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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 functional properties.

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 $-(\text{CH}_2)_n-$ 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**





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 ($m/z_{calc} = 873.3240$, [**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-



tion was performed for 1 h at 135 °C (Table S1,† entry 2). ^1H NMR analysis of the crude reaction mixture showed chemical shifts of the α -carbon protons as a function of the sulfur content within the polymer, which was consistent with the results of the model reaction performed for **M1** (refer Fig. S16 in the ESI†). Subsequently, additional aliquots of S_8 (*i.e.* 5.0 mol%) were added at a time interval of 30 min to the reaction mixture (Table S1†). Characterization *via* ^1H and ^{13}C NMR analyses of the crude reaction mixture after addition of 5.0, 25.0, 35.0 and 70.0 mol% aliquots of S_8 revealed the progressive insertion of elemental sulfur into the secondary disulfide-repeating unit *via* the sulfur exchange reaction (Fig. S17 and S18†). On the one hand, the magnetic resonance pattern observed in the ^1H NMR spectra of the crude reaction mixture after addition of 70.0 mol% S_8 disclosed a similar pattern consistent with the proof-of-concept molecule (Fig. 3). In other words, the upper limit of the sulfur atoms that can be introduced *via* the TBD mediated sulfur exchange reaction between each repeating unit of **P1** and S_8 was also 6 sulfur atoms, resulting in a maximum of 8 sulfur atoms per repeating unit. Furthermore, comparative analysis of ^{13}C NMR spectra (Fig. S18†) of the crude reaction mixtures after addition of 5.0, 25.0, 35.0 and 70.0 mol% aliquots of S_8 to **P1** indicated that the ester functional moiety remained intact (refer to 173.9 ppm and 64.2 ppm, respectively, at Fig. S18†), and the polymer did not undergo any depolymerization *via* thioesterification as one could have expected. On the other hand, SEC data clearly proved that the utmost amount attainable to polymer **P1** is 70.0 mol% S_8 (Fig. 2), resulting in a post-modified polymer with an apparent molar mass of 14 600 g mol^{-1} and with a dispersity of $D = 1.8$. Above this value, for instance at a loading of 75.0 mol% S_8 , the depolymerization of elemental sulfur started to compete with sulfur insertion, hence resulting in the degradation of the final polymer (refer Fig. S19 and Table S1 in the ESI†). As previously mentioned, this result proved that the sulfur exchange reaction was accelerated at higher sulfur loadings per disulfide bond (*i.e.* $x > 9$ sulfur atoms per disulfide bond), and depolymerization ensued, while at $x < 9$ sulfur atoms per disulfide bond, due to the dynamic S–S present in the polymer backbone, it was not unexpected to observe marginal differences in the molar mass of the elemental sulfur treated polymer. The latter was also consistent with the earlier studies of Pyun³⁹ and colleagues, who postulated that long chain polysulfides (with a high content of S–S bonds) are prone to thermally induced sulfur radical generation that is accompanied by fragmentation, and thus a decrease in the molar mass would be expected from the process.

Additional evidence for efficient sulfur insertion within the secondary disulfide bonds of **P1** was provided by detailed UV, IR, DOSY and elemental analysis. Intriguingly, the increased sulfur content in polymer **P1_S_70.0 mol%** resulted in a higher molar absorbance at a given wavelength and more red-shifted spectra in comparison with **P1**. Indeed, an absorption maximum at 260–330 nm became pronounced when the sulfur content increased in comparison with **M1** and **P1**, respectively



Fig. 5 UV-Vis spectra of **M1**, **P1** and **P1_S_70.0 mol%**. Sample concentrations were $1.23 \times 10^{-5} \text{ mmol mL}^{-1}$ (for **M1**) and $6.25 \times 10^{-2} \text{ mg mL}^{-1}$ (for **P1** and **P1_S_70.0 mol%**.) in THF. Solvent cut-off wavelengths λ_0 : 215 (λ_{max} : 220 nm in THF). For details, refer to the main text and the ESI.†

(Fig. 5). The IR spectra of the polymer before and after sulfur insertion (Fig. 4) showed the intact C=O stretching band of the ester functionality at 1736 cm^{-1} . Moreover, additional valence vibrations were observable at $495\text{--}512 \text{ cm}^{-1}$, associated with S–(S) $_x$ –S–. Furthermore, by evaluating the DOSY NMR measurements (Fig. S20 and S21 in the ESI†), particularly by applying the Stokes–Einstein equation (refer section B.2. in the ESI†), a hydrodynamic diameter of 6.5 nm for **P1** in CDCl_3 is determined. After sulfur insertion *via* the sulfur exchange reaction, the value increases by 90% to 11.9 nm for **P1_S_70.0 mol%**. The DOSY data were supported by the good agreement of the diffusion coefficients with each other (refer to Table S2†). Last but not least, elemental analysis confirmed the successful integration of sulfur atoms within the secondary disulfide bonds of polymer **P1** *via* the organocatalytic sulfur exchange reaction. The experimentally obtained values for **P1_S_70.0 mol%** (C: 56.30, H: 7.90, S: 28.20) compared to **P1** (C: 70.20, H: 9.85, S: 9.72) were in good agreement, reaffirming the fact that the sulfur exchange of **P1** with elemental sulfur (70.0 mol%) leads to the insertion of utmost six sulfur atoms in each –S–S– bond/repeating unit of the polyester derivatives.

In summary, we have pioneered the synthesis of a sustainable bio-based aliphatic polyester derivative that bears secondary disulfide groups in each repeating unit. We evidenced that this specific functionality enabled the introduction of high sulfur content (up to 6 additional sulfur atoms per disulfide bond of each repeating unit within the polymer) by virtue of the organocatalytically (*i.e.* TBD) triggered sulfur exchange reaction with elemental sulfur. The successful synthesis of the monomer **M1**, polymer **P1** and the sulfur-enriched polyester derivative **P1_S_70.0 mol%** was evidenced in depth *via* detailed analytical characterization by NMR, SEC, UV, IR, DOSY and elemental analysis. Hence, we believe that this powerful methodology could facilitate the synthesis of sustainable aliphatic polyesters with tailored functional properties (*e.g.* electrochemical, optical and chemical properties). Indeed, this



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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