**ABSTRACT:** The ring-opening copolymerization of epoxides with isothiocyanates (ITCs) is explored for the first time. In the presence of phosphazenium benzoxide, epoxides investigated in this work including propylene oxide, ethylene oxide, and cyclohexene oxide were successfully copolymerized with both aromatic ITC, phenyl isothiocyanate, and two aliphatic ITCs, ethyl isothiocyanate and hexyl isothiocyanate. Effects of the phosphazenium bases used, of the temperature, and of the presence of Lewis acids, triethyl borane and diethyl zinc (ZnEt₂), on the alternating copolymerization were investigated respectively. The thermal properties of the obtained copolymers were analyzed by differential scanning calorimetry and thermogravimetric analysis. The present work reports new ITC heteroallene monomers being alternating copolymerized with epoxides.

**INTRODUCTION**

Polymerizations involving two or more monomers to access copolymers can be traced back to the 1930s. Since that period, the synthesis of copolymers with different compositions and monomer sequences along the chain has never dwindled. By varying the composition and sequences of monomers, the properties of the obtained copolymers could indeed be tailored to the needs of specific applications. Typically, copolymers can be categorized into alternating copolymers, periodic copolymers, block copolymers, gradient copolymers, and random or statistical copolymers on the basis of the different arrangements of their comonomer units. Indeed, the properties, roles, and functions of macromolecules, such as protein, DNA, and RNA, depend on their monomer sequence. In the case of biomolecules (sequence-controlled polymers), a precisely controlled monomer sequence encodes information that governs their role and function and directs their behavior (e.g., genetic code and biocatalysis). By manipulating monomer sequences along polymer chains, the aim is to synthesize structurally controlled polymers that can exhibit unique properties as do biological polymers.

Typically, alternating copolymers represent a type of sequence-controlled polymer where two comonomers strictly alternate along the polymer chains (ABABAB...). The example of a styrene-maleic anhydride copolymer is undoubtedly one of the most well-known and most studied alternating copolymer systems; it has been commercialized as a molding resin and a compatibilizer and used in other applications. If the AB comonomer sequence is considered as one unit, a precisely sequence-controlled alternating structure can lead to and generate properties and functions as biodegradability, thermal properties, solubilities, and separating capacity that would not be achieved by (co)homopolymerizing the same A and B monomers in other sequence-controlled structures such as block or gradient copolymers. Although controlled/living polymerization techniques (i.e., living anionic polymerization, reversible-deactivation radical polymerization, ring-opening metathesis polymerization, and coordination polymerization) have significantly expanded the diversity of sequence-controlled polymer structures, monomer combinations leading to alternating copolymerization structures are still limited.

Epoxides are a class of monomers that have been and are still widely used for macromolecular engineering and the design of sequence-controlled structures. One well-known example is the discovery by Inoue in 1969 of the alternating copolymerization of epoxides with CO₂: this topic has received extensive attention especially during the past two decades to address the issue of over emission of CO₂; various aliphatic polycarbonates could be generated by alternating copolymerization of epoxides with CO₂ through metal-based catalysis, with heterogeneous and homogeneous catalysis and through a recently reported metal-free initiating system. The successful copolymerization of epoxides with CO₂ triggered attempts at copolymerization of epoxides with anhydrides, carbonyl sulfide, carbon disulfide, polymers carrying ester or thio carbonate linkages could be generated through the use of similar or the same initiating systems as those first disclosed for...
the copolymerization of epoxides with CO₂. As common
characteristics, comonomers such as CO₂, carbonyl sulfide, and
anhydrides that were copolymerized with epoxides are known
to be unable to homopolymerize. More recently, alternating
copolymerization of epoxides was successfully carried out with
isocyanates which are other heteroallenes that are very
challenging to polymerize.52 Adriaenssens and co-workers53
indeed first reported the alternating copolymerization of
epoxides and isocyanates using a dimagnesium catalyst. To
avoid the formation of isocyanurates and oxazolidinones, they
had to slowly add the isocyanates into the reaction medium,
and only cyclohexene oxide (CHO) was found suitable to
undergo such alternating copolymerization with this class of
monomers.54 Alternate copolymerization was successfully carried out with
isothiocyanates and phenyl isothiocyanate (PITC) which were
purified by distilling over sodium. Ethyl isothiocyanate (EITC), hexyl
isothiocyanate (HITC), and phenyl isothiocyanate (PITC) were
purified by distilling over CaH₂. The purified monomers were stored
in Schlenk flasks and kept in a glovebox.

**Instruments.** Nuclear magnetic resonance (NMR): ¹H and
¹³C NMR spectra were recorded on a Bruker AVANCE III-400 Hz
instrument in CDCl₃.

The matrix-assisted laser desorption ionization time-of-flight
(MALDI-TOF) mass spectra were collected on an Autoflex (Bruker)
mass spectrometer. The trans-2-[(4-fluorophenyl)-2-methyl-
propenylidene]malononitrile (DCTB) was used as the matrix with
a loading of 2:1 to sodium acetate which was used as the ionizing
agent.

Gel permeation chromatography (GPC): GPC traces were
derived on a VISCOTEK VE2001 system equipped with the
Styragel HR2 THF and Styragel HR4 THF using THF (1 mL/min)
as the eluent. The relative molar masses and distributions were
obtained at 35 °C using a RID detector and against linear polystyrene
standards.

Fourier-transform infrared spectroscopy (FTIR): FTIR spectra
were acquired on a NICOLET iS10 (Thermo Fisher Scientific)
spectrometer. In situ FTIR study of the copolymerization of 
époxides with ITCs was conducted using a ReactIR 700 system (Mettler
Toledo).

Differential scanning calorimetry (DSC): DSC measurements
were performed at a heating rate of 10 °C/min under a Mettler Toledo DSC1
system under a nitrogen atmosphere. The curve of the second
heating scan was adopted to determine the glass transition
temperature ($T_g$).

Thermogravimetric analysis (TGA): TGA experiments were
performed on a TGA Q500 analyzer (TA Instruments). Samples
were heated from 25 to 800 °C at a heating rate of 10 °C/min under a
N₂ atmosphere.

**Copolymerization of Epoxides with ITCs.** The typical
alternating copolymerization procedure for Entry 1 is described below. A 50
mL Schlenk tube was flame-dried and then immediately transferred
into a glovebox. The initiator (4-methylbenzyl alcohol), 1 eq. molar of
P4 (0.8 M in hexane), 100 eq. molar of EITC, and 100 eq. molar
of PITC was added. The polymerizations were run at 25 °C for 12 h unless otherwise noted. The polymers were characterized using ¹H NMR spectroscopy and GPC which means five-membered cyclic oxathiolane products. Determined by GPC in THF and with linear polystyrene as the standard. Calculated from the conversion of ITC. 22.5% trimer was formed. 4% trimer was formed. 24 h polymerization. 85% polymer was obtained.

### EXPERIMENTAL SECTION

**Materials.** All the reagents were purchased from Sigma-Aldrich
and used as received unless otherwise stated. 1-tert-Butyl-4,4,4-
tris(dimethylamino)-2,2-bis(tris(dimethylamino)-phosphoranylidenae-
mino)-2,4,4-tri-catenadi(phosphazene) (P4, 0.8 M in hexane), 1-tert-
butyl-2,2,4,4,4-pentakis(dimethylamino)-2,4,4-tri-catenadi-
phosphazene) (P2, 2 M in THF), tert-butylphosphorane-
tris(dimethylamino)phosphorane, N,N,N,N,N,N,N-hexa-
amethylenophosphorimidic triamide (P1), triethylborane (TEB, 1 M in
THF), and diethylzinc (ZnEt₂, 1 M in hexane) were used as received.

### Table 1. Copolymerization Data of Epoxides with ITCs

<table>
<thead>
<tr>
<th>entry</th>
<th>LB:LA</th>
<th>Ep:ITC</th>
<th>T (°C)</th>
<th>I:Ep:ITC</th>
<th>conv. (%)</th>
<th>polycyc</th>
<th>$M_n$ (kg mol⁻¹)/D</th>
<th>$M_n$ (theo.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1⁴⁺</td>
<td>P4</td>
<td>PO:EITC</td>
<td>25</td>
<td>1:100:100</td>
<td>58</td>
<td>55.2:25.5</td>
<td>9.8/1.08</td>
<td>4.6</td>
</tr>
<tr>
<td>2⁴⁺</td>
<td>P4</td>
<td>PO:HITC</td>
<td>25</td>
<td>1:100:100</td>
<td>70</td>
<td>32.7:24.5</td>
<td>10.6/1.06</td>
<td>10.1</td>
</tr>
<tr>
<td>3</td>
<td>P4</td>
<td>PO:ZnEt₂</td>
<td>25</td>
<td>1:100:100</td>
<td>26</td>
<td>95.5</td>
<td>5.1/1.17</td>
<td>4.8</td>
</tr>
<tr>
<td>4</td>
<td>P1</td>
<td>PO:ZnEt₂</td>
<td>25</td>
<td>1:100:100</td>
<td>&lt;1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>P2</td>
<td>PO:ZnEt₂</td>
<td>25</td>
<td>1:100:100</td>
<td>24</td>
<td>94.6</td>
<td>4.7/1.04</td>
<td>4.4</td>
</tr>
<tr>
<td>6⁵</td>
<td>P4</td>
<td>PO:ZnEt₂</td>
<td>60</td>
<td>1:100:100</td>
<td>66</td>
<td>87.13</td>
<td>7.5/1.40</td>
<td>11.1</td>
</tr>
<tr>
<td>7</td>
<td>P4</td>
<td>PO:PITC</td>
<td>25</td>
<td>1:500:500</td>
<td>39</td>
<td>91.9</td>
<td>31.6/1.25</td>
<td>31.8</td>
</tr>
<tr>
<td>8</td>
<td>P4</td>
<td>CHO:PITC</td>
<td>60</td>
<td>1:100:100</td>
<td>58</td>
<td>92.8</td>
<td>9.7/1.17</td>
<td>12.4</td>
</tr>
<tr>
<td>9</td>
<td>P4</td>
<td>TEB</td>
<td>25</td>
<td>1:100:100</td>
<td>&gt;99</td>
<td>82.18</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>P4</td>
<td>PO:ZnEt₂</td>
<td>25</td>
<td>1:100:100</td>
<td>31</td>
<td>98.2</td>
<td>6.3/1.07</td>
<td>5.9</td>
</tr>
<tr>
<td>11</td>
<td>P4</td>
<td>PO:ZnEt₂</td>
<td>25</td>
<td>1:100:100</td>
<td>64</td>
<td>92.8</td>
<td>9.6/1.15</td>
<td>11.4</td>
</tr>
<tr>
<td>12</td>
<td>P4:ZnEt₂</td>
<td>40</td>
<td>1:100:100</td>
<td>64</td>
<td>92.8</td>
<td>9.6/1.15</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>P4:ZnEt₂</td>
<td>40</td>
<td>1:100:100</td>
<td>64</td>
<td>92.8</td>
<td>9.6/1.15</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>P4</td>
<td>PO:ZnEt₂</td>
<td>25</td>
<td>1:100:100</td>
<td>66</td>
<td>91.9</td>
<td>11.1/1.15</td>
<td>57.9</td>
</tr>
<tr>
<td>15</td>
<td>P4</td>
<td>PO:ZnEt₂</td>
<td>25</td>
<td>1:100:100</td>
<td>45</td>
<td>94.6</td>
<td>16.3/1.18</td>
<td>81.6</td>
</tr>
<tr>
<td>16</td>
<td>P4:ZnEt₂</td>
<td>1:1</td>
<td>PO:PITC</td>
<td>25</td>
<td>1:100:100</td>
<td>17</td>
<td>87.13</td>
<td>11.8/1.23</td>
</tr>
<tr>
<td>17</td>
<td>P4:ZnEt₂</td>
<td>1:1</td>
<td>PO:PITC</td>
<td>60</td>
<td>1:500:500</td>
<td>36</td>
<td>92.8</td>
<td>10.1/1.29</td>
</tr>
</tbody>
</table>

*The polymerizations were run at 25 °C for 12 h unless otherwise noted. Determined by ¹H NMR spectroscopy and GPC means five-membered cyclic oxathiolane products. Determined by GPC in THF and with linear polystyrene as the standard. Calculated from the conversion of ITC. 22.5% trimer was formed. 4% trimer was formed. 24 h polymerization. 85% polymer was obtained.

**EXPERIMENTAL SECTION**

**Materials.** All the reagents were purchased from Sigma-Aldrich
and used as received unless otherwise stated. 1-tert-Butyl-4,4,4-
tris(dimethylamino)-2,2-bis(tris(dimethylamino)-phosphoranylidenae-
mino)-2,4,4-tri-catenadi(phosphazene) (P4, 0.8 M in hexane), 1-tert-
butyl-2,2,4,4,4-pentakis(dimethylamino)-2,4,4-tri-catenadi-
phosphazene) (P2, 2 M in THF), tert-butylphosphorane-
tris(dimethylamino)phosphorane, N,N,N,N,N,N,N-hexa-
amethylenophosphorimidic triamide (P1), triethylborane (TEB, 1 M in
THF), and diethylzinc (ZnEt₂, 1 M in hexane) were used as received.
154 epoxide were added to the Schlenk tube, respectively. Afterward, the
155 polymerization was quenched with few drops of 1 M HCl solution
156 (methanol). An aliquot of crude solution was taken for size-exclusion
157 chromatography (SEC) and $^1$H NMR analysis. A pure polymer was
158 obtained by precipitation three times in methanol followed by
159 overnight drying under vacuum.

161 ■ RESULTS AND DISCUSSION
162 Three representative ITC monomers, EITC, HITC, and PITC,
163 were selected for this study, where the first two ITCs carry
164 aliphatic groups as substituents and the third one an aromatic
165 phenyl group as the substituent. Before trying their
166 copolymerization with epoxides, the homopolymerization of
167 ITCs was first attempted in the presence of alkoxides. As
168 shown in Table S1, none of them could be homopolymerized,
169 and no polymers could be produced: no reaction occurred in
170 the case of PITC, and in the case of EITC and HITC, only
171 cyclic trimers were obtained with 14 and 11% conversion,
172 respectively, after 12 h at room temperature (see Figure S1).
173 Their copolymerizations were subsequently investigated first
174 with PO. As shown in Table 1 (entries 1, 2, and 3), the
175 obtained copolymers exhibit narrow polydispersities in all cases
176 but with different selectivity. As expected, the highest linear
177 versus cyclic selectivity (95:5) was observed in the case of
178 PITC because of its low self-reactivity; on the other hand, a
179 lower linear versus cyclic selectivity (55:22.5) in the case of
180 PO/EITC copolymerization (Figure S2) and (72:24) in the
181 case of PO/HITC copolymerization was observed; cyclic
182 trimers were also formed as in the case of homopolymerization.
183 Higher conversions were obtained for the two latter cases (58
184 and 70%) in comparison to PO/PITC copolymerization
185 (26%). The obtained copolymers were all characterized by
186 $^1$H NMR (Figures 1A, S3, and S4), the methyl group from the
187 initiator 4-methylbenzyl alcohol (MBzOH) was clearly
188 detected at 2.40 ppm, and the absence of characteristic peaks
189 corresponding to polyether linkages at 3.57 and 3.42 ppm
190 (Figure S5) and matched integral ratios of ITC to epoxide
191 moieties indicate their alternating structures. All the measured
192 FTIR spectra showed a strong adsorption peak at 1617 cm$^{-1}$
193 [Figure S6 for poly(PO-alt-PITC)], 1629 cm$^{-1}$ [Figure S7 for
194 poly(PO-alt-EITC)], and 1633 cm$^{-1}$ [Figure S8 for poly(PO-
195 alt-HITC)] which correspond to the C$\equiv$N stretching. The
196 peak at 895 cm$^{-1}$ corresponding to C$\equiv$S stretching further
197 confirmed the presence of C$\equiv$N linkages; C$\equiv$S stretching
198 normally expected at 1180–1200 cm$^{-1}$ could not be
199 detected, confirming its disappearance after copolymerization
200 with PO (Figures S6–S8). In addition, the characteristic peak
201 seen at 156 ppm from the $^{13}$C NMR spectrum (Figure 1B) and
202 the absence of any peak around 200 ppm corresponding to the

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure1.png}
\caption{(A) $^1$H NMR and (B) $^{13}$C NMR spectra of PO/PITC alternating copolymer poly(propylene carbonimidothioate) in CDCl$_3$.}
\end{figure}
203 carbamothioate linkage\textsuperscript{56} attest to the formation of carbonimidothioate O(S)C≡N linkages rather than carbamothioate O(N)C≡S ones; the correlation of this peak at 156 ppm with methylene protons H\textsubscript{1} from PO units as characterized by \textsuperscript{1}H-\textsuperscript{13}C heteronuclear multiple bond correlation (Figure S9) further confirms the presence of carbonimidothioate O(S)C≡N linkages. The absence of consecutive PITC linkages is consistent with results reporting on the copolymerization of PO and PITC. Because of the stronger basicity and larger size of its associated cation. Increasing the temperature of polymerization resulted in an increase of the rate of polymerization (entry 7); however, the linear versus cyclic selectivity decreased, the polydispersity index of obtained molar mass distribution was broadened, and the GPC molar mass value was much lower than the expected one; backbiting reactions are suspected to be the main cause of such gap between expected and actual molar masses. In contrast, the molar mass drawn from NMR characterization (11.6 kg mol\textsuperscript{-1}, Figure 1A) for the sample obtained at room temperature was consistent with the value determined by GPC (10.8 kg mol\textsuperscript{-1}, entry 6).

The copolymerization behaviors of other epoxides such as EO and CHO with PITC were investigated next (entries 8 and 9, \textsuperscript{1}H NMR Figure S10 and S11, and IR Figures S12 and 13). Under the same copolymerization conditions as those of PO, alternating polycarbonimidothioates were obtained with >92\% selectivity in both cases, where EO exhibited the highest activity among the three epoxides tried. The molar masses (Figure S14) of copolymers obtained were found close to the expected values, and narrow polydispersity indexes were measured. In the case of EO, the alternating copolymerization of the latter epoxide with PITC afforded a copolymer with a molar mass up to 31.6 kg mol\textsuperscript{-1} with a narrow polydispersity index (\(\overline{D} = 1.25\)).

A kinetic study (Figure 2) was performed using PO and PITC as monomers with a feeding ratio of 100:100:1 to the phosphazinium benzoxide for a better understanding of the copolymerization process. As shown in Figure 2C, the intensity of the O(S)C≡N infrared absorption peak at 1630 cm\textsuperscript{-1} followed by in situ FTIR, and corresponding to the production of poly(propylene carbonimidothioate), increased linearly with PITC conversion, with a 257
narrow polydispersity (<1.2), indicating a "living"/controlled copolymerization (at low polymerization temperature). A small shoulder on the high-molar-mass side of GPC traces (Figure 2B) was however observed for samples with high monomer conversion, which may be caused by the dimerization of chain-end thiolate species.61

To further demonstrate the living character of the propagation, sequential block copolymerizations were carried out. A first poly(PO-alt-PITC) block was prepared in a Schlenk tube charged with an excess of PITC. After unreacted PO was removed under vacuum, EO was subsequently added as a second epoxide to the above solution. As shown in Figure S15, an obvious shift of GPC traces can be seen with an increase of \( M_n \) from 4.9 to 7.4 kg mol\(^{-1}\) which attests to the successful chain extension of the second block. The obtained block copolymer poly(PO-alt-PITC)-b-(EO-alt-PITC) exhibits indeed a unimodal and narrow \( (D = 1.08) \) distribution. The characteristic peaks at 5.36 and 4.46 ppm from PO-alt-PITC and EO-alt-PITC linkages (Figure S16) further confirm the formation of a block copolymer.

Based on our previous work which showed that the utilization of a Lewis acid like TEB helps to suppress the backbiting reactions and the formation of cyclics, we wanted to check whether the formation of an ate complex between TEB and the growing species can also prevent cyclic formation in the copolymerization of PO with ITC.41,54 To our surprise, the presence of TEB increased the conversion of PO and only favored the homopolymerization of PO leading to the formation of the sole poly(propylene oxide) (entries 9 and 10). Taking into consideration the quantitative calculation results reported by Kepp,62 which indicates that the scales of oxophilicity and thiophilicity of borane are 1 and 0, we realized that the expected ate complexes between thioanions and TEB are unlikely formed. On the other hand, the coordination of TEB with oxyanions lowered its nucleophilicity, preventing the insertion of PITC to form the carbonimidothioate linkage. Following Kepp’s calculation, we observed that zinc has a higher scale of thiophilicity (0.8) than that of oxophilicity (0.2); diethyl zinc (ZnEt\(_2\)) was thus used in our attempts to copolymerize PO with PITC. As expected, the linear versus cyclic selectivity increased up to 98% without any ether linkages. In the presence of ZnEt\(_2\), the PO/PITC copolymerization showed a living character (Figures S17 and S18), indicating that the addition of this Lewis acid had no side effect and did not promote side reactions. The well-defined structure of the obtained copolymer was further analyzed by MALDI-TOF spectrometry. As shown in Figure 3, all four populations exhibit alternating structure with peak to peak interval values \( (m/z = 193.3) \) corresponding to the mass of PO and PITC \( (m/z = 88.1 + 135.2 = 193.3) \) with the incorporation of the...
f5 350 between 170 and 220 f4 332 in Figure 4 in the presence of ZnEt2. First, the super base, P4, up to 32 kg/mol. In the presence of ZnEt2, the TON values versus cyclic selectivity. In the case of copolymerization of EO benzoxide a epoxides with PITC in the presence of phosphazenium (P4) In conclusion, the ring-opening copolymerization of various copolymers obtained from alternating copolymerization of aromatic PITC with the following epoxides, EO, PO, and copolymers formed with high linear and other heteroallene monomers.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acs.macromol.1c01460.

1H NMR spectra, IR spectra, and GPC characterization data (Table S1 and Figures S1–S18) (PDF)

AUTHOR INFORMATION

Corresponding Authors

Yves Gnanou – Physical Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia; orcid.org/0000-0001-6253-7856; Email: yves.gnanou@kaust.edu.sa

Xiaoshuang Feng – Physical Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia; orcid.org/0000-0001-7473-1728; Email: fx101@gmail.com

Author

Chao Chen – Physical Sciences and Engineering Division, King Abdullah University of Science and Technology (KAUST), Thuwal 23955, Saudi Arabia

Complete contact information is available at: https://pubs.acs.org/doi/10.1021/acs.macromol.1c01460

Notes

The authors declare no competing financial interest.

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CONCLUSIONS

In conclusion, the ring-opening copolymerization of various epoxides with PITC in the presence of phosphazenium (P4) benzoxide affords alternating copolymers with high linear versus cyclic selectivity. In the case of copolymerization of EO with PITC, the molar mass of the obtained polymer reached up to 32 kg/mol. In the presence of ZnEt2, the TON values increased significantly from tens to 450 and the linear versus cyclic selectivity as well. The success of alternating copolymerization of epoxides with ITCs expands the scope of alternating copolymerizable monomers and provides a new route to the modification of the properties of poly(carbonates or polyesters produced by copolymerization of epoxides with other heteroallene monomers.)
Int. Ed.

493 Unsymmetrical, chiral N-heterocyclic carbene ligand.

492 Alternating copolymerizations using a Grubbs-type initiator with an
Charleux, B. Nitroxide-mediated polymerization.

491 Fragmentation chemistry in polymer synthesis.

488 Polymerization: Features, developments, and perspectives.

485 Synthesis by Nitroxide Mediated Living Radical Polymerizations.

483 Polymers.

482 Polymer in Wood Based Composites.

479 Anhydride copolymerization reactions.

477 Radical Polymerizations


