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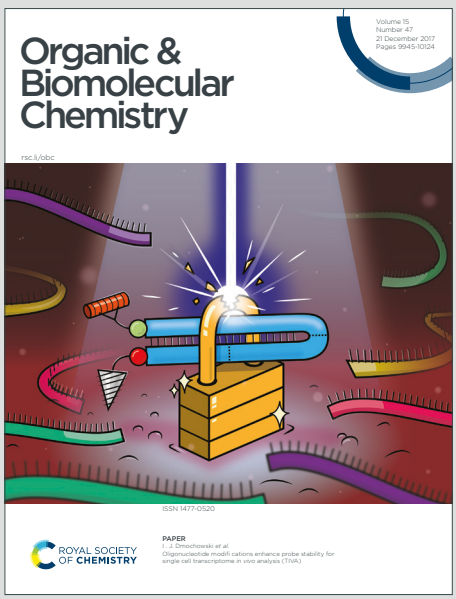

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Paper

Chemoselective cycloadditions to epoxide derivatives of erucic acid with CO_2 and CS_2: Controlled access to value-added bio-derived compounds

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The potential for application of bio-derived molecules in our everyday lives is attracting vast interest as attention moves towards development of a truly circular and sustainable economy. Whilst a large number of molecules are naturally available and contain a variety of functional groups, few of these compounds are able to be immediately transferred to applications where they can directly replace established oil-derived species. This issue presents both a challenge and an opportunity for the synthetic chemistry community. This study demonstrates how erucic acid, a molecule containing an olefin and a carboxylic acid, which is readily available from commonly cultivated rapeseed oils, can be used as a platform to be chemoselectively converted into a range of value-added compounds using established and high yielding synthetic procedures. In particular, the work showcases approaches towards the chemoselective (and in cases regioselective) oxidation with *m*-CPBA and incorporation of cyclic carbonate and cyclic dithiocarbonate functionalities which have potential to be employed in a range of applications. Expedient routes to unusual derivatives containing both cyclic carbonate and cyclic dithiocarbonates are also presented taking advantage of the distinct reactivities of the two different epoxides in the intermediate compounds. This work also provides a rare example of the synthesis of internal cyclic dithiocarbonates. These new products have potential to be applied as monomers in the growing field of bio-based non-isocyanate polyurethane synthesis.

Introduction

Rapeseed (*Brassica napus*) is a commonly cultivated crop in many parts of the world and is particularly recognisable when it produces its bright yellow flowers. It is almost exclusively cultivated for its oil-rich seeds, from which, the extracted oil finds use in the production of animal feeds, edible vegetable oils, and biodiesel.[1,2] Indeed, rapeseed oil is one of the leading edible vegetable oils produced globally. Historically, however, rapeseed oil was only used for lighting homes and as a lubricant, and not as an edible oil due to presence of high quantities of erucic acid (often reaching over 50 % of the total extract depending on the cultivator). This aforementioned oil is known as High Erucic Acid Rapeseed (HEAR) and is not suitable for direct human consumption because erucic acid can have toxic effects on the heart. In order to develop edible oils, low erucic acid producing cultivators have been introduced which produce oils with less than 2 % acid content (known as Low Erucic Acid Rapeseed; LEAR). These latter oils are considered safe for human consumption and are widely used.[3] Despite the rise of these low erucic acid cultivators, traditional high erucic acid containing oils are still grown and are used as sources of erucic acid, a compound which has found many applications. One example is its derivatisation to form Erucamide which is prepared through the condensation of erucic acid with ammonia and is employed as an anti-slip agent in plastic manufacturing.[4,5] The scale at which rapeseed crops are globally grown presents the opportunity to access erucic acid as a sustainably derived compound on bulk scale, in addition, Erucic acid is a bio-derived compound that does non-compete with food crops. These advantages can be a limitation to the large-scale industrial application of many other bio-derived feedstocks, thus making erucic acid a very appealing and considerably under-used bio-derived compound.

Erucic acid itself contains two useful functional groups which have potential to be readily chemically modified to provide novel value-added compounds (Scheme 1(a)). Indeed, in general fatty acids present interesting platforms for further upgrading.[6] In the case of erucic acid, the internal olefin can be readily oxidised to form epoxides using traditional oxidation procedures (eg. *meta*-chloroperbenzoic acid; *m*-CPBA), which are useful synthetic intermediates for a range of further transformations. Meanwhile, the carboxylic acid functionality can be derivatised, most easily, forming esters and amides.
Within our research group, we are interested in the preparation of bio-derived cyclic carbonate compounds and as such, the ease of access to the epoxides of erucic acid attracted our attention. Cyclic carbonates can be readily obtained from the

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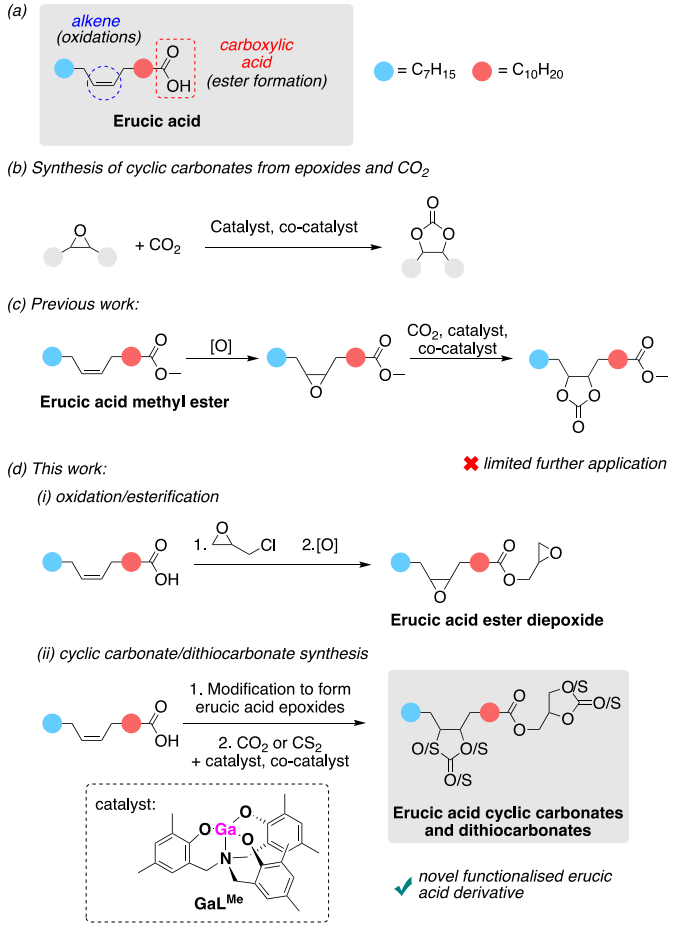
Electronic Supplementary Information (ESI) available: Experimental details, including all synthesis and characterization data. See DOI: 10.1039/x0xx00000x



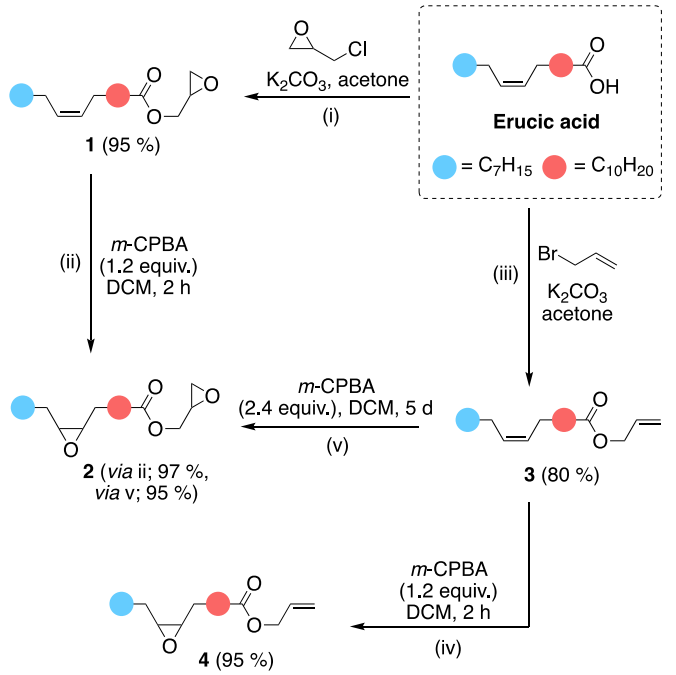
Scheme 1 (a) Structure of erucic acid and proposed synthetic transformations of the functional groups present. (b) General synthesis of cyclic carbonates from epoxides and CO_2. (c) Previous conversions of erucic acid derivatives in the context of cyclic carbonate synthesis. (d) An overview of the erucic acid derivatives reported in this work and the structure of the gallium catalyst employed for the cycloaddition reactions.

atom efficient reaction of an epoxide with carbon dioxide (CO_2), a reaction which is commonly promoted by a Lewis acid catalyst (Scheme 1(b)), providing an attractive approach for their synthesis.[7] In this context, and unsurprisingly, with significant attention turning towards the circular economy and the application of bio-derived feedstocks, cyclic carbonates based on the methyl ester of erucic acid[8] and other fatty acids[9] have already been reported (Scheme 1(c)), with the latter recently finding interesting applications.[10] However, in general, application of these products is restricted because they only contain one reactive functional group.[11] In an effort to extend this work and apply our recently developed highly active gallium-based binary catalyst system for the synthesis of cyclic carbonates from epoxides and CO_2,[12] we proposed that ester formation with a compound bearing a functional group other than what can be synthetically considered as a "blocking methyl" might lead to bio-derived products with increased potential for further application. In particular, the addition of an epoxide was proposed, which can be incorporated through the coupling of epichlorohydrin to the carboxylic acid (Scheme 1(di). Epichlorohydrin presents an interesting reagent as it can be derived from glycerol,[13] a readily available bio-derived compound. Thereafter, subsequent epoxidation of the internal olefin of this epichlorohydrin-erucic acid intermediate provides a facile route towards a bio-derived compound containing two chemically distinct epoxide functionalities; an internal epoxide and a terminal epoxide. These epoxides present rather distinct reactivities which can be chemoselectively exploited by the synthetic chemist. In addition to the formation of esters with the aforementioned epichlorohydrin, esters can also be synthesised through the coupling of allyl bromide, which although is not a preferred reagent, allows ready access to esters with olefins that can be further derivatised (eg. forming an epoxide using *m*-CPBA, in a similar manner as for the internal olefin).

Herein, this work demonstrates how readily available erucic acid can be easily converted into various value-added compounds using established chemical reactions. The remarkable chemoselective formation of epoxides derived from erucic acid is key to this work. These epoxides can then be used to prepare *bis*-cyclic carbonates or *bis*-cyclic dithiocarbonates (Scheme 1(dii)) as will be exemplified. Meanwhile, it has also been possible to take this one step further and prepare unusual cyclic carbonate and cyclic dithiocarbonate mixtures by exploiting the diverse reactivities of the distinct epoxides.

Results and Discussion

Our study commenced with the optimisation of the coupling of erucic acid with epichlorohydrin (Scheme 2, step (i)). This conversion requires an excess of base as the first product that



Scheme 2 Synthesis of epoxide derivatives of erucic acid. Conditions: (i) K_2CO_3 (2.0 equiv.), epichlorohydrin (10 equiv.), acetone, 90 °C, overnight; (ii) *m*-CPBA (1.2 equiv.), DCM, rt, 2h; (iii) allyl bromide (1.2 equiv.), K_2CO_3 (2.0 equiv.), acetone, reflux, overnight; (iv) *m*-CPBA (1.2 equiv.), DCM, rt, 2h; (v) *m*-CPBA (2.4 equiv.), DCM, rt, 5 days. *m*-CPBA = 3-chloroperbenzoic acid. Isolated yields reported after work-up; products were sufficiently pure to use without the need for column chromatography.

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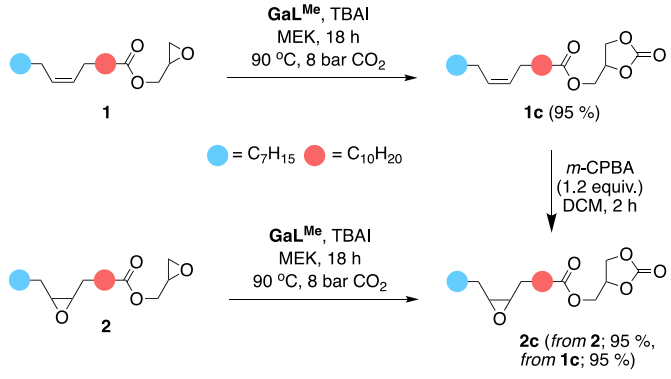
is formed is a compound arising from the addition of the carboxylic acid to the epichlorohydrin (a 1,2-halohydrin compound) through a ring-opening of the epoxide with a carboxylate. Thereafter, the second equivalent of base deprotonates the halohydrin intermediate, which is followed by ring-closure, forming the desired epoxide product, **1**, in almost quantitative yield. The internal olefin functionality of this compound can then be epoxidized using *m*-CPBA (Scheme 2, step (ii)), furnishing a compound with both an internal and a terminal epoxide, **2**. This conversion was again found to proceed in almost quantitative yield and takes place without damage to the ester or epoxide functionalities of the starting compound. Additionally, this reaction could be readily performed on gram-scale.

Erucic acid can also be readily esterified with allyl bromide in the presence of a suitable base (K_2CO_3) to form compound **3** which now contains two distinct olefins; an internal and a terminal olefin (Scheme 2, step (iii)). These olefins can again be epoxidized using *m*-CPBA. However, these internal and terminal olefins present significantly different rates of reaction with *m*-CPBA. Reaction of compound **3** with *m*-CPBA for only two hours leads to chemoselective oxidation of the internal olefin, with no detectable oxidation of the terminal functionality, as internal olefins react much faster than their terminal olefin counterparts with *m*-CPBA (Scheme 2, step (iv)). This reaction provides access to compound **4** which contains the corresponding internal epoxide and terminal olefin. Meanwhile, prolonged reaction of compound **3** with *m*-CPBA for 5 days leads to oxidation of both olefins. This offers a different route towards the *bis*-epoxide derivative, compound **2** (Scheme 2, step (v)). With all these reactions completed, and with a range of *mono* and *bis*-epoxides at hand, further upgrading towards the corresponding cyclic carbonates and cyclic dithiocarbonates was then studied.

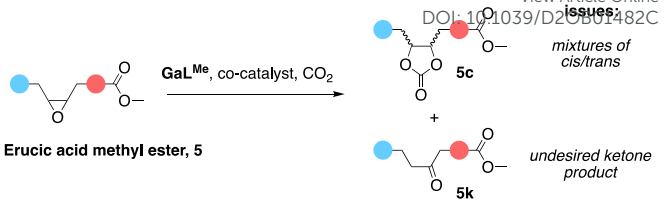
Cyclic carbonate synthesis

Using our previously reported gallium catalyst system for the formation of cyclic carbonates from epoxides and CO_2,[12] we set about preparing the cyclic carbonate products. Compound **1**

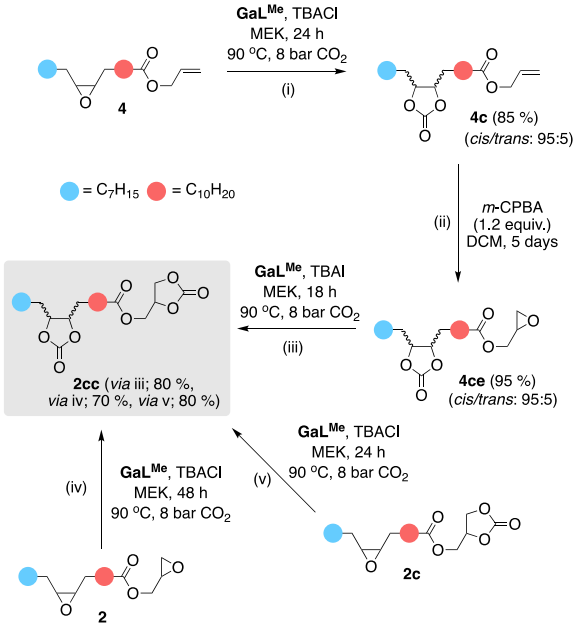


Scheme 3 Synthesis of terminal cyclic carbonates from erucic acid derivatives **1** and **2**. Conditions: *Cycloaddition*: catalyst (**GaL^{Me}**, 0.5 mol%), TBAI (2.0 mol%), MEK (0.5 mL), 18 h, 90 °C, 8 bar CO_2. *Epoxidation*: *m*-CPBA (1.2 equiv.), DCM, rt, 2h. TBAI = *tert*-butylammonium iodide, *m*-CPBA = 3-chloroperbenzoic acid, MEK = 2-butanone. Isolated yields reported after column chromatography. Selectivity towards cyclic carbonate product >99 %.

(a) Model compound for reaction condition optimization of internal cyclic carbonates synthesis



*(b) Synthesis of internal cyclic carbonates from erucic acid derivative **2** and **4***



Scheme 4 (a) Model reaction used to optimize the reaction conditions required for the internal cyclic carbonate synthesis. (b) Synthesis of internal cyclic carbonates from erucic acid derivatives **2** and **4**. Conditions: (i) catalyst (**GaL^{Me}**, 2.0 mol%), TBACl (10 mol%), MEK (0.5 mL), 24 h, 90 °C, 8 bar CO_2; (ii) *m*-CPBA (1.2 equiv.), DCM, rt, 5 days; (iii) catalyst (**GaL^{Me}**, 0.5 mol%), TBAI (2.0 mol%), MEK (0.5 mL), 18 h, 90 °C, 8 bar CO_2; (iv) catalyst (**GaL^{Me}**, 4.0 mol%), TBACl (10 mol%), MEK (0.5 mL), 24 h, 90 °C, 8 bar CO_2. (v) catalyst (**GaL^{Me}**, 2.0 mol%), TBACl (10 mol%), MEK (0.5 mL), 24 h, 90 °C, 8 bar CO_2. TBAI = *tert*-butylammonium iodide, TBACl = *tert*-butylammonium chloride, *m*-CPBA = 3-chloroperbenzoic acid, MEK = 2-butanone. Isolated yields reported after column chromatography. Selectivity towards cyclic carbonate product >99 %. *Cis/trans* ratio reported for conversion of **4** and **4c**, this ratio is not affected by reaction at other points of the molecule, thus ratio for **2cc** *via* (iii) is also 95:5. This ratio cannot be calculated for conversion of **4ce**, **2** or **2c** as ^{1}H NMR spectra has other signals in the region.

contains a terminal epoxide which could be easily transformed to the corresponding terminal cyclic carbonate, **1c**, in an almost quantitative yield of 95 % (Scheme 3, top). This compound retains the original olefin from the erucic acid, which can thereafter be post-modified. Meanwhile, the *bis*-epoxide, compound **2**, could be transformed into **2c**, a compound with a terminal cyclic carbonate and an internal epoxide under the same reaction conditions, also in excellent yield and selectivity (Scheme 3, bottom). This selectivity is possible due to the ease of converting terminal epoxides over internal ones. Of additional note is that compound **1c** can be cleanly converted to compound **2c** through reaction with *m*-CPBA, under the same conditions as for conversion of the internal olefin in Scheme 2, without affecting the cyclic carbonate functionality. The selective conversion of one epoxide in compound **2c** presents an interesting scaffold for

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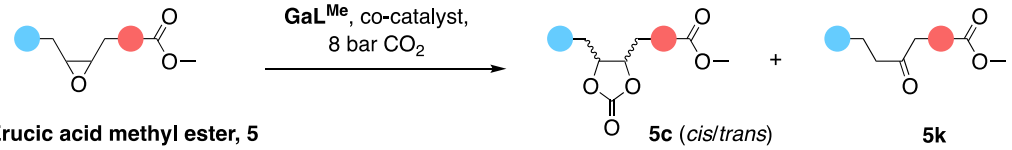
Table 1 Reaction condition optimisation for the conversion of erucic acid methyl ester, **5**, to its corresponding cyclic carbonate, **5c**, using the **GaL^{Me}** catalyst.[a,b]



Erucic acid methyl ester, 5 **5c** (*cis*/*trans*) **5k**

Entry	**GaL^{Me}** (mol%)	Co-cat (mol%)	*T* (°C)	Time (h)	Conversion (%)[c,d]	Selectivity (**5c**:**5k**)[c,d]	*cis*/*trans* ratio of **5c**[c]
1	0.5	TBAI 2.0	rt	24	0	-	-
2	0.5	TBAI 2.0	60	24	13	75:25	75:25
3	0.5	TBAB 2.0	60	24	12	80:20	85:15
4	1.0	TBAB 4.0	80	24	25	90:10	85:15
5	1.0	TBAB 4.0	80	72	65	98:2	85:15
6	2.0	TBAB 8.0	80	24	60	95:5	85:15
7	1.5	TBAB 6.0	80	48	90	92:8	85:15
8	2.0	TBAB 8.0	80	48	>99	88:12	75:25
9	2.0	TBAB 8.0	90	24	85	90:10	89:11
10	2.0	TBACl 8.0	90	24	93	>99:trace	98:2
11	2.0	PPNCl 8.0	90	24	25	>99:trace	98:2
12	2.0	PPNCl 8.0	90	48	65	>99:trace	95:5
13	**2.0**	**TBACl 10**	**90**	**24**	**>99**	**>99:trace**	**95:5**
14	2.0	TBACl 12	90	24	>99	>99:trace	95:5
15	-	TBACl 10	90	24	0	-	-

[a]MEK used as solvent in all reactions. [b]Reactions carried out on a 0.5 mmol scale. [c]Values calculated from the ^{1}H NMR spectra of the crude reaction mixtures. [d]In all cases only **5c** and **5k** were observed as products.

further modification, which will be exemplified later in this study.

Once the terminal epoxide containing derivatives of erucic acid had been selectively converted, we turned our attention to the conversion of the more challenging internal epoxide (Scheme 4). In this case it was necessary to optimise the binary catalyst system for selective conversion for two important reasons; (i) conversion of internal epoxides can result in *cis*/*trans* isomers depending on the reaction conditions/catalyst employed[8,14] and (ii) during the synthesis of cyclic carbonates from internal epoxides of fatty acids several reports have noted the propensity for the formation of a ketone by-product as a result of a Lewis acid promoted Meinwald rearrangement.[8a,b,g,j,15] In order to optimise this reaction with our gallium-based binary catalyst system, the methyl ester of erucic acid, compound **5**, was selected as a model substrate (Scheme 4(a) and Table 1).

Applying this gallium-based binary catalyst system using *tetra*-butylammonium iodide (TBAI) as co-catalyst at room temperature resulted in no observed conversion of the substrate (Table 1, entry 1). However, when increasing the temperature to 60 °C, 13 % conversion was found (Table 1, entry 2). Whilst this was an encouraging result, the selectivity towards the cyclic carbonate was only 75 % (remainder ketone product **5k**) and the *cis*/*trans* ratio was poor at only 75:25. Changing the co-catalyst to *tetra*-butylammonium bromide (TBAB) under identical conditions resulted in a similar conversion of substrate (Table 1, entry 3; 12 %), although a slightly increased selectivity towards the cyclic carbonate and an improved *cis*/*trans* ratio. A combination of the doubling of the binary catalyst system loading and an increase in the temperature to 80 °C resulted in an increase in both the conversion (Table 1, entry 4; 25 %) and selectivity for the cyclic carbonate product (90 %), while the *cis*/*trans* ratio remained constant at 85:15. When the same reaction was left for 72 hours, instead of 24 hours, a 65 % conversion was obtained (Table 1, entry 5) and a selectivity towards the cyclic carbonate of 98 % was observed. With this promising result, the binary catalyst system loading was doubled, achieving similar results to those for the aforementioned 72-hour reaction (Table 1, entry 6). A slight decrease in the binary catalyst system loading and increase in time to 48 hours, resulted in a conversion of 90 %, with a 92 % selectivity for the cyclic carbonate and 85:15 *cis*/*trans* ratio (Table 1, entry 7).

Returning to the higher catalyst system loading for 48 hours provided the first quantitative conversion (Table 1, entry 8). However, an increase in temperature to 90 °C, and reduction in time to 24 hours did not permit quantitative conversion (Table 1, entry 9). Thereafter, change from TBAB to *tetra*-butylammonium chloride (TBACl) under these conditions provided a 93 % yield, but more importantly, excellent selectivity towards the cyclic carbonate product (>99 %) and a *cis*/*trans* ratio of 98:2 (Table 1, entry 10). Similar excellent selectivities were found when using *bis*(triphenylphosphine)iminium chloride (PPNCl) as co-catalyst, however, a significantly reduced yield was obtained (Table 1, entries 10 and 11; 93 % *vs*. 25 %). Even extending the reaction time to 48 hours using PPNCl as co-catalyst did not result in the desired quantitative conversion (Table 1, entry 12). Finally, a slight increase in the binary catalyst system loading to 2.0 mol% catalyst and 10 mol% TBACl provided quantitative conversion with >99 % selectivity towards the cyclic carbonate product and

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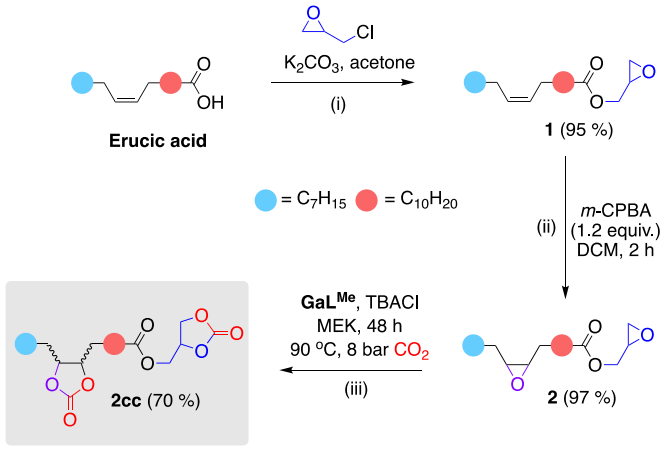


Scheme 5 Summary of the three-step synthesis of *bis*-cyclic carbonate **2cc** from erucic acid (black atoms and bonds), epichlorohydrin (blue atoms and bonds), *m*-CPBA (purple atom and bonds) and CO_2 (red atoms and bond). Conditions: (i) K_2CO_3 (2.0 equiv.), epichlorohydrin (10 equiv.), acetone, 90 °C, overnight; (ii) *m*-CPBA (2.4 equiv.), DCM, rt, 5 days; (iii) catalyst (**GaL^{Me}**, 4.0 mol%), TBACl (10 mol%), MEK (0.5 mL), 48 h, 90 °C, 8 bar CO_2. TBAI = *tert*-butylammonium iodide, *m*-CPBA = 3-chloroperbenzoic acid, MEK = 2-butanone. Isolated yields reported after column chromatography. Selectivity towards cyclic carbonate product >99 %.

a *cis*/*trans* ratio of 95:5 (Table 1, entry 13). Further increase in the binary catalyst system loading did not have any influence on the selectivity or *cis*/*trans* ratio (Table 1, entry 14). In the absence of gallium catalyst, no conversion of the substrate was observed (Table 1, entry 15).

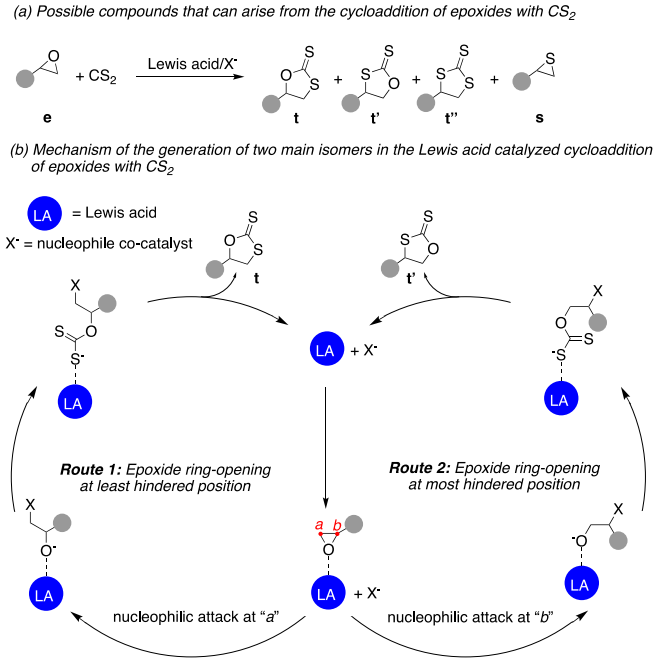
These optimised conditions are remarkable since, in many previous cases, it has been reported that it has been challenging of obtain high *cis*/*trans* ratios with this substrate.[8a,b,d,g,h,j] Meanwhile, others have achieved high *cis*/*trans* ratios, but low yields/selectivities.[8e,i] To the best of our knowledge there are only two examples of high yielding/selective catalyst systems which present high *cis*/*trans* ratios.[8c,f] One of these latter reports details the use of a catalyst system based on the aluminium congener of our gallium catalyst. In this example a lower binary catalyst system loading compared to this work was applied obtaining high yield/selectivity and *cis*/*trans* ratio, albeit using PPNCl compared to TBACl in this work.[8c] With the final mixture of possible compounds **5c**$_{trans}$, **5c**$_{cis}$, it has been possible to isolate pure **5c**$_{cis}$ using column chromatography (without the **5c**$_{trans}$) and its isolated spectra are shown in the Supplementary Information (Figures S61-64)

These optimised reaction conditions for the methyl ester, **5**, were then employed for the conversion of the internal epoxide containing compound **4** to form the corresponding cyclic carbonate product **4c** (Scheme 4(b), step (i)). This was found to be a smooth transfer with selectivities and *cis*/*trans* ratios similar to those observed with model compound **5**. The compound **4c**$_{cis}$ could be separated from **4c**$_{trans}$ by column chromatography (For spectra of the pure *cis* compound see Supplementary Information; Figures S41-44). Compound **4c** could also be further reacted with *m*-CPBA to selectively form the corresponding compound, **4ce**, which contains an internal cyclic carbonate and terminal epoxide, without any damage to the internal cyclic carbonate (Scheme 4(b), step (ii)). This compound is the opposite of **2c** in terms of it being an internal cyclic carbonate/terminal epoxide rather than internal epoxide/terminal cyclic carbonate. Further conversion of the terminal epoxide applying the reaction conditions used for the conversion of terminal epoxides into cyclic carbonates furnished the novel *bis*-cyclic carbonate product, compound **2cc** (Scheme 4(b), step (iii). This compound can also be directly obtained from the reaction of *bis*-epoxide compound **2** with CO_2 under slight modification of the optimised reaction conditions for the internal epoxide conversion in a single step reaction (Scheme 4(b), step (iv). In the case of compound **2cc**, neither from **4ce**, **2c** or **2**, it has not been possible to calculate the *cis*/*trans* ratio due to the complexity of the spectra. However, as **4ce** has a 95:5 *cis*/*trans* ratio, it would be assumed that the *bis*-cyclic carbonate arising from this substrate would also be obtained with the same ratio as this functionality is not involved in the reaction.

Notably, when using the route starting from compound **2**, all the atoms in the product (compound **2cc**) with the exception of one of the oxygen atoms from the *m*-CPBA oxidation have come from either CO_2 or a bio-derived source in only 3 steps (Scheme 5), if epichlorohydrin is considered to have been sourced from glycerol.

Cyclic dithiocarbonate synthesis

With the study into the synthesis of cyclic carbonate derivatives of erucic acid completed, we extended our explorations towards the synthesis of products obtained from the cycloaddition of epoxides with carbon disulfide (CS_2). In comparison to the cycloaddition reaction with CO_2, little attention has been paid to this analogous reaction.[16,17] CS_2 is a toxic gas, mainly produced during the manufacture of viscose fibres.[18] The CS_2 produced in this process predominantly arises



Scheme 6 Cycloaddition of terminal epoxides and CS_2. (a) Possible products (**t**, **t'**, **t''** and **s**) obtained from the cycloaddition of epoxides with CS_2. (b) Mechanism to explain the formation of the two prevalent cyclic dithiocarbonate products, **t** and **t'**.

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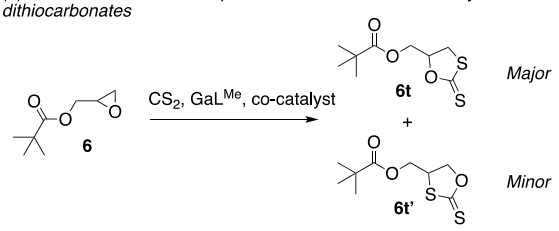
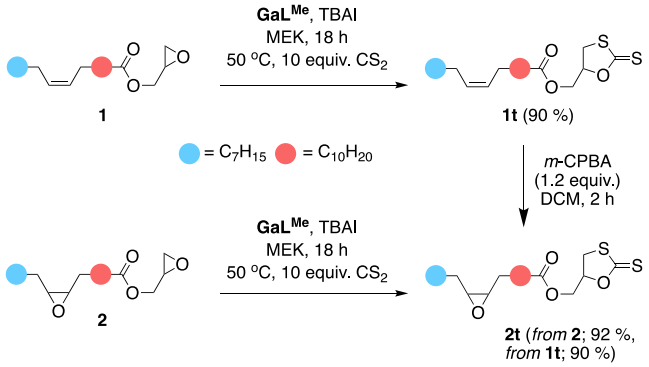
(a) Model reaction used to optimize reaction conditions for synthesis of terminal dithiocarbonates



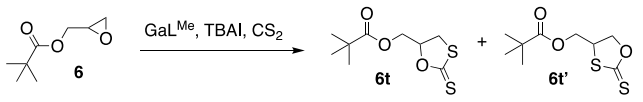
*(b) Synthesis of terminal cyclic dithiocarbonates from erucic acid derivatives **1** and **2***



Scheme 7 (a) Model reaction used to optimize the reaction conditions required for the internal cyclic carbonate synthesis. (b) Synthesis of terminal cyclic dithiocarbonates from erucic acid derivatives **1** and **2**. catalyst (**GaL^{Me}**, 0.5 mol%), TBAI (2.0 mol%), MEK (0.5 mL), 18 h, 50 °C, CS_2 (10 equiv.). *Epoxidation*: *m*-CPBA (1.2 equiv.), DCM, rt, 2h. TBAI = *tert*-butylammonium iodide, *m*-CPBA = 3-chloroperbenzoic acid, MEK = 2-butanone. Isolated yields reported after column chromatography. Selectivity towards cyclic dithiocarbonate product = >99 %. Traces of **1t'** and **2t'** found in the crude (<5 %).

from evaporative emissions as CS_2 is used as solvent. When released into the atmosphere CS_2 is readily converted to COS and SO_2 which can have potential negative impacts on the environment. Should these emitted CS_2 gases have value/application, it would likely result in interest in the capture of these waste gases and thus lower the potential negative impact on the environment. Cyclic dithiocarbonates themselves are more reactive than their cyclic carbonate analogues and their relatively facile cationic ring opening to directly form poly-dithiocarbonates is an attractive route towards these polymers.[19] As such, dithiocarbonates based on bio-derived compounds present opportunities to prepare bio-based

Table 2 Reaction condition optimisation for the conversion of 6 to the corresponding cyclic dithiocarbonate, **6t**, using **GaL^{Me}** catalyst.[a]



Entry	**GaL^{Me}** (mol%)	TBAI (mol%)	T (°C)	Yield (%)[b,c]
1	0.5	2.0	rt	50
2[d]	0.5	2.0	rt	>99
3	1.0	4.0	rt	>99
4	**0.5**	**2.0**	**50**	**>99**
5	-	2.0	50	-

[a]General reaction conditions: **6** (1.34 mmol), **GaL^{Me}**, TBAI, CS_2 (10 equiv.), temperature, 18 h. [b]Values calculated from the ^{1}H NMR spectra of the crude reaction mixtures. [c]Only minor traces of **6t'** could be observed. [d]Reaction time of 48 h.

polythiocarbonates. However, one of the issues with the cycloaddition reaction with CS_2 is that several sulfur containing compounds can be obtained (Scheme 6a). The two isomers are derived from the selectivity in the ring-opening step of the epoxide (Scheme 6b). Nucleophilic attack at the least hindered position (atom *a*) results in the cyclic dithiocarbonate with the O-atom located nearest to the R group of the epoxide substrate, **t**, whereas attack at the most hindered position (atom *b*) results in the other isomer, **t'**.

As our previous work only considered the cycloaddition of epoxides with CO_2,[12] it was necessary to again re-optimize the binary gallium-based catalyst system for the cycloaddition of epoxides and CS_2. Initial studies started with the use of a model substrate, compound **6**, which permitted optimisation of the conversion with the terminal epoxide (Scheme 7a). This substrate was selected due to its similarity to the terminal epoxides derived from erucic acid used in this study. Taking the binary gallium-based catalyst system at room temperature and using TBAI as co-catalyst furnished a moderate yield of 50 % (Table 2, entry 1). It is notable that only very minor traces of compound **6t'** were observed in the crude, indicating an excellent selectivity for attack at the least hindered carbon atom (Scheme 6), as might be expected. Furthermore, no other compounds were observed in the reaction crude, indicating excellent selectivity towards the desired cyclic dithiocarbonate products. Extending the reaction time to 48 hours resulted in a yield of >99 % (Table 2, entry 2), again with excellent selectivity towards compound **6t**. Doubling of the binary catalyst system loading allowed for quantitative yield when the reaction was performed at room temperature (Table 2, entry 3). Use of the reduced binary catalyst system loading at an elevated temperature of 50 °C also provided quantitative yield (Table 2, entry 4). In the absence of the gallium catalyst, with the co-catalyst alone, no product was formed, and the substrate remained intact (Table 2, entry 5). With excellent yields and selectivities obtained for this conversion, no further optimisation was attempted, and it was decided to use the lowest binary catalyst system loading possible. Optimal conditions of 0.5 mol% **GaL^{Me}** and 2.0 mol% TBAI at 50 °C were selected.

With the reaction conditions for the cycloaddition of the terminal epoxide and CS_2 in hand, attempts were made to convert compounds **1** and **2** to the corresponding cyclic dithiocarbonate products (Scheme 7b). Pleasingly, both compounds could be cleanly converted to the corresponding terminal cyclic dithiocarbonates in excellent yields, with no evidence of reaction with the internal epoxide in compound **2**. Again, as with the cyclic carbonate derivative, compound **1c**, compound **1t** can be readily converted to compound **2t** without damage to the dithiocarbonate using *m*-CPBA as oxidant.

In a similar approach to the optimization for the conversion of the internal epoxide to the internal cyclic carbonate, the methyl ester of the epoxide of erucic acid, compound **5**, was selected for optimisation studies towards the internal cyclic dithiocarbonate (Scheme 8(a) and Table 3). It is important to note that there are relatively few examples of the conversion of internal epoxides to their corresponding cyclic dithiocarbonate

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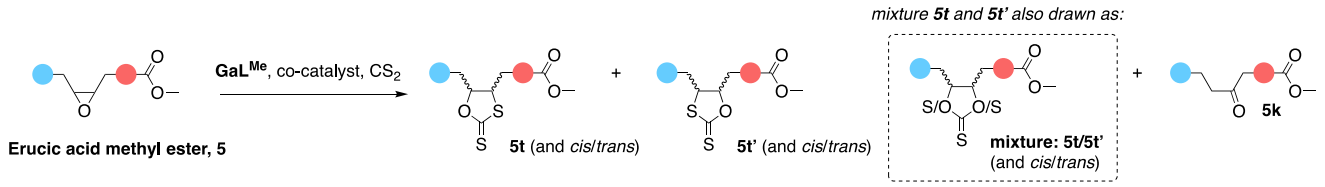
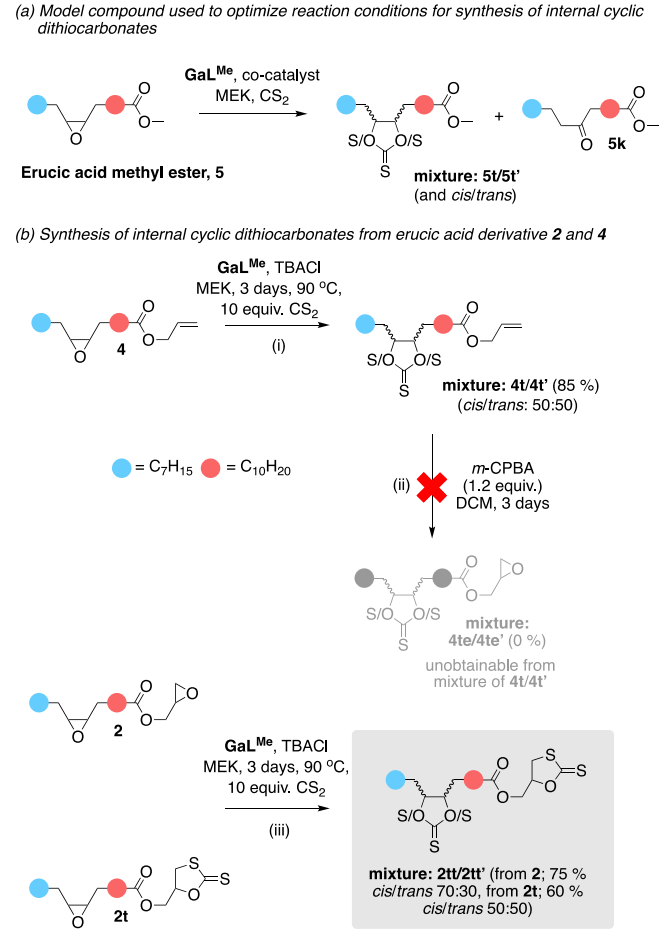
Table 3 Reaction condition optimisation for the conversion of Erucic acid methyl ester, **5**, to its corresponding cyclic dithiocarbonate, **5t/5t'**, using **GaL^{Me}** catalyst.[a]



Entry	**GaL^{Me}** (mol%)	Co-cat (mol%)	*T* (°C)	Time (h)	Conversion (%)[b,c]	Selectivity (%; for **5t** and **5t'**)[b,c]	*cis*/*trans* ratio of **5t/5t'**[b]
1	0.5	TBAI (2.0)	50	18	0	-	-
2	1.0	TBAI (4.0)	50	18	0	-	-
3	0.5	TBAI (2.0)	70	24	0	-	-
4	1.0	TBAI (4.0)	80	72	90	50	traces:>99
5	0.5	TBAI (2.0)	90	24	75	5	-[d]
6	5.0	TBAB (5.0)	90	48	>99	65	50:50
7	**5.0**	**TBACl (5.0)**	**90**	**72**	**>99**	**95**	**40:60**
8	2.0	TBACl (10)	90	24	90	40	50:50

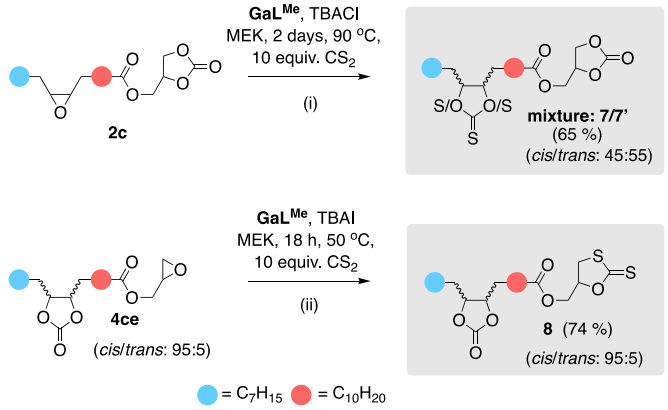
[a]Reactions carried out on a 0.5 mmol scale. [b]Values calculated from the ^{1}H NMR spectra of the crude reaction mixtures. [c]In all cases only **5t/5t'** and **5k** were observed as products. [d]Not calculated due to the low yield obtained.



Scheme 8 (a) Model reaction used to optimize the reaction conditions required for the internal cyclic dithiocarbonate synthesis. (b) Synthesis of internal cyclic dithiocarbonates from erucic acid derivatives **2** and **4**. Conditions: (i) catalyst (**GaL^{Me}**, 5.0 mol%), TBACl (5.0 mol%), MEK (0.5 mL), 3 days, 90 °C, CS_2 (10 equiv.); (ii) *m*-CPBA (1.2 equiv.), DCM, rt, 3 days; (iii) catalyst (**GaL^{Me}**, 5.0 mol%), TBACl, 5.0 mol%), MEK (0.5 mL), 3 days, 90 °C, CS_2 (10 equiv.). TBACl = *tert*-butylammonium chloride, *m*-CPBA = 3-chloroperbenzoic acid, MEK = 2-butanone. Isolated yields reported after column chromatography. *Cis*/*trans* ratios reported for conversion of **4**, **2** and **2t**.

products and in all cases only low yields have been reported, indicating the challenging nature of this conversion.[16c,d,e,f,g,i,j] In addition, both of the carbon atoms of the epoxide are almost equivalent in the internal epoxide and therefore, unlike with CO_2 cycloaddition, two distinct cyclic dithiocarbonates can be formed depending on which carbon atom is attacked by the co-catalytic nucleophile. In this context, as both products are extremely similar, and it is not possible to identify them using common spectroscopic techniques (eg. ^{1}H or ^{13}C{^{1}H} NMR), the product is donated as a mixture of **5t** and **5t'** for conversion of erucic acid methyl ester, **5**.

Initial attempts to transfer the optimised reaction conditions for the terminal cyclic dithiocarbonate synthesis resulted in a failure to convert the substrate (Table 3, entry 1). This result is not surprising as conditions for conversion of terminal epoxides to the corresponding cyclic carbonates are not usually suitable for conversion of internal epoxides. Thereafter, neither individually doubling of the binary catalyst system loading or increasing the time or temperature to 70 °C from 50 °C provided conversion of the substrate (Table 3, entries 2 and 3). Gratifyingly, a combination of increasing the binary catalyst system to 1.0 mol% gallium catalyst with 2.0 mol% TBAI and applying a reaction temperature of 80 °C for 72 hours resulted in an almost quantitative conversion of the substrate (Table 3, entry 4; 90 %). However, selectivity towards the cyclic dithiocarbonate products was poor (only 50 %), but it is notable that the *trans* isomer was selectively obtained. Decreasing the binary catalyst system loading and time to 24 hours, whilst further increasing the temperature to 90 °C resulted in a 75 % conversion, although with a significantly decreased cyclic dithiocarbonate selectivity of 5 % (Table 3, entry 5). With the challenge of low selectivity remaining, we radically changed our screening strategy and tried a 1:1 catalyst:co-catalyst loading at 90 °C for 48 hours using TBAB. This trial provided a quantitative conversion with a selectivity of 65 % (Table 3, entry 6). Finally, under these reaction conditions



Scheme 9 Synthesis of mixed cyclic carbonate/dithiocarbonate compounds using products obtained from the cyclic carbonate and dithiocarbonate studies. Conditions: (i) catalyst (**GaL^{Me}**, 5.0 mol%), TBACl (5.0 mol%), MEK (0.5 mL), 2 days, 90 °C, CS_2 (10 equiv.); (ii) catalyst (**GaL^{Me}**, 0.5 mol%), TBAI (2.0 mol%), MEK (0.5 mL), 18 h, 50 °C, CS_2 (10 equiv.). TBACl = *tert*-butylammonium chloride, *m*-CPBA = 3-chloroperbenzoic acid, MEK = 2-butanone. Isolated yields reported after column chromatography. *Cis*/*trans* ratio reported for conversion of **2c**. Compound **4ce** has *cis*/*trans* ratio of 95:5 and this is not affected by the cycloaddition with CS_2.

replacing TBAB with TBACl both quantitative conversion and good selectivity towards the cyclic dithiocarbonate product could be achieved. Given the similarity of these conditions, in terms of co-catalyst choice, to the optimal ones for the internal cyclic carbonate synthesis, we also trialled these conditions (Table 3, entry 8). Here, almost quantitative conversion was indeed achieved (90 %), but a very poor selectivity towards the cyclic dithiocarbonate was observed. Transfer of this optimised procedure for the formation of internal dithiocarbonates to compound **4** resulted in the obtention of the mixture of compounds **4t** and **4t'** (Scheme 8(b), step (i)). The *cis* and *trans* isomers could be successfully separated by column chromatography and their spectra are shown in the Supplementary Information (Figures S49-56).

Unlike with the compound with internal cyclic carbonate and terminal olefin, the terminal olefin of this compound could not be subsequently oxidised to form the mixture of compounds **4te** and **4te'**. Indeed, after the attempted epoxidation, the starting material had decomposed and no product was observed (Scheme 8(b), step (ii)). The *bis*(cyclic dithiocarbonate) compound could however be obtained directly from the reaction of compound **2** using conditions for the conversion to internal cyclic dithiocarbonates (Scheme 8(b), step (iii)). Further to this, we have been able to calculate the *cis*/*trans* ratio of mixture **2tt**/**2tt'**, whereby a 1:1 ratio is present starting from **2t**, although an improved ratio (*cis*/*trans* ratio of 70:30) was observed starting from **2**, an observation that we are unable to explain, but a result that should be highlighted. It has been possible to isolate both the *cis* and *trans* isomers through column chromatography and their spectra are shown in the Supplementary Information (Figures S29-32).

Mixed Cyclic carbonate/dithiocarbonate compound synthesis

With all the compounds in hand from both the cyclic carbonate and dithiocarbonate studies, it was apparent that some of these compounds present the opportunity to synthesise unusual mixed cyclic carbonate/dithiocarbonate products. It was therefore proposed to attempt the synthesis of these mixed compounds (Scheme 9), which would result in unprecedented synthetic control as a result of our approach to sequential modification of the erucic acid precursor. To our delight it was possible to obtain the compound **mixture 7/7'** by reaction of the internal epoxide of **2c** with CS_2 under the conditions for internal cyclic dithiocarbonate synthesis. In this case the *cis*/*trans* ratio could be calculated and the *cis* and *trans* isomers could be separated by column chromatography (See Supplementary Information for spectra; Figures S78-85).

Further, compound **8** could be obtained from the reaction of **4ce** with CS_2 using the conditions for terminal cyclic dithiocarbonate synthesis. Given the difference in the chemical shifts of the cyclic carbonate and cyclic dithiocarbonate it was again possible to successfully calculate the *cis*/*trans* ratio, unlike in the case of **2cc**. Finally, it was found not to be possible to obtain compound **8** from the **2t**, as during the cycloaddition reaction the cyclic dithiocarbonate moiety was observed to decompose.

Conclusions

In conclusion, we have demonstrated that it is possible to selectively synthesise *bis*(cyclic carbonate) and *bis*(cyclic dithiocarbonate) derivatives from erucic acid derivatives. Access to these new compounds is made possible through the functionalisation of the carboxylic acid with epichlorohydrin, providing a new reactive functionality, and oxidation of the olefin with *m*-CPBA. Other compounds have also been prepared from an intermediate which is prepared from the esterification of erucic acid with allyl bromide. Exploitation of the unique selectivities of *m*-CPBA with internal/terminal olefins and catalytic cycloaddition reactions of epoxides with CO_2 towards internal/terminal olefins and epoxides, has also provided chemoselective access to a range of derivatives of erucic acid. As a result of the different products obtained it has also been possible to, for the first time, selectively synthesize unusual mixed cyclic carbonate/cyclic dithiocarbonate compounds as a result of the level of control we have developed. Throughout the work we have also attempted to explain selectivities where relevant, in particular, the formation of *cis*/*trans* products and the regioselective synthesis of cyclic dithiocarbonate. Overall, this study demonstrates the potential of applying established chemoselective synthetic procedures for the preparation of new value-added products from bio-derived feedstocks.

Conflicts of interest

The authors declare no competing financial interest.

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