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The unrevealed potential of elemental sulfur for the synthesis of high sulfur content bio-based aliphatic polyesters†

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We introduce a novel sulfur-containing polyester derivative based on a renewable monomer bearing secondary disulfide groups. Specifically, we demonstrate that this secondary disulfide moiety, placed in each repeating unit within the polymer, enables the introduction of high sulfur content by virtue of an organocatalytically triggered sulfur exchange reaction using elemental sulfur, thereby facilitating the synthesis of sustainable aliphatic polyesters with tailored functionalities.

Commodity polymers are ubiquitous to human life, and the current state of the art reveals a tremendous number of studies devoted to the development of new approaches for the synthesis of novel synthetic polymeric materials with elaborate structures and functions.¹ Albeit, these powerful methods have enabled transformative advances, most of them entail the use of depleting petroleum-based commodity chemicals as monomers, which also has adverse effects on the environment. Recently, taking advantage of the structural diversity of alternative inexpensive resources (*e.g.* elemental sulfur,² as a by-product of the oil and gas industry, and diverse biomass³ derivatives), significant interest has been shown towards the design of novel sustainable polymers. On the one hand, carbon dioxide-neutral renewable monomers have shown immense potential as a natural analogue replacement for fossil-based chemicals.⁴ In this context, vegetable oils and their corresponding fatty acid derivatives have proven to be valuable resources.^{5,6} Nevertheless, modern applications of these well-known resources require more research to introduce additional functionalities, which in terms of chemical func-

tional groups exhibit higher reactivities compared to the available double bonds in fatty acids. Indeed, many examples disclose the application of sulfur⁷ chemistry (explicitly, thiol-ene/yne reaction)⁸ as a promising and efficient strategy for the introduction of reactive functional groups into methyl oleate to deliver precursors for the synthesis of diverse aliphatic and aromatic polymers (*e.g.* polyurethanes, polyamides and polyesters amongst others). However, from a chemical structural perspective, all of the aforementioned thiol-containing sustainable polymers are composed of carbon–sulfur single bonds, *i.e.* –S–, per repeating unit, and hence are inadequate to address the demand of the growing complexity of modern polymeric materials. On the other hand, elemental sulfur (S₈) as a cost-effective raw material⁹ is readily available as a by-product of a process called hydrodesulfurization¹⁰ and has regained increasing attention in the last decade. Explicitly, S₈ has been employed as a reaction medium (*e.g.* solvent) and comonomer in the presence of a variety of crosslinkers for the synthesis of chemically stable and processable high sulfur content¹¹ polymeric materials *via* a simple, scalable, and highly atom efficient method named inverse vulcanization.¹² Indeed, this new method, as an excellent example of green chemistry,¹³ has delivered polymeric materials with radically different properties (*e.g.* electrochemical, optical, and redox-regulated structural dynamic properties) in comparison with their merely carbon containing counterparts. For instance, Theato and colleagues reported on the sustainable preparation of polymeric, high sulfur content-based vegetable oil composites from S₈ and vegetable oils, which were further evaluated as cathode materials in Li–S batteries.¹⁴ Despite the tremendous progress that has been made in inverse vulcanisation for improving the synthesis of polymeric materials with high content of sulfur, there are still issues to be addressed, such as the restriction of the type of crosslinker solely to polyene derivatives. Despite the nearly unlimited plethora of polyene derivatives ranging from industrial feedstock derivatives (such as divinyl benzene, dicyclopentadiene, *etc.*)^{12,15,16} to the ones based on renewable resources (*e.g.* limonene, squalene, diallyl

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disulfide and triglycerides amongst others),^{14,17,18} their direct use in inverse vulcanisation reactions is still energy intensive (elevated reaction temperatures, *e.g.* above 140 °C), and requires long reaction times to drive the reaction towards high conversion. Furthermore, very accurate comonomer stoichiometry is essential to obtain high-molecular-weight products. Critically, during the process, addition of S₈ to polyenes results in branching of the polymeric chains, ultimately leading to hyperbranched or insoluble crosslinked materials. Therefore, in order to overcome the above-mentioned limitation and further optimize the reaction conditions, catalytic inverse vulcanisation methods have been recently postulated.¹⁹ Although effective, the latter examples still do not fully exploit the potential advantages of S₈ within the field of synthetic polymer chemistry. Indeed, to the best of our knowledge, there exists no example of a linear high sulfur content polymer, particularly a polyester derivative, derived *via* inverse vulcanisation. Thus, going beyond the conventional aliphatic polyester based materials and with the idea to unlock the full potential of S₈, we exploit the organocatalytically triggered reaction of S₈ with secondary disulfide bonds, which were present in each repeating unit of the sustainable polyester derivative, to deliver high sulfur content aliphatic polyester derivatives with tailored properties (Fig. 1).

Accordingly, we designed a bio-based aliphatic monomer that is functionalized with internal secondary disulfide bonds. The disulfide renewable monomer dimethyl 9(10),9'(10')-dithiodistearate, **M1** (depicted in Scheme 1), was synthesized in a consecutive three-step synthesis starting from the methyl ester derivative of oleic acid (**MO**), an abundantly available renewable feedstock.²⁰ As a side note, the utilization of bio-based raw materials (such as **MO**) is in the spotlight of the chemical industry, particularly due to the fact that vegetable oils are one of the most prominent platform chemicals for the synthesis of sustainable polymers (*e.g.* polyesters) by virtue of their high availability, inherent biodegradability and low price, as mentioned above.²⁰ Furthermore, in technically relevant polyester derivatives, the aliphatic segments are relatively short, typically amounting to six atoms or shorter linear carbon chains; hence **M1** is considered an attractive monomer for the synthesis of a bio-based polyester derivative that contains a longer aliphatic segment $-(CH_2)_n-$ as a structural



Fig. 1 Organocatalytically triggered reaction of S₈ with secondary disulfide bonds, which are placed in each repeating unit of the sustainable polyester derivative, to deliver high sulfur content linear polyester derivatives with tailored properties.



Scheme 1 Synthetic route for the preparation of renewable monomer **M1** (dimethyl 9(10),9'(10')-dithiodistearate) bearing secondary disulfide groups, suitable to undergo the organocatalytic sulfur exchange reaction.

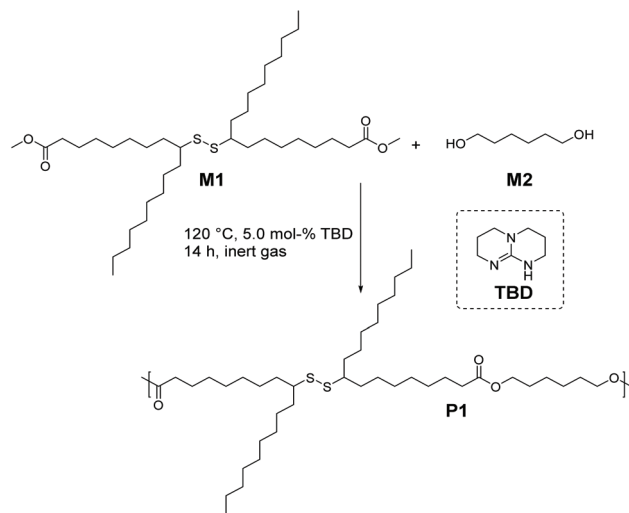
feature along with an *n*-alkyl dangling side chain and a secondary disulfide bond.³ Critically, the dynamic nature of the latter, *i.e.* the secondary disulfide bond, would also account for unique properties (*e.g.* stimuli triggered adaptability, stress resistance, self-repair, degradability or sulfur exchange reaction) in the resulting polyester.⁷

Because of the possibility of adding virtually any functional group to olefins, the photochemically induced thiol-ene addition of thioacetic acid to **MO** under UV irradiation ($\lambda = 320$ nm) was initially performed, by adopting slightly modified reaction conditions of a previously reported procedure (refer section A.2 in the ESI†).²¹ Intriguingly, after the reaction of the internal C=C double bond, a dangling alkyl chain remains in the structure of the so-formed molecule. In fact, these dangling chains can interfere with efficient packing of the derived polymers, and lead to less dense polymers compared to the linear ones. Nevertheless, the protected thiol intermediate, methyl 9(10)-(acetylthio)stearate (Scheme 1), was isolated as a mixture of two regio-isomers in reasonable yields (~90%) after column chromatography. Subsequently, this intermediate compound was converted into the corresponding monomer dimethyl 9(10),9'(10')-dithiodistearate (**M1**) as follows: first the free-thiol derivative, methyl 9(10)-mercaptostearate, was obtained by the base-catalysed alcoholysis²² of methyl 9(10)-(acetylthio)stearate, which was further oxidized in a straightforward manner with elemental iodine to yield the disulfide **M1** (for preparative details refer section A.2.3 in the ESI†). Our efforts for ensuring the environmentally benign nature of **M1**



were not limited to biomass as a source. We employed 1,5,7-triazabicyclo[4.4.0]dec-5-ene, TBD, as a safe and non-toxic sustainable organocatalyst for the hydrolysis of the protected thiol derivative.²³ Nevertheless, each of the above-mentioned transformations was evidenced by nuclear magnetic resonance (NMR) in addition to mass spectrometry (either by gas chromatography–mass spectrometry, GC-MS, or high-resolution electrospray ionization mass spectrometry, ESI-MS) analyses (Fig. S1–S8 in the ESI†). While the ¹H NMR spectrum of methyl 9(10)-(acetylthio)stearate in Fig. S1† shows no magnetic resonances associated with the olefin region (5.38–5.30 ppm) of **MO**, a new signal appeared at 3.48 ppm corresponding to the protons of the α -carbon (*i.e.* the methanetriyl group (>CH–), **9_a** in Fig. S1†), to which the acetylthio group is also attached. Besides, the resonances arising from the hydrogens (**8_a** and **10_a**, respectively) of the α -methylene groups adjacent to the methanetriyl functionality shifted to the region between 1.63 and 1.54 ppm. Concomitantly, the synthesis of the free-thiol derivative methyl 9(10)-mercaptostearate was confirmed by the disappearance of the resonance at 2.30 ppm (arising from the methyl functionality of the thioacetyl group, **21**, compare Fig. S1 and S2 in the ESI†), in addition to the shifting of the resonances associated with the protons of the methanetriyl group (**9_b**) from 3.48 ppm to the regions of 2.80 and 2.72 ppm. Attributable to the instability of free thiols that makes them oxidizable under ambient conditions, the oxidative formation of **M1** was also detected during the purification step of methyl 9(10)-mercaptostearate. In particular, the resonances of the methanetriyl group (**9_c**) of **M1** shifted to the regions of 2.62 and 2.50 ppm (Fig. S3†). Nonetheless, in addition to the latter resonance, the ¹H NMR spectra of **M1** showed a singlet at 3.67 ppm associated with the terminal methyl ester group, and the shifted resonances in the regions of 1.60 and 1.48 ppm arising from the hydrogens (**8_c** and **10_c**, respectively) of the α -methylene groups adjacent to the methanetriyl functionality. The important features of the ¹³C NMR spectrum of **M1** in Fig. S4† are magnetic resonances at 174.14 ppm, and at 52.32 and 34.06 ppm, which are associated with the carbon atom of the ester unit in addition to the carbon atoms of the methanetriyl group and the α -methylene groups adjacent to it, respectively. Last but not least, conventional two-dimensional NMR (COSY and HSQC) experiments were employed for the determination of the exact structure of **M1** possessing a unique secondary disulfide bond (Fig. S5 and S6 in the ESI†). Additional analysis of a solution of **M1** in THF : MeOH (3 : 2, v/v) using a Q-Exactive Orbitrap mass spectrometer evidenced the expected compound with m/z_{exp} 681.4915 [**M** + Na]⁺ (refer Fig. S8 in the ESI†).

Having demonstrated the successful synthesis of **M1**, we sought to leverage its melt polycondensation with 1,6-hexanediol (**M2**) to deliver the aliphatic polyester derivative **P1** (depicted in Scheme 2). Industrially, 1,6-hexanediol is prepared by the hydrogenation of adipic acid, and since the first pilot plant producing adipic acid *via* the fermentation process using non-food, plant-based feedstock has been recently set up, **M2** can be considered (potentially) a biomass derived compound,²⁴ thus contributing to the sustainability of **P1**.



Scheme 2 Synthetic route for the preparation of bio-based aliphatic polyester **P1** *via* organocatalytic melt polycondensation of **M1** (dimethyl 9(10),9'(10')-dithiodistearate) with **M2** (1,6-hexanediol).

On the one hand, differential scanning calorimetry (DSC) analyses confirmed that **M1** was thermally stable up to 200 °C, and thus it could be polymerized under solvent-free conditions. On the other hand, the DSC chromatogram of **M1** showed a unique thermal behaviour attributed to the fact that **M1** is a long chain alkyl monomer composed of mixtures of regio-isomers with different lengths of *n*-alkyl side chains (*e.g.* *n* is either 8 or 9). In other words, **M1** exhibits a glass transition temperature, T_g , of –63.4 °C attributed to the *n*-alkyl dangling side chain, and two melting points with onset temperatures at –24 and –14 °C, respectively (see Fig. S9 in the ESI†). Interestingly, although disulfide bonds are known to be temperature responsive,²⁵ no homolytic scission or any other side reactions were observed at elevated temperatures during the DSC measurements of **M1**. Hence, test polymerizations of **M1** with **M2** were carried out at 120 °C, since the catalyst of choice, *i.e.* TBD, has been recognized as a highly effective and sustainable transesterification catalyst within this temperature range for the synthesis of fatty acid derived polycondensates with a vast array of chemical functionalities.^{26–31} Different loadings of TBD (1.0, 5.0 and 10.0 mol%) per ester group of **M1** were tested (refer section A.3 in the ESI†). Even though **M1** is thermally stable under the abovementioned reaction temperatures, hydroquinone (2.0 $\mu\text{mol}\%$) was added to the polymerization mixture as a radical quencher to avoid any plausible cleavage of secondary disulfide linkages during melt polycondensation. The size exclusion chromatography (SEC) and NMR spectroscopy results of these preliminary polymerization experiments disclosed that 1.0 mol% catalyst yielded only oligomers (see Fig. S10 in the ESI†), while a higher amount of TBD (10.0 mol%) resulted in undesired side reactions as depicted explicitly by ¹H NMR analyses (see Fig. S11 in the ESI†).

Accordingly, **P1**, with an apparent molar mass of 13 500 g mol^{-1} and with a dispersity of $D = 1.7$ (as determined by SEC





Fig. 2 SEC trace of the parent polymer **P1** (black line) and **P1_S_70.0 mol%** (red line).

relative to polymethacrylate standards, Scheme 2 and Fig. 2), was synthesized under the most optimal conditions for polymerization, which were determined to be 120 °C, 5.0 mol% catalyst and a reaction time of 14 h under a continuous flow of an inert gas.

The ^1H NMR spectrum of **P1** in Fig. 3 displays the proton resonances of the methanetriyl unit in the region between 2.62 and 2.50 ppm (h), which remained intact during the polymerization process. Furthermore, the proton resonances of the α -methylene units adjacent to the ester and methanetriyl groups were identified at 4.06 (a'), 2.28 (a), and in the range between 1.63 and 1.54 ppm (g and i), respectively. Critically, the singlet corresponding to the terminal methyl ester ($\text{CH}_3\text{O}-$) group of **M1** at 3.67 ppm was significantly lower in intensity, also leading to the success of polymerization. Furthermore, it is worth highlighting that along with ^1H NMR, ^{13}C NMR analysis also demonstrated that the secondary disulfide functionality remained intact and did not interfere with any other functional group, indicating the compatibility



Fig. 3 Analysis of **P1** and **P1_S_70.0 mol%** by ^1H NMR spectroscopy, indicating the success of each transformation, the synthesis of the parent polymer **P1** and the subsequent organocatalytic sulfur exchange reaction with 70.0 mol% elemental sulfur added incrementally.



Fig. 4 Analysis of **M1**, **P1** and **P1_S_70.0 mol%** by attenuated total-reflectance infrared spectroscopy, indicating the success of each transformation, *i.e.*, synthesis of the parent polymer **P1** and the subsequent transformation into high sulfur content polyester **P1_S_70.0 mol%**. The inset shows the zoomed-up region from 1800–1400 cm^{-1} , respectively.

of melt polycondensation chemistry with this specific functionality (Fig. S12 in the ESI†). In addition, an attenuated-total-reflectance IR (ATR-IR) assay provided supplemental spectroscopic proof for the successful synthesis of polymer **P1**, although secondary disulfide bonds lack a distinctly strong IR handle (Fig. 4). Nevertheless, the subsequent disappearance of the symmetrical and antisymmetrical $-\text{O}-\text{CH}_3$ deformation bands (1435 cm^{-1}), along with the respective shift of the characteristic $\text{C}=\text{O}$ stretching band of the ester functionality from $\sim 1740 \text{ cm}^{-1}$ to a lower wavenumber (1736 cm^{-1}) underpinned the successful transformation of the monomeric methyl ester groups of **M1** into the polymeric ester derivatives of **P1** (zoomed-up inset in Fig. 4).

Next, in order to evaluate the efficiency of the anticipated reaction (*i.e.* the organocatalytically (*i.e.* TBD) triggered sulfur exchange reaction, Scheme 3a) between the secondary disulfide bonds of the new polymer system **P1** and S_8 , a proof-of-concept molecule (**M1_S_x**, where x indicates the number of sulfur atoms introduced after the sulfur exchange reaction) was designed, and further assessed by diverse analytical methods. Equimolar amounts of **M1** and S_8 were reacted for 1 h at 135 °C (*i.e.* the temperature at which S_8 starts to melt) under an inert gas atmosphere with and without the catalyst, respectively. For the first case, 2.0 mol% of the strong nucleophile TBD ($\text{p}K_{\text{a, MeCN}}$ of 26)³² was utilized as the catalyst. Interestingly, quite recently, it has been shown that nitrogen-based nucleophilic activators such as pyridine derivatives are capable of ring-opening S_8 under various conditions and enhancing the reactivity of sulfur exchange reactions at low reaction temperatures within short reaction times.¹⁹ Similarly, DBU, another well-known guanidine derivative, was utilized for the direct cleavage of disulfide into the corresponding thiol derivatives.³³ ^1H NMR analysis of the catalyst-free final reaction mixture of **M1_S_x** gave results along expected lines, *i.e.* no





Scheme 3 The organocatalytically (*i.e.* TBD) triggered sulfur exchange reaction between S_8 and the secondary disulfide bonds of: (a) monomer **M1** to synthesize a proof-of-concept molecule **M1_{S_x}** and (b) polymer **P1** to deliver **P1_{S_Y}** mol-%, respectively. "x" indicates the number of sulfur atoms introduced after the sulfur exchange reaction and "Y" stands for the loading of S_8 (in mol%) during the reaction.

sulfur exchange reaction took place, while the TBD-catalyzed reaction delivered the targeted high sulfur content compound **M1_{S_x}**. The 1H NMR spectrum recorded after the purification of **M1_{S_x}** exhibited chemical shifts of the α -carbon protons as a function of sulfur content within the molecule (Fig. S13 in the ESI †). Explicitly, the multiplet in the region between 2.62 and 2.50 ppm associated with the hydrogen atom at the α -carbon adjacent to the disulfide bond was shifted to the following ranges: 3.03–2.93, 2.93–2.87 and 2.85–2.79 ppm, respectively, in such a way that each series of multiplets is assigned to the respective sulfur rank, hence nicely depicting the high sulfur content of the compound. In fact, this shift in the resonances of the disulfide bond in NMR analyses has been noted for polysulfides whose α -carbon protons exhibit multiplets, as in the current case.^{34,35} It can be postulated that these changes in chemical shifts result, in part, from the an-

isotropy or inductive effects of sulfur atoms, as reported previously.³⁶ Notably, NMR analysis also revealed that the terminal methyl ester functional moiety remained intact and did not undergo any reaction, such as thioesterification as expected (refer to Fig. S13 †). To shed further light on the process, an experiment was conducted under ambient atmosphere, which revealed that the presence of oxygen inhibits the process (data not disclosed). Furthermore, SEC traces in Fig. S14 † revealed that the molar mass of **M1** before and after the reaction (*i.e.* **M1_{S_x}**) varied significantly enough to be displayed as a new peak in the SEC traces. Although SEC and NMR spectroscopy evidenced the successful introduction of high sulfur content within **M1**, these data alone do not provide insight into the exact chemical composition of the model compound. Therefore, additional high resolution ESI-MS allowed assigning the incorporation of the high sulfur content, evidencing all possible fragments that can arise (Fig. S15 in the ESI †). Due to the shift of the molecular weight of the charged sodium cations of **M1** by 31.972 m/z , it was apparent that the upper limit of sulfur content that can be additionally introduced *via* the TBD mediated sulfur exchange reaction between **M1** and S_8 is 6 sulfur atoms ($m/z_{\text{calc}} = 873.3240$, [**M1_{S_{x=6}}** + Na] †). In other words, the maximum total sulfur content within the proof-of-concept molecule is 8 sulfur atoms per molecule. Importantly, this high sulfur content molecule is chemically stable and does not readily depolymerise back to **M1** and S_8 , as it was bench stable for over a month under ambient conditions, in contrast to polymeric sulfur.

Consequently, the final key step is to demonstrate that the custom designed polymer **P1** decorated with secondary disulfide can also deliver high sulfur content polymers (**P1_{S_Y}** mol-% in Scheme 3b, and Table S1 in the ESI †) with the aid of S_8 by virtue of the sulfur exchange reaction ("Y" stands for the loading of S_8 (in mol%) during the reaction). Initially, an equimolar mixture of **P1** and elemental sulfur was reacted in the presence of 2.0 mol% TBD at 135 °C in a similar manner as it was performed for **M1** (Table S1, † entry 1). Surprisingly, SEC traces of the reacted polymer **P1_{S_{100.0}}** mol-% (where 100.0 mol% indicates the equimolar loading of S_8) after 1 h of reaction shifted to higher retention time revealing some degradation with decreasing apparent molar mass (see Fig. S16 in the ESI †). Indeed, it is conventionally considered that the sulfur content in the repeating unit of any polymeric structure is thermodynamically limited to a maximum of 9 sulfur atoms before the homopolymerization of elemental sulfur starts to compete with depolymerization, since the average bond dissociation energy of the –S–S– bond is expected to decrease to a certain value, resulting in an accelerated sulfur exchange reaction.³⁷ Furthermore, it has also been reported that the reactivity of the thiolate anion decreases with increasing number of S atoms in the propagating chain because of negative charge stabilization, presumably *via* delocalization along the disulfide bond.³⁸ To circumvent this problem, *in situ* incremental addition of elemental sulfur was postulated. Accordingly, under bulk conditions with a continuous flow of an inert gas, the first aliquot of S_8 (5.0 mol%) was added to **P1** and the reac-



approach may constitute a platform, as advanced yet simple, to implement these high sulfur content polymers in the formation of various materials with specified functions (e.g. self-organization, adaptive self-sorting, molecular motion, replication and transcription amongst others). For instance, these properties and functions may effectively be used for generating materials with potential applications ranging from biomedicine (such as protein biochips)⁴⁰ to energy storage (e.g. Li-S batteries⁴¹ or IR imaging).⁴²

Conflicts of interest

The authors declare no conflict of interest.

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