerization of EEGE and GC

The synthesis of the copolymers was performed employing an initiator/catalyst system consisting of tetraoctylammonium



Scheme 2. Reaction mechanism for the copolymerization of EEGE and GC initiated by NOct₄Br: i) formation of the “ate”-complex; ii) activation of the monomers by complexation and nucleophilic attack of bromide; iii) chain growth; iv) termination by addition of water; and v) acidic cleavage of the acetals.

Table 1. Copolymerization of EEGE with GC using [*i*-Bu₃Al]/[NOct₄Br] as a catalyst–initiator system (synthesis in toluene, –72 °C).

No.	Copolymer composition ^{a)}	Theoretical composition EEGE:GC ^{a),b),d)}	$M_n^{(th)c)}$ [g mol ^{–1}]	$M_n^{(d)}$ [g mol ^{–1}]	$\bar{D}^{d)}$	[<i>i</i> -Bu ₃ Al]/[NOct ₄ Br] ^{e)}
1	PGC	0:100	10 000	2600	1.19	4.5
2	P(EEGE _{0.17-co} -GC _{0.83})	19:81	10 000	2200	1.20	4.5
3	P(EEGE _{0.27-co} -GC _{0.73})	30:70	10 100	2300	1.34	5.0
4	P(EEGE _{0.70-co} -GC _{0.30})	69:31	10 200	4600	1.21	4.5
5	P(EEGE _{0.81-co} -GC _{0.19})	80:20	10 100	3800	1.19	4.5
6	P(EEGE _{0.84-co} -GC _{0.16})	85:15	10 100	3400	1.09	5.0
7	P(EEGE _{0.92-co} -GC _{0.08})	92:8	10 700	4500	1.28	5.0
8	P(EEGE _{0.97-co} -GC _{0.03})	96:4	10 100	4400	1.11	5.0

^{a)} Obtained from ¹H NMR spectra; ^{b)} The theoretical composition refers to the calculated $M_n^{(th)}$ in column 3; ^{c)} $M_n^{(th)}$ was calculated via the [monomer]/[initiator] ratio;

^{d)} Determined by SEC measurements in DMF (RI detector, PEG standards); ^{e)} Catalyst/initiator ratio.

bromide (NOct₄Br) as an initiator and triisobutylaluminum *i*-Bu₃Al as a catalyst. The catalyst was used in excess (Scheme 2),^[9] because *i*-Bu₃Al acts simultaneously as a monomer activator in addition to forming an “ate”-complex with NOct₄Br. Since the initiator/catalyst ratio influences the propagation rate and molecular weight distributions, the ratio has to be adjusted specifically for each monomer system. Full removal of the catalyst and the hydrolyzed initiator residues represents a critical issue. There are different approaches in literature.^[34] In our work, by termination with Milli-Q water, *i*-Bu₃Al was transformed into the amphoteric aluminum hydroxide and removed by filtration. Subsequent dialysis in dichloromethane/methanol (3:2) removed the residues of the initiator.

Table 1 summarizes the data obtained by size exclusion chromatography (SEC) (RI detector, DMF, PEG standards) for the series of copolymers prepared with GC. Molar masses between 2200 and 4600 g mol^{–1} were obtained with dispersities ($\bar{D}$) be-

tween 1.09 and 1.34. The SEC traces of all P(EEGE-*co*-GC) copolymers and the PGC homopolymer (Figure 1; Figure S5, Supporting Information) display monomodal molecular weight distributions. GC was incorporated in any desired ratio. All batches targeted molecular weights of 10 000 g mol^{–1}. The primary reason for the discrepancies seen in the molecular weights is the SEC calibration, carried out using PEG standards, which only provides exact values for pure PEG. This finding is substantiated by a comparison with the literature. Schömer et al. targeted a PEEGE homopolymer of 7500 g mol^{–1} and measured 2700 g mol^{–1} despite full monomer conversion.^[35] A similar discrepancy of about 60% between the theoretical and molecular weight determined by SEC can be observed for sample P(EEGE_{0.97-co}-GC_{0.03}) (entry 8, Table 1), which shows the lowest content of GC and features the most similar structure to a PEEGE homopolymer. In general, the molecular weight deviation increases with the amount of GC incorporated in the copolymers, since the

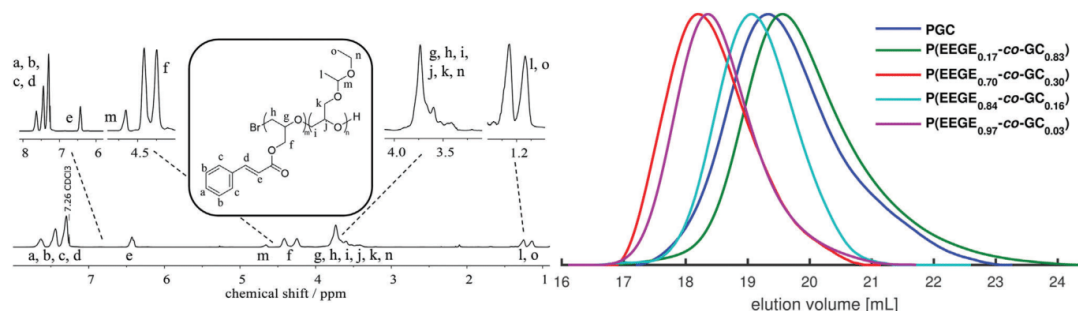


Figure 1. ^1H NMR spectrum (600 MHz, CDCl_3) of $\text{P}(\text{EEGE}_{0.84}\text{-co-GC}_{0.16})$ (entry 6, Table 1) and SEC traces (RI detector, DMF, PEG standards) of selected $\text{P}(\text{EEGE-co-GC})$ copolymers and PGC homopolymer.

hydrodynamic radius of the copolymers differs to an increasing extent from that of the PEG standards. PEEGE and PGC both represent substituted hydrophobic polyethers, which cause a change of the hydrodynamic radius of the copolymer coils to a varying extent. The overlap of RI and UV signal proves homogeneous incorporation of GC and EEGE over the entire molecular weight distribution of the copolymers (Figure S6, Supporting Information).

Due to the absence of a functional initiator, solely the incorporation ratios can be determined via ^1H NMR, but no absolute molecular weights are accessible. MALDI-ToF characterization (Figure S7, Supporting Information) for $\text{P}(\text{EEGE}_{0.97}\text{-co-GC}_{0.03})$ (entry 8) does not only verify the bromide-initiated synthesis of the copolymers, but also demonstrates that molecular weights of at least 8400 g mol^{-1} were achieved (MALDI-ToF is known for its mass discrimination effects).^[36]

Monomer incorporation was in agreement with the monomer ratios employed (Table 1). Characteristic signals at 6.4 ppm (proton of GC double bond) and 4.7 ppm (methine proton of EEGE) from the ^1H NMR spectrum (Figure 1) were used for the evaluation. Additional inverse gated ^{13}C NMR and 2D NMR spectra are provided in Figures S8–S10, Supporting Information. As the monomer-activated monomer polymerization technique is well-known for the suppression of the chain transfer reaction under basic conditions (Figure S11, Supporting Information), the absence of allyl-initiated polymer chains in ^1H NMR analysis confirms the controlled copolymerization of EEGE and GC.^[33,37]

The last column of Table 1 indicates the catalyst/initiator ratio, which had to be adjusted for each copolymerization with different monomer ratios to provide optimal reaction conditions. For propylene oxide (PO), Carlotti et al. already showed that high catalyst–initiator ratios caused broadening of the molecular weight distributions and that no polymerization took place at a ratio ≤ 1 .^[5,38] The amount of catalyst must be chosen according to the structure of the comonomers and EEGE exhibits a strong coordination capability with the catalyst. In general, increasing oxygen content in the monomer structure requires higher amounts of catalyst for the copolymerization due to interaction and complexation of the aluminum catalyst (Figure S12, Supporting Information).^[9]

2.3. In-Situ ^1H NMR Kinetics

In-situ ^1H NMR spectroscopy has become an established method for the investigation of monomer gradients in living copolymerizations. We recently employed in-situ NMR studies for the monomer-activated AROP to elucidate the microstructure of the resulting copolymers.^[39,40] This method is advantageous, since the copolymerization takes place undisturbed in the NMR tube without manual sample removal, avoiding an external manipulation. In this manner, possible contamination by traces of oxygen or water is avoided. In addition, the safety aspect is not negligible, since $i\text{-Bu}_3\text{Al}$ is pyrophoric and reacts violently in air. In the case of copolymerization with the gaseous, toxic, carcinogenic and mutagenic EO, this technique can also prevent possible contamination of the environment by undissolved gas, which can occur when withdrawing samples for kinetic studies.^[41] In a previous work, we published the reaction kinetics of EO with the glycidyl esters MEP and ^tBEP via MAROP, resulting in a random and gradient structure, respectively.^[11] To the best of our knowledge, the reaction kinetics of glycidyl esters with glycidyl ethers has not been investigated to date via real-time ^1H NMR spectroscopy. The monomer distribution in copolymers is highly dependent on the chemical nature of the monomers for the monomer-activated anionic ring-opening copolymerization. The copolymerization of different glycidyl ethers results in a random monomer sequence,^[40,42] while the copolymerization of EO and glycidyl ethers provides strongly tapered copolymer structures with a preferred incorporation of EO in case of monomer activation by $i\text{-Bu}_3\text{Al}$.^[39] The same applies to the copolymerization of glycidyl ethers and propylene oxide (PO), which behaves similar to EO in this case.^[9] Comparing the reactivity ratios of EO and PO, a higher reactivity of EO can be observed.^[38]

Relying on the integrals of the signals for the proton of the GC double bond (6.4 ppm) and the methylene protons of EEGE (3.1 ppm), the decrease of the monomer concentrations was monitored (Figure 2) via in-situ ^1H NMR kinetics at $-20\text{ }^\circ\text{C}$ in toluene- d_8 . Although the polymerization temperature impacts the copolymerization rates, the reactivity ratios remain independent of temperature.^[35,43] Thus, the selection of a copolymerization temperature of $-20\text{ }^\circ\text{C}$ was expected to result in a suitable reaction rate for NMR kinetics. The SEC trace of the resulting

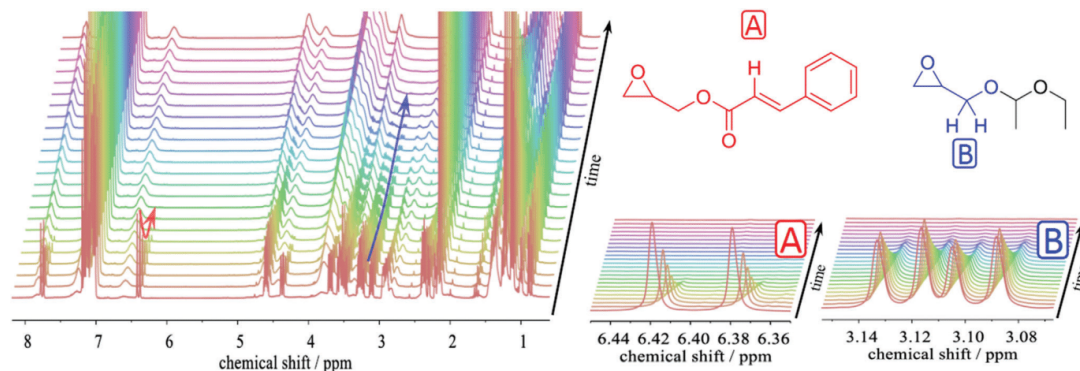


Figure 2. ^1H NMR spectra for the copolymerization of EE and GC in toluene- d_8 at -20°C , monomer activation method; right: zoom-in of relevant areas of the spectrum for evaluation.

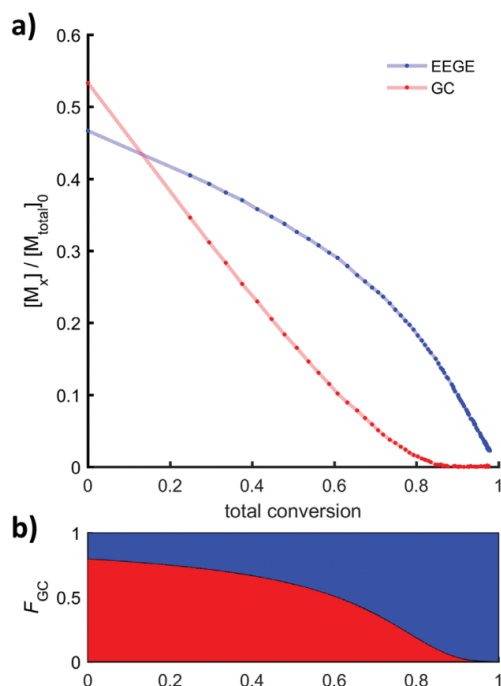


Figure 3. Top a): monomer concentration plotted versus total monomer conversion determined by ^1H NMR spectroscopy in toluene- d_8 at -20°C , applying the monomer-activated AROP. Blue line: conversion of EE, red line: conversion of GC. Bottom b): calculated P(EE-co-GC) microstructure based on the reactivity ratios determined from the ideal model (ideal integrated equation).^[44]

copolymer demonstrates the successful copolymerization (Figure S13, Supporting Information). The decrease of the monomer signals can be directly translated to their incorporation into the copolymer chains formed, since no transfer or termination reac-

Table 2. Reactivity ratios for the monomer-activated ring opening copolymerization of EE and GC in toluene at -20°C , initiated with NOct_4Br and $i\text{-Bu}_3\text{Al}$ as catalyst.

Method	r_{EE}	r_{GC}
Ideal-Integrated	0.28	3.6
Jaacks	0.25	3.9
Meyer-Lowry	0.16	2.7

tions occur. **Figure 3a** illustrates the concentration of EE and GC plotted versus total conversion, indicating a gradient structure of the copolymers.

The data obtained by the in-situ measurement can be fitted by various copolymerization models to obtain reactivity ratios. For Wall's^[45] copolymerization model (ideal/non-terminal) the ideal-integrated method^[44] and Jaacks^[46] method was used. For the fit of the Mayo-Lewis^[47] model (terminal) the Meyer-Lowry^[48] equation was used (Table 2).

The corresponding fits are supplied in Figures S14–S16, Supporting Information. All methods provide similar reactivity ratios and demonstrate the preferred incorporation of GC. Our group has shown in the past that fits using the more-complex Mayo-Lewis model can lead to overfitting.^[49] For this reason, we use the reactivity ratios by the less error-prone ideal model for the calculation of the copolymer microstructure. Based on the reactivity ratios determined by the ideal-integrated equation, the average comonomer composition along the polymer chains can be calculated.^[50] The result is shown in Figure 3b, revealing a gradient-like microstructure. The resulting copolymerization diagram is depicted in Figure S17, Supporting Information. The reactivity ratios observed are consistent with work by Labbé et al. who demonstrated that glycidyl methacrylate (GMA) incorporates faster than glycidyl methyl ether (GME) ($r_{\text{GME}} = 0.37$; $r_{\text{GMA}} = 1.24$).^[10]

As an explanation for the EE/GC reactivity ratios, steric influence can be ruled out, since GC is incorporated preferentially, despite the bulky side group. Instead, the pronounced gradient must be a result of the chemical nature of the monomers. To

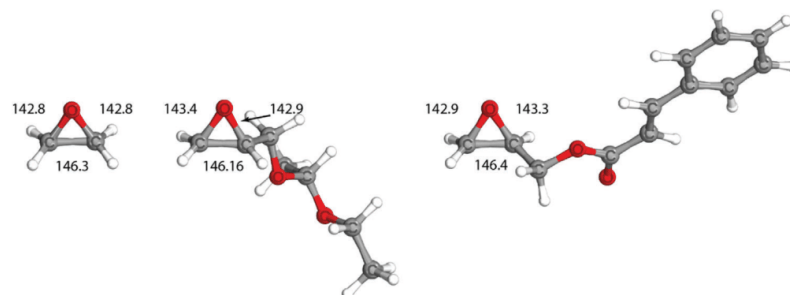


Figure 4. Determined bond lengths (in picometers) for EO, EEGE, and GC via DFT calculations.

correlate the reactivity ratios to the molecular structure of EEGE and GC, quantum mechanical calculations (B3LYP-D3-gCP/def2-TZVP//B3LYP-D3-gCP/def2-TZVP) were performed. As a simplified model, the bond length of the epoxide C–O bond, which is attacked during propagation to form the backbone (for coordinates, see Tables S1–S3, Supporting Information), was investigated. In the case of EEGE, this bond is slightly longer (143.4 pm) compared to GC (142.9 pm) or EO (142.8 pm). This leads to an increased ring strain toward the site for nucleophilic attack in GC compared to EEGE. Furthermore, the bond lengths in EO and GC show only slight differences, thus similar ring strain and reactivity can be expected. In a previous report by our group, a pronounced gradient was observed for EO and EEGE, when copolymerized via monomer-activated AROP ($r_{EO} = 8.00$; $r_{EEGE} = 0.125$).^[39] From the calculated ring geometries, GC can be expected to show similar reactivity as EO (Figure 4), which is considerably more reactive in the monomer-activated copolymerization than EEGE. This is in line with our findings regarding gradient type copolymerization of EEGE and GC.

2.4. Removal of the Acetal Protective Groups to Release Hydroxyl Groups

Cleavage of the acetal group subsequent to the polymerization without affecting the GC ester bonds is not trivial. For this purpose, the acidic ion exchange resin Dowex 50WX8 was used for deprotection. Quantitative removal of the protective groups was achieved using a methanol/toluene mixture and reduced pressure. Continuous removal of the cleavage products acetaldehyde and ethanol resulted in shifting of the reaction equilibrium toward the product side. Consequently, a drastic difference in the polarity of the polymer samples could be observed. While all the protected samples of Table 1 were only soluble in organic solvents such as dichloromethane, the deprotected samples 11–15 (Table 3) could be dissolved in water, which is crucial for the preparation of hydrogels, as discussed below. Table 3 gives the SEC data for all deprotected P(G-co-GC) copolymers. Apparent molecular weights are in the range of 1900 to 3700 g mol^{−1} with $\bar{D}$ below 1.35.

A superposition of selected SEC traces of P(G-co-GC) copolymers is shown in Figure 5 and demonstrates the monomodal distributions obtained. In direct comparison, all individual eluograms are shifted to higher elution volumes (lower molecular

Table 3. Characterization data of deprotected polyglycerol copolymers.

No. ^{a)}	Copolymer composition ^{b)}	Theoretical composition	M_n ^(th) [g mol ^{−1}]	M_n ^(c) [g mol ^{−1}]	$\bar{D}$ ^(c)
9 ⁽²⁾	P(G _{0.18} -co-GC _{0.82})	19:81	9300	1900	1.25
10 ⁽³⁾	P(G _{0.29} -co-GC _{0.71})	30:70	8900	2200	1.33
11 ⁽⁴⁾	P(G _{0.70} -co-GC _{0.30})	69:31	7100	3500	1.32
12 ⁽⁵⁾	P(G _{0.81} -co-GC _{0.19})	80:20	6400	3700	1.21
13 ⁽⁶⁾	P(G _{0.86} -co-GC _{0.14})	85:15	6100	2400	1.30
14 ⁽⁷⁾	P(G _{0.92} -co-GC _{0.08})	92:8	6000	3300	1.34
15 ⁽⁸⁾	P(G _{0.98} -co-GC _{0.02})	96:4	5400	3600	1.21

^{a)} Exponent specifies precursor from Table 1; ^{b)} Obtained from ¹H NMR spectra; ^{c)} Determined by SEC measurements in DMF (RI detector, PEG standards).

weights), when compared to the protected precursors. Successful deprotection is also evidenced by the ¹H NMR spectrum, shown for the deprotected P(G_{0.18}-co-GC_{0.82}) copolymer (entry 9, Table 3) in Figure 5. The typical signals of the acetal protecting group at 4.7 ppm and 1.2 ppm are absent, confirming quantitative cleavage. In addition, all characteristic signals of glycidyl cinnamate are still present. The Supporting Information includes additional ¹³C NMR and 2D NMR spectra (Figures S18–S20, Supporting Information) and additional SEC curves of deprotected copolymers (Figure S21, Supporting Information, entries 10,12,14 in Table 3).

2.5. Thermal Characterization of the Copolymers

Thermal properties of the copolymers were investigated by differential scanning calorimetry (DSC). Table 4 documents the thermal characteristics for both P(EEGE-co-GC) and the deprotected P(G-co-GC) copolymers as well as PGC homopolymer. All values were determined from the second heating curve (for DSC diagrams see Figures S22 and S23, Supporting Information). The glass transition temperatures (T_g s) vary in the range of −60 °C (entry 8, Table 4) for protected copolymers and −13 °C (entry 15, Table 4) after deprotection, to 21 °C (entry 1, Table 4). The glass transition increases in line with the amount of GC. As expected, due to the generally atactic structure of the copolymers, amorphous materials were obtained and consequently no melting points were observed.

In Figure 6, the approximately linear relationships between the T_g of the acetal protected P(EEGE-co-GC) copolymers, the

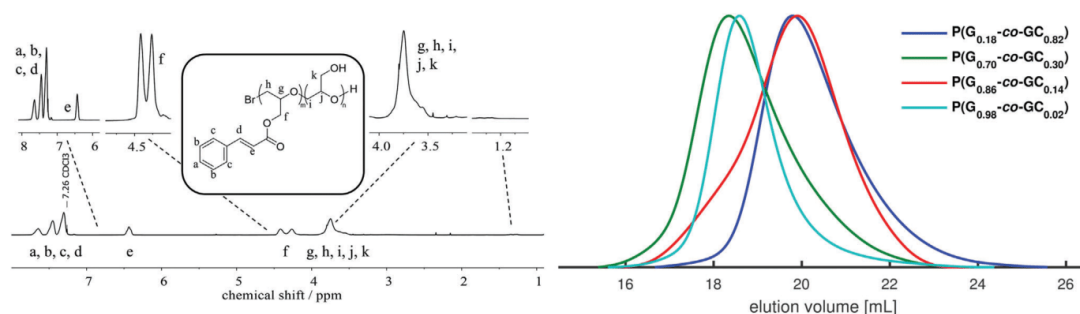


Figure 5. ^1H NMR spectrum (600 MHz, CDCl_3) of $\text{P}(\text{G}_{0.18}\text{-co-GC}_{0.82})$ (entry 9, Table 3) and SEC traces (RI detector, DMF, PEG standards) of selected $\text{P}(\text{G-co-GC})$ copolymers.

Table 4. Thermal properties of $\text{P}(\text{EEGE-co-GC})/\text{P}(\text{G-co-GC})$ copolymers and PGC homopolymer.

No. ^{a)}	Copolymer composition ^{b)}	T_g [°C]
1	PGC	21
2	$\text{P}(\text{EEGE}_{0.17}\text{-co-GC}_{0.83})$	8
3	$\text{P}(\text{EEGE}_{0.27}\text{-co-GC}_{0.73})$	-4
4	$\text{P}(\text{EEGE}_{0.70}\text{-co-GC}_{0.30})$	-42
5	$\text{P}(\text{EEGE}_{0.81}\text{-co-GC}_{0.19})$	-46
6	$\text{P}(\text{EEGE}_{0.84}\text{-co-GC}_{0.16})$	-53
7	$\text{P}(\text{EEGE}_{0.92}\text{-co-GC}_{0.08})$	-54
8	$\text{P}(\text{EEGE}_{0.97}\text{-co-GC}_{0.03})$	-60
9 ⁽²⁾	$\text{P}(\text{G}_{0.18}\text{-co-GC}_{0.82})$	16
10 ⁽³⁾	$\text{P}(\text{G}_{0.29}\text{-co-GC}_{0.71})$	16
11 ⁽⁴⁾	$\text{P}(\text{G}_{0.70}\text{-co-GC}_{0.30})$	9
12 ⁽⁵⁾	$\text{P}(\text{G}_{0.81}\text{-co-GC}_{0.19})$	1
13 ⁽⁶⁾	$\text{P}(\text{G}_{0.86}\text{-co-GC}_{0.14})$	-9
14 ⁽⁷⁾	$\text{P}(\text{G}_{0.92}\text{-co-GC}_{0.08})$	-16
15 ⁽⁸⁾	$\text{P}(\text{G}_{0.98}\text{-co-GC}_{0.02})$	-13

^{a)} Exponent specifies precursor 2–8; ^{b)} Obtained from ^1H NMR spectra.

deprotected $\text{P}(\text{G-co-GC})$ copolymers and the PGC homopolymer are plotted as a function of their GC content. Please note that the T_g s of PEEGE and PG homopolymers were taken from literature and amount to -67 ^[35] and -14 °C,^[51] respectively. The T_g s of the copolymers are within these limits. The nearly linear trend for the $\text{P}(\text{EEGE-co-GC})$ copolymers demonstrates the effect of the incorporation of the comonomers EEGE and GC. However, the observed deviations can be derived from the gradient copolymer structure.

The systematic increase of the glass transition with rising GC content is due to the substituent effects. Bulky side chains, such as the sterically demanding cinnamic acid ester groups, impede mobility of the main chain and thus lead to an increase of the T_g .^[52] Upon deprotection and release of the hydroxyl groups, a general increase of the T_g s in the series of $\text{P}(\text{G-co-GC})$ copolymers is observed ($\Delta T_{g-15} = 47$ °C), which is due to hydrogen bond interaction.^[53] This effect becomes smaller with increasing GC content ($\Delta T_{2-9} = 8$ °C) demonstrating that the large, sterically

demanding GC side groups possess a major impact on the glass transition of the respective samples.

For evaluation, the linear plot of the Fox Equation (1)^[54] and the simple, linear combination based on the empirical Jenckel–Heusch Equation (2)^[55] were used:

$$\frac{1}{T_g} = \frac{x_{\text{EEGE/G}}}{T_{g_{\text{PEEGE/PG}}}} + \frac{x_{\text{GC}}}{T_{g_{\text{PGC}}}} \quad (1)$$

$$T_g = x_{\text{EEGE/G}} \times T_{g_{\text{PEEGE/PG}}} + x_{\text{GC}} \times T_{g_{\text{PGC}}} \quad (2)$$

Here, x is the mole fraction of the monomer units EEGE/G and GC, whereas $T_{g_{\text{PEEGE/PG}}}$ and $T_{g_{\text{PGC}}}$ correspond to the respective homopolymer. These equations represent a simplified approach, which does not take specific interaction terms into account.^[56] Direct comparison demonstrates that the measured T_g values for the protected $\text{P}(\text{EEGE-co-GC})$ copolymers agree reasonably well with the course of the Fox and modified Jenckel–Heusch equation. Thus, the glass transitions can be predicted for arbitrary $\text{P}(\text{EEGE-co-GC})$ copolymer compositions using these equations. For the deprotected $\text{P}(\text{G-co-GC})$ copolymers, a considerable deviation from the course of the fits is observed, which reaches its maximum at a composition of 40–50 mol% GC. This behavior can be attributed to the gradient copolymer structure as well as interactions and the considerations of the chemical nature of the comonomers.^[57] As a consequence of hydrogen bonding between the ester function of GC and the hydroxyl groups of the glycerol moieties, higher T_g s are observed.^[58]

2.6. Photocrosslinking of $\text{P}(\text{G-co-GC})$ Copolymers

Polyether copolymers with cinnamic acid functionality are promising for traceless photocrosslinking.^[59a–d,60] The reactive double bond in the cinnamic acid side chain permits photodimerization and thus crosslinking of the copolymers, as shown in Figure S24, Supporting Information. In general, photocrosslinking of cinnamate derivatives requires UV radiation with $\lambda > 280$ nm (here 312 and 365 nm).^[21,60,61] As a result, cinnamate units exhibit a substantial advantage, since no other reagents such as photoinitiators are required for crosslinking. The following section discusses the photodimerization-based crosslinking of the

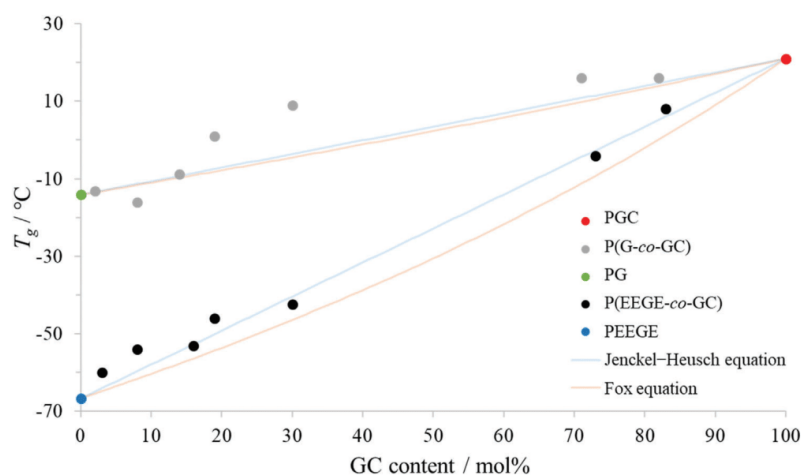


Figure 6. Glass transition temperatures of P(EEGE-co-GC)/P(G-co-GC) copolymers and PG/PEEGE/PGC homopolymers as a function of the GC content, including fits for the modified Jenckel-Heusch (blue curve) and Fox equation (red curve).

Table 5. Swelling behavior of the P(G-co-GC) hydrogels.

No. ^{a)}	Copolymer composition ^{b)}	SR [%]	Q _m
11 ⁽⁴⁾	P(G _{0.70} -co-GC _{0.30})	79	1.8
12 ⁽⁵⁾	P(G _{0.81} -co-GC _{0.19})	172	2.7
13 ⁽⁶⁾	P(G _{0.86} -co-GC _{0.14})	175	2.8
14 ⁽⁷⁾	P(G _{0.92} -co-GC _{0.08})	220	3.2
15 ⁽⁸⁾	P(G _{0.98} -co-GC _{0.02})	—	—

^{a)} Exponent specifies precursor; ^{b)} Obtained from ¹H NMR spectra.

synthesized P(G-co-GC) copolymers in ethanol (14 wt%) by use of UV irradiation, allowing swelling of the crosslinked copolymer disks in water and formation of hydrogels.^[62]

Direct crosslinking via photodimerization in aqueous solution failed, which might be attributed to the gradient-like microstructure of the copolymers that could lead to shielding of the less soluble glycidyl cinnamate units by the polar polyglycerol chains. A series of experiments was performed, varying both the concentration and UV irradiation times. Finally, the use of ethanol as a solvent turned out to be the best option as all P(G-co-GC) copolymers possessing a GC content below 30% were soluble. The copolymers were successfully photocrosslinked, and the solvent was allowed to evaporate slowly. For successful formation of hydrogels, the GC content in the copolymers must exceed 2 mol% (cf. entry 15, Table 5). After irradiation of the soft and adhesive (“sticky”) starting material, a solid hydrogel was formed. Noticeable differences in the properties of the crosslinked copolymers were observed, depending on the amount of GC in the copolymers employed. While photocrosslinking of P(G_{0.92}-co-GC_{0.08}) (entry 14, Table 3) resulted in an elastic material, crosslinked polymer films with higher amount of GC were quite brittle.

To confirm the successful photodimerization, IR spectroscopy was conducted as a qualitative method due to the insolubility of the crosslinked copolymers. Figure S25, Supporting Information, shows the superimposed, normalized IR spectra of the P(G-co-GC) copolymers after crosslinking. In particular, the wave number range of 1800 to 1600 cm⁻¹ demonstrates successful crosslinking of the P(G-co-GC) copolymers. In the case of the non-crosslinked polymers, the unsaturated ester carbonyl band appears at $\nu_{\text{C=O}} = 1709 \text{ cm}^{-1}$, and the C=C stretching mode at $\nu_{\text{C=C}} = 1636 \text{ cm}^{-1}$ (Figure 7). The IR spectrum shows a strong decrease of the C=C stretching mode after the photodimerization and a shift of the carbonyl band to 1731 cm⁻¹. According to Coleman et al., the difference between the unsaturated C=O and the saturated carbonyl stretching band is a consequence of the formation of saturated C-C crosslinks from the cinnamoyl double bonds (cf. Figure S24, Supporting Information).^[63]

For the characterization of the hydrogels, the equilibrium swelling ratio (SR, Equation (3), see the Experimental Section) and mass swelling (Q_m, Equation (4), see the Experimental Section) in water were examined. Table 5 summarizes the SR and Q_m results for the P(G-co-GC) hydrogels.

The SR was calculated using Equation (3) and varies from 220% to 79%. However, the mass swelling (Equation (4)) decreases from 3.2 to 1.8, which is illustrated in Figure S26, Supporting Information. As expected, with increasing GC content, the water uptake decreases due to increasing crosslink density. The hydrogels exhibit rather low water uptake compared to PEG hydrogels.^[64] This behavior is tentatively attributed to the microstructure of the P(G-co-GC) copolymers. According to the in-situ ¹H NMR kinetic measurements, the copolymer chains show a gradient-like distribution and consequently no uniformly distributed GC units. A large water uptake capacity requires rather long hydrophilic segments, leading to a large mesh size.^[65] Instead, the crosslinks are concentrated in the GC-rich segments due to the gradient, resulting in a decreased mesh size and in reduced water uptake.^[66]

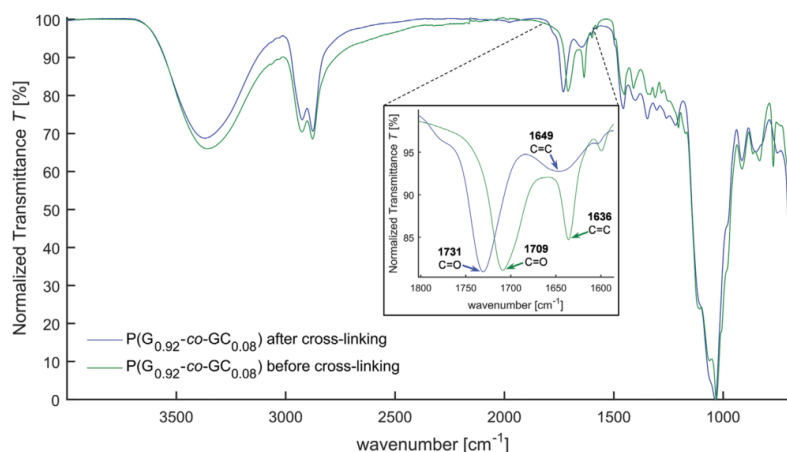


Figure 7. Normalized IR spectra of $P(G_{0.92}\text{-co-GC}_{0.08})$ (entry 14, Table 3) before and after photocrosslinking, including a zoom-in of the GC double bond region.

3. Conclusion

By using the peculiar features of MAROP, the copolymerization of GC and EEGE has been introduced. Incorporation of the photoresponsive GC monomer in the biocompatible PG chains allows for the formation of cinnamoyl-crosslinked copolymer networks without additional photoinitiator and gives rise to promising candidates for biomedical applications. The results demonstrate that such reactive glycidyl esters, as a hardly studied class of epoxide monomers, are amenable to ring-opening polymerization reactions, if the monomer activation technique is employed. The amount of incorporated GC in the polymers varied from 3 mol% to 100 mol%, relying on an excess of triisobutylaluminum ($i\text{-Bu}_3\text{Al}$) as a catalyst in combination with tetraoctylammonium bromide (NOct_4Br) as an initiator. The obtained $P(\text{EEGE-co-GC})$ copolymers showed apparent molecular weights ranging from 2600 to 4600 g mol^{-1} with dispersities ($\bar{D}$) below 1.34. Detailed characterization of the microstructure using *in situ* ^1H NMR kinetics revealed a gradient incorporation of the comonomers via the ideal copolymerization model ($r_{\text{EEGE}} = 0.28$; $r_{\text{GC}} = 3.6$). Density functional theory (DFT) calculations confirmed similar ring strain of GC and EO, for which a strong monomer gradient in the monomer-activated copolymerization with EEGE was recently demonstrated by our group.^[39]

Selective cleavage of the acetal protecting groups, avoiding ester hydrolysis of the GC units, was achieved using Dowex ion exchange resin. The molecular weights of the resulting deprotected $P(\text{G-co-GC})$ copolymers varied from 1900 to 3700 g mol^{-1} while the dispersities $\bar{D}$ were in the range of 1.21 to 1.34. An investigation of the thermal properties demonstrated the effect of hydrogen bonds in the $P(\text{G-co-GC})$ copolymers. The glass transition temperatures (T_g s) ranged between -13 (deprotected polyethers) and -60 (protected polymer) to 21 $^\circ\text{C}$ for the PGC homopolymer. Photocrosslinking of the cinnamate-containing copolymers via UV irradiation enabled the formation of hydrogels with a water equilibrium swelling of up to 220%.

These characteristics render $P(\text{G-co-GC})$ copolymers interesting candidates for biomedical applications, particularly since the respective hydrogels are accessible without addition of initiators or crosslinking agents.^[67] The results of this work may be of a general nature for the polymerization and copolymerization of the hitherto scarcely studied monomer class of glycidyl esters. By esterification of carboxylic acids with glycidol, a vast variety of different side chains is conveniently accessible, greatly enhancing the structural diversity of polyethers.

4. Experimental Section

Terminology: Linear polyglycerol is hereafter abbreviated as PG.

Instrumentation: ^1H NMR spectra (400 MHz or 600 MHz) were recorded on a Bruker Avance II 400 or Bruker Avance III 600 spectrometer. All spectra are referenced internally to residual proton signals of the deuterated solvent. *In situ* ^1H NMR kinetics were measured on a Bruker Avance III HD 400 spectrometer equipped with a 5 mm BBFO Smart-Probe (Z-gradient probe) and an ATM as well as a SampleXpress 60 auto sampler. SEC measurements were performed on an Agilent 1100 Series, equipped with a Polymer Standards Service (PSS) HEMA column (300/100/40 Å porosity), RI and UV (275 nm) detector. Dimethylformamide (containing 1 g L^{-1} of lithium bromide [LiBr]) was used as a solvent at 50 $^\circ\text{C}$ and poly(ethylene glycol) standards provided by PSS were employed for calibration. All SEC samples were prepared in DMF (1 g L^{-1} LiBr) at a concentration of 1 mg L^{-1} . DSC measurements were performed on a Perkin Elmer 8500 with a temperature range of -80 to 80 $^\circ\text{C}$, using heating and cooling rates of 20 (first cycle) and 10 $^\circ\text{C min}^{-1}$ (second cycle). For evaluation, the data points of the second heating cycle were used. IR spectra were recorded on a Nicolet iS10 Fourier transform infrared spectrometer (Thermo Fisher Scientific) with attenuated total reflection. Matrix-assisted Laser Desorption Ionization Time-of-Flight (MALDI-ToF) Mass Spectrometry was conducted on a Bruker MALDI-ToF MS AutoFlex Max in the linear modulus. *Trans*-2-[3-(4-*tert*-Butylphenyl)-2-methyl-2-propenylidene]malononitrile (DCTB) and AgTFA were selected as matrix and salt additive, respectively.

DFT Calculations: Quantum mechanical calculations were carried out with the ORCA 3.0.2 software suite.^[68] All structures were optimized using

the B3LYP DFT hybrid functional with geometrical counterpoise correction (gCP)^[69] and dispersion correction (D3)^[70] using def2-TZVP^[71] as basis set and RIJK-COSX^[72] as approximation. In all cases frequency analysis was performed and no imaginary frequency was detected.

Reagents: Chemicals and solvents were purchased from commercial suppliers (Acros, Sigma-Aldrich, Fisher Scientific, Alfa Aesar) and used without prior purification, unless otherwise stated. Deuterated solvents were obtained from Deutero GmbH. *i*-Bu₃Al (1.1 M solution in toluene, Acros Organics) and toluene (99.85%, Acros Organics) were used without further purification. NOct₄Br (98%, TCI) was azeotropically dried with benzene overnight under reduced pressure. GC was purified by stirring over CaH₂ and distillation. EECE was synthesized according to Fitton et al.^[27] and dried analogously. Dialysis membranes (regenerated cellulose, MWCO = 1000 g mol⁻¹) were obtained from Orange Scientific.

Monomer Synthesis (Glycidyl Cinnamate): GC was prepared in a two-step synthesis. For the preparation of potassium cinnamate (PC), cinnamic acid (2 g, 13 mmol, 1 equiv.) was dissolved in THF (20 mL) in a round-bottom flask and heated to 30 °C. While stirring, freshly ground potassium hydroxide (0.8 g, 13 mmol, 1 equiv.) was added to the reaction solution. After one hour, the solvent was removed in vacuo. Yield: quantitative.

The second reaction step was performed according to a slightly modified procedure of Rusu et al.^[14] PC (1.5 g, 8 mmol, 1.0 equiv.) and epichlorohydrin (7.9 mL, 101 mmol, 12.5 equiv.) were placed in a reaction flask. Subsequently, tetrabutylammonium bromide (130 mg, 0.4 mmol, 0.05 equiv.) was added and the reaction mixture was stirred at reflux of 115 °C for 3.5 h. The clear orange solution was diluted with dichloromethane (40 mL) and potassium chloride was filtered off. After washing twice with a saturated, aqueous NaHCO₃ solution (100 mL), the organic phase was dried over MgSO₄ and concentrated using a rotary evaporator. By distillation of the orange solution under reduced pressure, the product was isolated as a colorless, viscous liquid. Yield: 85%.

¹H NMR (400 MHz, CDCl₃): δ (ppm) = 2.67 (dd, 1H, H_a), 2.84 (t, 1H, H_a), 3.26 (m, 1H, H_b), 4.02 (dd, 1H, H_c), 4.53 (dd, 1H, H_c), 6.45 (d, 1H, H_d), 7.35 (m, 3H, H_e, H_f, H_g), 7.50 (m, 2H, H_g), 7.71 (d, 1H, H_e). ¹³C NMR (100 MHz, CDCl₃): δ (ppm) = 44.64 (C_a), 49.43 (C_b), 65.04 (C_c), 117.30 (C_e), 128.11 (C_i), 128.88 (C_h), 130.44 (C_j), 134.16 (C_g), 145.50 (C_f), 166.49 (C_d).

Copolymerization of EECE and GC: The following protocol was performed in analogy to the literature procedure for the polymerization of EECE according to Carloti and Deffieux^[9] and refers to the sample P(EECE_{0.17}-co-GC_{0.83}) (entry 2, Table 1, (*M_n*th) of 10 000 g mol⁻¹, theoretical molar composition of EECE:GC = 19:81). Tetraoctylammonium bromide (0.1 g, 0.09 mmol, 1 equiv.) was freeze-dried with benzene (3 mL) in a Schlenk tube. Anhydrous toluene (5 mL) and the dried monomers GC (0.7 mL, 3.84 mmol, 42 equiv.) and EECE (0.1 mL, 0.91 mmol, 10 equiv.) were added to the initiator via syringe under argon atmosphere. After cooling to -72 °C with an ethanolic/dry ice bath, the polymerization was initiated by injection of the catalyst *i*-Bu₃Al (0.4 mL, 0.41 mmol, 4.5 equiv.), resulting in a strong yellow color that decreased during the reaction. The reaction mixture was slowly warmed to room temperature. Termination was carried out after 48 h by addition of Milli-Q water (1 mL). Al(OH)₃ precipitated as a white solid, which was removed by filtration. The polymer solution was concentrated in vacuo. For purification the copolymer was dissolved in dichloromethane and dialyzed against dichloromethane/methanol (3:2) for 24 h. Drying under vacuum afforded the copolymer in yields of 90%.

¹H NMR (600 MHz, CDCl₃): δ (ppm) = 1.15 (br, H_o), 1.22 (br, H_i), 3.36–4.01 (br, H_g, H_h, H_j, H_k, H_l, H_m), 4.32 (br, H_f), 4.70 (s, H_m), 6.43 (br, H_e), 7.30–7.45 (br, H_a, H_b, H_c), 7.64 (br, H_d). ¹³C NMR (150 MHz, CDCl₃): δ (ppm) = 15.28 (C_q), 19.80 (C_n), 60.99 (C_p), 63.71 (C_h, C_j, C_i), 69.51 (C_m), 77.74 (C_i, C_k), 99.81 (C_o), 117.69 (C_f), 128.17–128.85 (C_b, C_c), 130.33 (C_a), 134.25 (C_d), 145.20 (C_e), 166.69 (C_g).

Deprotection of P(EECE-co-GC): Removal of the acetal protecting group under acidic conditions was performed using the ion exchange resin Dowex 50WX8. For this purpose, the copolymer was dissolved in a methanol/toluene mixture (2:1, 20 wt%) to which Dowex was added. In order to shift the reaction equilibrium, the volatile by-products (acetaldehyde and ethanol) were removed under reduced pressure at 30 °C for 12

h. The resin residue was filtered before the polymer was dried in vacuo. Yield: 90% to quantitative.

¹H NMR (600 MHz, CDCl₃): δ (ppm) = 3.48–3.97 (br, H_g, H_h, H_i, H_j, H_k), 4.34 (br, H_f), 6.43 (br, H_e), 7.30–7.45 (br, H_a, H_b, H_c), 7.60 (br, H_d). ¹³C NMR (150 MHz, CDCl₃): δ (ppm) = 63.62 (C_h, C_j, C_i), 69.72 (C_m), 77.74 (C_i, C_k), 117.61 (C_f), 128.21–128.91 (C_b, C_c), 130.37 (C_a), 134.22 (C_d), 145.28 (C_e), 166.75 (C_g).

In-Situ ¹H NMR Kinetic Studies: In the first step the initiator tetraoctylammonium bromide (NOct₄Br, 50 mg) was dried in a Schlenk tube by dissolving it in 2 mL benzene and stirring under vacuum for 30 min at 60 °C. After removing the solvent under vacuum for 24 h, 0.5 mL dry toluene-*d*₈ were added. A Norell S-5-400-VT-7 NMR tube was evacuated overnight and filled with argon. 0.1 mL of the initiator solution (NOct₄Br, 1 equiv.) was added in the NMR tube, followed by 0.55 mL toluene-*d*₈. Glycidyl cinnamate (GC) and EECE were dried over CaH₂ and distilled under reduced pressure. 47 μL GC (15 equiv.) and 40 μL EECE (15 equiv.) were placed in the NMR tube. After cooling with an acetone/dry ice bath for 20 min, 83 μL *i*-Bu₃Al solution (1.1 M in toluene, 5 equiv.) was injected via syringe. The NMR tube was sealed with a Teflon stop-cock and shaken vigorously in order to homogenize the solution before placing the tube in the NMR spectrometer with the probe gas flow adjusted to -20 °C. When a stable temperature in the probe head was reached (≈10 min, ΔT = 0.1 K), the first spectrum was recorded. Sample spinning was turned off. Spectra were recorded with 16 scans at 2 min intervals throughout the entire measurement. The measurement was stopped at full conversion (≈2 h). SEC data of the isolated P(EECE_{0.50}-co-GC_{0.50}) copolymer is shown in Figure S13, Supporting Information.

Crosslinking by UV Irradiation and Study of Swelling Behavior: Crosslinking experiments were performed in small PTFE pans (φ = 20 mm). For this purpose, an ethanolic P(G-co-GC) solution (c = 140 g L⁻¹) was transferred into the pans. The pans were covered with a quartz glass slide in order to avoid contamination and rapid evaporation of the solvent. For the irradiation, a UV lamp was used, into which UV tubes with wavelengths of 312 nm and 364 nm were installed. After 180 min, the crosslinked copolymer films were removed from the pans.

For the study of the swelling properties, the hydrogels were placed in Milli-Q water for 48 h in order to reach equilibrium swelling. Subsequently, the swollen hydrogels were removed and weighed after removal surface adsorbed water by Kimwipes. The hydrogels were allowed to swell in water again for 1 h and the process was repeated three times to determine the standard deviation. Swelling ratio (SR) was determined using the following expression:^[73]

$$WSR = \left(\frac{w_s - w_d}{w_d} \right) \times 100 \quad (3)$$

where *w_s* and *w_d* are the weights of the swollen and dry hydrogels, respectively. The mass swelling (Q_m) was calculated according to:^[73]

$$Q_m = \frac{w_s}{w_d} \quad (4)$$

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

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Curriculum Vitae

LIST OF PUBLICATIONS

- (1) Wadgaonkar, S. P.; Schüttner, S.; Berger-Nicoletti, E.; Müller, A. H. E.; Frey, H. Anionic copolymerization of 4-trimethylsilylstyrene: from kinetics to gradient and block copolymers. *Macromolecules*, **2022**, 55, 11, 4721–4732.
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