Polymers from sugars and CS$_2$: synthesis and ring-opening polymerisation of sulfur-containing monomers derived from 2-deoxy-D-ribose and D-xylene†

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Thionocarbonate (–O–CS–O–) and xanthate (–S–CS–O–) cyclic monomers were synthesised by cyclothiocarbonation of 2-deoxy-D-ribose- and D-xylene-derived diols with carbon disulfide, then polymerised using organocatalytic ring-opening methods. Regular polymer linkages were obtained, with the sugar backbone influencing the regioselectivity of monomer opening. Thermal analysis revealed lower glass transition temperatures compared to carbonate analogues and a low onset of thermal degradation.

Natural monosaccharides are a pool of readily available and functional building blocks that are cheap, non-toxic, stereochemically diverse, and offer a renewable alternative to petroleum-based resources for the synthesis of monomers and polymers. Sugars have been used in polymer synthesis for example as pendant groups or incorporated into main polymer chains via step-growth methods from aldarc esters and aldilols. Driven by the versatility and accurate control offered by ring-opening polymerisation methods (ROP), combined with the ability of sugars to be functionalised to adjust the properties of the resulting polymers, recent efforts have been devoted to the synthesis and subsequent ROP of sugar-based cyclic monomers. These include lactams, phosphoesters and cyclic carbonates. Some of our own work in this field has involved using CO$_2$ to produce sugar-based cyclic carbonates without the need for phosgene derivatives.

Substitution of some oxygen atoms with sulfur in polymer backbones can result in enhanced physical (e.g. increased crystallinity), thermal, mechanical, electrical and optical properties, as well as advanced characteristics such as adhesion to metals, biological and chemical resistance, and biocompatibility. Therefore, we set out to utilise carbon disulfide (CS$_2$), the sulfur analogue of CO$_2$, to make novel sugar-based materials. Sulfur-containing analogues of sugar-based cyclic carbonates have been reported, but these have been synthesised using CSCl$_2$ or Im$_2$CS (Im = imidazole) reagents, and investigated mainly for their tendency to undergo O–S rearrangements. No polymerisation studies have been reported. Furthermore, while being used in the viscose process, CS$_2$ has only been explored in polymer synthesis as a monomer for homopolymerisation or copolymerisation with epoxides and oxetanes.

Herein, we report the synthesis and polymerisation of novel cyclic xanthate and thionocarbonate monomers from sugar diols and carbon disulfide.

First, the synthesis of a 6-membered cyclic thionocarbonate trans-fused to a sugar furanose ring was targeted. Our hypothesis was that CS$_2$, conversely to CO$_2$, would allow the cyclocarbonation of the trans 1,3-diol motif of ribofuranose sugars, because of the longer C–S bond (155.3 pm) in CS$_2$ compared to C–O (116.3 pm) in CO$_2$. The resulting monomer would also be highly strained, and therefore prone to ROP. Using an analogous procedure to the one reported previously in our group for the synthesis of cyclic carbonates from diols and CO$_2$, CS$_2$ was added to a solution of 1-O-methyl-2-deoxy-D-ribofuranose in acetonitrile, in the presence of 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU). The reaction mixture changed rapidly from colourless to yellow, and $^1$H NMR analysis revealed insertion of CS$_2$ into the sugar hydroxy groups (Fig. S1 and S2 in the ESI†). Furthermore, the C$_3$ and C$_5$ atoms of the sugar moiety remained deshielded (signals around 75 ppm), so no O–S rearrangement is believed to take place at this stage. Subsequent addition of mesyl chloride in the presence of triethylamine then led to the formation of cyclic xanthate 1, which was isolated by column chromatography in a 10% yield.

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Scheme 1 Synthesis of monomers 1–3 (see ESI† for detailed procedures).

(Scheme 1). Integration of the anomic protons in the $^1$H NMR spectrum confirmed a 1:1 mixture of the two anomers (Fig. S3†). To the best of our knowledge, 1 is the first cyclic xanthate (and in fact the first cyclic carbonate analogue), transfused to a sugar furanose ring. The nature of 1 was determined by NMR and FTIR spectroscopies, as well as electrospray ionisation mass spectrometry and elemental analysis (see ESI†). In particular, the $^{13}$C($^1$H) NMR signal for the C=S bond is observed around 208 ppm, characteristic of the C(S)SO$_2$ edge environment in cyclic xanthates. $^{sc}$ Because of an adjacent, more electropositive sulfur atom, the C$_3$ signal in 1 (Fig. S4†) also appears at significantly lower chemical shift (37–38 ppm) compared to the related cyclic carbonates (67 ppm).$^{sb}$ The $^3$J$_{HE3H4}$ coupling constants (8.7 and 8.8 Hz) are also larger than for the cis-configured cyclic monomers we reported previously (4.9 and 5.7 Hz),$^{6}$ and consistent with a trans-fused cyclic monomer. The structure was further corroborated by X-ray diffraction of a co-crystal of both anomers, obtained by recrystallization from hexanes (Fig. S40†). For the α anomer, the furanose ring adopts a 4-exo-3-endot twist conformation ($^2$T$_{4e}$), whereas for the β anomer, the furanose ring has a 3-endot ($^2$E) conformation. From previous mechanistic understanding of the analogous reaction with CO$_2$, $^{11}$ 1 is not the expected thionocarbonate product, which would form from insertion of CS$_2$ into a hydroxy group, mesylation of the resulting xanthate, then cyclisation via a nucleophilic addition–elimination pathway. As cyclo-thiocarbonation attempts using Im$_2$CS$^{sc}$ proved unsuccessful, we suspect that the trans-configuration of the diol prevents cyclisation, or that the product is highly unstable. Formation of 1 could however be explained by a putative minor pathway (hence the low yields obtained): insertion of CS$_2$ into the secondary hydroxy group, followed by mesylation of the 5-OH, then cyclisation via intramolecular nucleophilic substitution. 1 could also result from various S-O rearrangements.

Using 1,2-O-isopropylidene-α-β-xylofuranose as a substrate was then considered, as in this case the cis-configuration of the 1,3-diol motif should facilitate cyclisation and give the expected thionocarbonate. Using the same procedure, two products were isolated after purification by column chromatography: xanthate 2 and thionocarbonate 3, in 15% and 48% yield respectively (Scheme 1). 2 displayed a xanthate signal in the $^{13}$C($^1$H) NMR signal at 208.6 ppm, while a signal at 187.4 ppm was observed for 3, consistent with a thionocarbonate species (Fig. S15 and S24† respectively). $^{sc}$ Confirmation of the structure of 2 and 3 by NMR and FTIR spectroscopies, as well as electrospray ionisation mass spectrometry and elemental analysis, was further corroborated by single-crystal X-ray diffraction (Fig. S41 and S42†). As expected, using a cis 1,3-diol motif yielded thionocarbonate 3, likely via an addition–elimination mechanism for the ring-closing step.$^{11}$ However, 2 was still formed in small quantity. The possibility that 2 could result from an alternative Sn$_2$-type mechanism was therefore verified experimentally. 1,2-O-isopropylidene-α-β-xylofuranose was tosylated at the 5-position into 4 (Scheme S5†), which, upon addition of CS$_2$ and DBU, should only lead to the substitution of the tosyl group by the xanthate salt (Scheme S6†). Formation of 2 was indeed observed with approximately 50% conversion after 30 minutes (Fig. S39†). While 3 has been previously synthesised using Im$_2$CS$^{sc}$ to the best of our knowledge 2 is the first cyclic xanthate cis-fused to a sugar furanose ring. These two compounds are the sulfur analogues of the carbonate monomer reported by Gross and coworkers.$^{ni}$

Ring-opening polymerisation of monomers 1–3 were next studied at room temperature in dichloromethane, using 1,5,7-triazabicyclo[4.4.0]dec-5-ene (TBD) organocatalyst, 4-methylbenzyl alcohol initiator, and 1 mol L$^{-1}$ initial monomer concentration (Table 1). TBD is one of the most active organo-

| Entry | M | [C] : [I] | Time (h) | Conv. (%) | $M_n$ (calc) | $M_n$ (SEC) | D/
|-------|---|-----------|---------|--------|------------|------------|---
| 1     | 1 | 25 : 1 : 1 | 0.25    | >99    | 5.3        | 5.1        | 1.6 |
| 2     | 1 | 50 : 1 : 1 | 0.25    | >99    | 10.4       | 5.2        | 1.8 |
| 3     | 1 | 100 : 1 : 1| 0.25    | >99    | 20.7       | 11.3       | 2.2 |
| 4     | 1 | 25 : 1 : 1 | 0.25    | 86     | 5.5        | 6.0        | 1.5 |
| 5     | 2 | 50 : 1 : 1 | 0.25    | 87     | 10.9       | 5.3        | 2.2 |
| 6     | 2 | 50 : 1 : 1 | 2       | >99    | 12.5       | 12.6       | 1.5 |
| 7     | 2 | 100 : 1 : 1| 0.25    | 86     | 21.5       | 15.7       | 1.7 |
| 8     | 3 | 25 : 1 : 1 | 0.25    | 42     | 2.6        | 5.2        | 1.5 |
| 9     | 3 | 50 : 1 : 1 | 0.25    | 40     | 4.8        | 7.4        | 1.3 |
| 10    | 3 | 50 : 1 : 1 | 2       | 65     | 7.8        | 6.7        | 1.2 |
| 11    | 3 | 50f : 1 : 1| 0.25    | 52     | 6.2        | 7.5        | 1.5 |
| 12    | 3 | 50f : 1 : 1| 0.5     | 61     | 7.2        | 10.0       | 1.3 |
| 13    | 3 | 50f : 1 : 1| 3       | 62     | 7.3        | 10.3       | 1.3 |
| 14    | 3 | 100f : 1 : 1| 0.25   | 44     | 10.3       | 10.6       | 1.5 |

$^a$ Polymersisations carried out at room temperature in anhydrous CH$_2$Cl$_2$ solvent with initial [M]$_0$ = 1 mol L$^{-1}$ ([M] = monomer), unless stated otherwise; all entries correspond to separate experiments. $^b$ C is the catalyst, TBD, and 1 is the initiator, 4-MeBnOH. $^c$ Conversion measured by $^1$H NMR determined by relative integration of the anomic proton in the $^1$H NMR spectrum in CD$_2$Cl$_2$. $^d$ In 10$^{-3}$ g mol$^{-1}$, calculated as $M_n$/([M]$_0$/([M]$_n$) × conv×100%). $^e$ In 10$^{-3}$ g mol$^{-1}$, estimated by SEC (RI detector) versus polystyrene standards with THF eluent. $^f$ D = $M_n$//$M_w$. $^{g}$ [M]$_0$ = 1.58 mol L$^{-1}$.
catalysts for the ROP of cyclic carbonates,\textsuperscript{12} which usually gives good polymerisation control and limits the amount of cyclic species formed by direct nucleophilic initiation, as with diazabicyclo[5.4.0]undec-7-ene (DBU).\textsuperscript{13} Early trials with DBU gave indeed poor control and decreased activity. Monomer conversion was determined by \textsuperscript{1}H NMR spectroscopy. Conformational changes brought about by the release of ring strain upon opening led for all monomers to a downfield shift of H-3 and coalescing of the signals assigned to H-5, as well as a general broadening of the resonances (Fig. S43, S44 and S65\textsuperscript{†} for 1–3, respectively). Polymers of 1 proceeded rapidly, reaching >99% conversion in less than 15 min at various monomer : initiator : catalyst feed ratios (Table 1, entries 1–3). Polymerisation of 2 was slightly slower, consistent with the less strained nature of this xanthate compared to 1 (Table 1, entries 5–8), with around 86% monomer conversion after 15 min and >99% after 2 h for a monomer : initiator : catalyst ratio of 50:1:1 (Table 1, entries 5 and 6). Polymerisation of 3 (entries 8–14 in Table 1) proceeded even slower and reached a monomer conversion plateau (66% after 2 hours), indicating a concentration dependent equilibrium polymerisation. A slightly higher initial concentration of monomer : initiator : catalyst feed ratios (Table 1, entries 8–14) proceeded even slower and reached a monomer conversion plateau (66% after 2 hours), indicating a concentration dependent equilibrium polymerisation.

Size exclusion chromatography (SEC) in THF confirmed the polymeric nature of the products, and was used to estimate number-average molecular weights ($M_n$) and dispersities ($D$) versus polystyrene standards. Polymers of up to 11 300 g mol\textsuperscript{−1} ($D$ 2.2) and 15 700 g mol\textsuperscript{−1} ($D$ 1.7) could be achieved from 1 and 2, respectively, but limited agreement between predicted and SEC $M_n$, as well as broad and varying distributions, were observed. The ROP of 3 was more controlled, with better agreement between theoretical molecular weights and those determined by SEC, as well as narrower dispersities. Polymers of up to 10 600 g mol\textsuperscript{−1} ($D$ 1.5) could be obtained from 3. However, for most polymers, inconsistencies and discrepancies between theoretical $M_n$, SEC $M_n$ and those estimated by NMR (via the relative integration of the 4-methylbenzyl alcohol end-group, which only accounts for linear polymers) highlight the limited control of the ROP of 1–3 under these organocatalytic conditions. This suggests the formation of cyclic species by backbiting or sensitivity to traces of chain-transfer agent like adventitious moisture (leading to smaller $M_n$ than expected), as well as trans chain exchange phenomena, as sometimes seen in the ROP of cyclic carbonates, including in the polymerisation of sugar-based monomers.\textsuperscript{1b,c,d}

The FTIR spectra of all polymers were characterised by several strong absorption bands in the 1290–1020 cm\textsuperscript{−1} region and none at 1757 cm\textsuperscript{−1}, indicative of C=S\textsuperscript{bd,14} but no C=O bonds (Fig S53, S64 and S75†). Analysis by \textsuperscript{13}C\textsuperscript{[1]H} NMR also supported the absence of O–S rearrangement during polymerisation as no carbonyl resonance was observed. \textsuperscript{13}C\textsuperscript{[1]H} NMR was used to investigate further the microstructure of polymers (Fig. 1). For poly(3), three distinct thionocarbonate environments (differing by 0.3–1 ppm) were detected around 193.8 ppm (compared to 187.4 ppm for the monomer), and assigned to tail–tail (or head–head), head–tail, and head–head (or tail–tail) thionocarbonate linkages (Fig. S66†). Their 1:2:1 ratio suggests random cleavage of the thioalcohol–oxygen bond at either side of the thionocarbonate carbonyl and subsequent nonselective propagation of the chain to yield regiorandom polymers. For poly(1), one distinct xanthate resonance was observed at 213.0 ppm (compared to the monomer signals at 208.1 and 207.8 for both anomers) (Fig. S44†). Thus, the thionocarbonyl region suggests a preference for regioregular opening of 1 (likely to liberate a more acidic primary thiol) and subsequent selective propagation of the chain to yield a poly (xanthate). In stark contrast, the polymer resulting from xanthate 2 displayed mainly two distinct thionocarbonyl resonances of similar intensities. Based on the literature,\textsuperscript{1b,d} the resonance at 222.5 ppm is assigned to a thionocarbonate (C(S)S\textsubscript{2})\textsuperscript{†}, and the one at 193.1 ppm is assigned to a thionocarbonate (C(S)O\textsubscript{3}) (Fig. S55†). This suggests an alternating opening of the monomer at either side of the xanthate thionocarbonyl, and subsequent selective propagation of the chain to yield regioregular polymers with alternating C(S)\textsubscript{2} and C(S)O\textsubscript{2} linkages. The origin of this regioregularity is so far unknown.

Analysis of the polymers by Matrix-assisted laser desorption/ionisation time-of-flight (MALDI-ToF) mass spectrometry was conducted to confirm the microstructures deduced by NMR, but proved extremely challenging. However, for poly(3) a major cyclic polymer series, with no end-groups and an integer number of sugar thionocarbonate repeat units ($m/z$ ~232.25) was observed, likely due to backbiting of the polymer chain. A minor linear polymer series with 4-MePhCH\textsubscript{2}O and OH end groups was also present (Fig. S71†). Poly(1) yielded poor data, although two different polymer series (cyclic and

Fig. 1 Ring-opening polymerisation of monomers 1–3 and linkages observed by \textsuperscript{13}C NMR for the respective polymers.
linear) with sugar xanthate repeat units (m/z ∼206.27) were
detected, in agreement with NMR analysis (Fig. S49†). However,
results from poly(2) (Fig. S60†) disagreed with the
major alternating sequence inferred by NMR, revealing poly
(xanthate) series (cyclic and linear) with repeating unit m/z
∼248.31, which could come from the selective ionisation of
side-products. Such poly(xanthate) traces can actually be
detected by NMR in the 13C NMR spectrum (trace signal at
213.0 ppm in Fig. 1).

Thermal properties of the polymers were evaluated by
thermogravimetric analysis (TGA) and differential scanning
 calorimetry (DSC) of representative samples. Analysis of poly
(1) with Mₙ 11 300 g mol⁻¹ (Table 1, entry 3) showed two degra-
dation steps with onsets at ∼120 °C and ∼182 °C, with associat-
ed mass losses of 58 and 10% respectively (Fig. S50 and S51†). A glass transition temperature (T_g) of 55 °C was
measured (Fig. S52†). Although direct comparison with the
analogous polycarbonate is not possible for synthetic reasons,
poly(1) displays thermal properties which are very similar to
the reported values for a related polycarbonate with a cis-fused
motif (T_g ∼ 58 °C and T_d (onset) ∼ 125 °C for Mₙ 25 600
 g mol⁻¹).6,6 Yxlose-derived polymers were slightly more ther-
 mally stable. Poly(2) with Mₙ 12 500 g mol⁻¹ (Table 1, entry 6)
featured two thermal degradation steps (Fig. S61 and S62†),
with onsets at ∼77 °C and ∼135 °C, corresponding to mass
losses of 6% and 72%, respectively. TGA analysis of poly(3)
with Mₙ 10 600 g mol⁻¹ (Table 1, entry 14) showed three degra-
dation steps, with onsets at ∼77 °C (10% mass loss), ∼161 °C
then ∼298 °C (combined 79% mass loss) (Fig. S72 and S73†).
Similar T_g values were measured for poly(2) (46 °C, Fig. S63†)
and poly(3) (∼48 °C, Fig. S74†). These T_g values are signifi-
cantly lower than the value for the analogous xylose carbonate,
reported by Gross and coworkers (T_g 128 °C), for which no
thermal degradation was reported.6,1

This decrease in glass transition temperatures when replac-
ing O by S is consistent with the literature, in particular for
aromatic polycarbonates.7,15 For aliphatic polymers, data is
rare, but poly(trimethylene monothiocarbonate) (PTMMTC)
has been shown to have a T_g between −17 and −25 °C,7,7 similar
to the one reported for poly(trimethylene carbonate)
(PTMC) of −25 °C.6,6 However, Darenbourg, Zhang and co-
workers further noted that when S/O rearrangements occurred
(yielding for example thionocarbonate linkages), T_g fell to
−41 °C. PTMMTC is also semi-crystalline (up to 71% crystalli-
nity while PTMC is amorphous) and displays better thermal
stability with onset of degradation occurring at 228.5 °C vs.
197 °C for PTMC. Another example by Endo and coworkers is
the comparison done between a norbornene-substituted poly
(trimethylene carbonate) and the analogous polythionocarbo-
nate, for which the sulpher aliphatic polymer shows a decrease
in T_g (82 °C vs. 108 °C) but an increase in the temperature of
degradation onset (T_d (onset) 258 °C vs. 207 °C).16 A possible
explanation for the decrease in T_g is the difference in the bond
lengths of C–O (1.43 Å) and C–S (1.815 Å) as well as the van
der Waals radii of O (1.52 Å) and S (1.85 Å) atoms, which
increase the free volume in the polymer. Asymmetrical link-
ages have also been invoked to explain the enhanced inter-
molecular interactions between poly(thiocarbonate) chains,
leading to crystallinity and higher thermal stability.

Conclusions

In summary, in our attempt to use CS₂ in the direct cyclothio-
carbonation of the trans 1,3-diol motif of a ribofuranose, we
discovered that cyclic xanthate structures could be accessed.
We thus isolated the first two examples of 6-membered cyclic
xanthate monomers, trans and cis-fused to sugar furanose
rings, derived from natural sugars 2-deoxy-D-ribose and
D-xyllose, respectively. Polymers from these two monomers and
from a xylose-derived thionocarbonate, also made using CS₂,
were obtained by ROP under mild reaction conditions, with
organocatalyst TBD and 4-MeBnOH alcohol initiator.
MALDI-ToF MS revealed both linear and cyclic topologies, in
agreement with the limited control over the polymerisation
observed. 13C{1H} NMR analysis suggests that no O–S
rearrangement occurs during polymerisation, and that both
the nature of the monomer and that of the sugar used influ-
ence the regioselectivity of ring-opening. While the deoxyri-
bose xanthate monomer yields a poly(xanthate) species, the
xylose cyclic xanthate produces a polymer with alternating
tri(thiocarbonate) and thionocarbonate linkages, and the xylose-
derived poly(thionocarbonate) shows regionarom linkages.
Thermal analysis revealed lower glass transition temperatures
compared to carbonate analogues and a low onset of thermal
degradation. Building from this communication, current
efforts are focusing on controlling the polymerisation of these
novel sulfur-containing monomers and extending our methodo-
logy to other sugar feedstocks, in order to accurately investi-
gate the effect of replacing O by S in the linkages of sulfur-
richbased polycarbonates, and gain a better understanding of the
structure–property relationships of the resulting polymers.
Because of their sugar backbone and the high refractive index
and Abbe’s number of sulphur analogues of polycarbonates,17
these materials could be used in optical and biomedical appli-
cations where degradability and biocompatibility is required.

Conflicts of interest

There are no conflicts to declare.

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