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Remote regio- and stereocontrol by the sulfinyl group: Diels–Alder reaction of sulfinyl dienols and 8,8-dimethylnaphthalene-1,4,5(8*H*)-trione

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ABSTRACT

Diels–Alder cycloaddition of 8,8-dimethylnaphthalene-1,4,5(8*H*)-trione with diastereomeric hydroxysulfinyldienes proceeded with high yields and good π-facial and regioselectivities. The hydroxysulfoxide moiety controls the regio- and stereoselectivities, through hydrogen bonds in the suggested transition state.

1. Introduction

The Diels–Alder reaction constitutes as one of the most important tools for the synthesis of six-membered rings.[1,2] Depending on the substituents attached to the reactants, it is possible to achieve high regio- and stereoselectivity, thus controlling the absolute configuration of newly formed asymmetric centers.[3,4] Several elements such as chiral auxiliaries,[5] catalysts,[6] or solvents[7] have been used to achieve this. Non-classical techniques such as high pressure reactions or microwave synthesis have also been utilized.[8]

Among these elements, chiral sulfoxides constitute a very important group of compounds that has been increasingly used as chiral auxiliaries in asymmetric synthesis.[9] This group is considered as one of the most versatile chiral auxiliaries to build carbon–carbon and carbon–heteroatom bonds. The sulfinyl group is also present in many natural compounds with interesting biological properties.[10]

The sulfinyl group has been employed in asymmetric Diels–Alder reactions generally attached to the dienophile. In a seminal investigation,[11] the influence of a sulfinyl group bound directly to the dienophile system revealed that this group was not able to efficiently control the *endo*- and facial selectivity. The authors suggested the introduction of another electron-withdrawing group attached to the double bond to increase the reactivity and reduce the conformational degrees of freedom of the dienophile, to improve the sulfinyl's ability to act as a chiral inductor. Following this suggestion, over the past few decades, several examples of Diels–Alder reactions of dienophiles containing a sulfinyl and a second electron-withdrawing group have been reported.[12]

The remote stereocontrol caused by the chiral sulfinyl group in asymmetric DA reactions was recently investigated by Maestro et al.[13] The authors concluded that, as was the case for DA reactions where the chiral auxiliary was bound directly to the double bond, the sulfinyl group by itself was not able to control the selectivity of the reaction. A second electron-withdrawing group, attached to the diene, in addition to a chelating agent, was required to achieve the desired stereocontrol.

The result of attaching a sulfinyl group to the diene in asymmetric DA reactions has been less investigated.[14,15] Although the number of papers in this particular area has increased substantially over the last decade, the sulfinyl group was always attached directly to a diene system. In most cases, high *endo* and π-facial selectivities were observed. In a recent example of the DA cycloadditions of amido-2-sulfinyl-butadienes with *N*-phenylmaleimide (NPM), it was shown that the chiral sulfur atom was capable of controlling the diastereoselectivity of the process.[16]

To the best of our knowledge, there are no reports of Diels–Alder reactions with remote stereocontrol caused by a sulfinyl group not directly attached to the diene. Herein we report the synthesis of anthraquinone derivatives from a naphthoquinone and chiral α-hydroxy-β-sulfinyldienes. Reactions proceeded with good regio- and diastereoselectivities, that are governed by hydrogen-bond interactions in the transition state.

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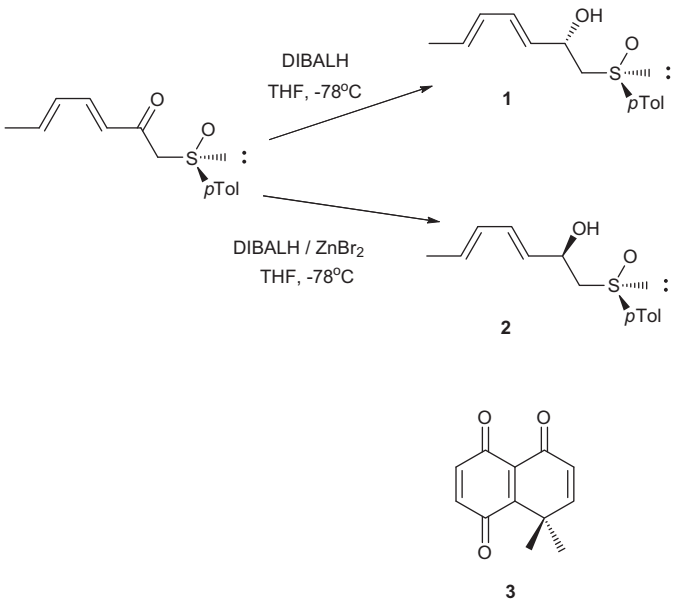
2. Results and discussion

The synthesis of diene **1** and naphthoquinone **3** has already been reported on.[17] Dienes were obtained by the stereoselective reduction of (*R*)-1-(*p*-tolylsulfinyl)-3,5-heptadien-2-one[18] (Scheme 1). When DIBALH was used, diene (2*S*,*SR*)-1-(*p*-tolylsulfinyl)-3,5-heptadien-2-ol **1** was obtained in 94 % yield and with a diastereomeric excess of >99%. When this reduction was carried out in the presence of $ZnBr_2$ (see Section 4), diene (2*R*,*SR*)-1-(*p*-tolylsulfinyl)-3,5-heptadien-2-ol **2** was obtained stereoselectively in 84% yield with a diastereomeric excess of 90%. Both products were further purified by column chromatography (silica gel), to obtain the enantiomerically pure dienes **1** and **2**.



Scheme 1. Preparation and structures of dienes **1** and **2**, and structure of naphthoquinone **3**.

The reaction of dienols **1** or **2** with naphthoquinone **3** was carried out in benzene at room temperature. The product mixture was enolized readily on silica, leading to a mixture of tricyclic hydroquinones **4**–**7** (Scheme 2).

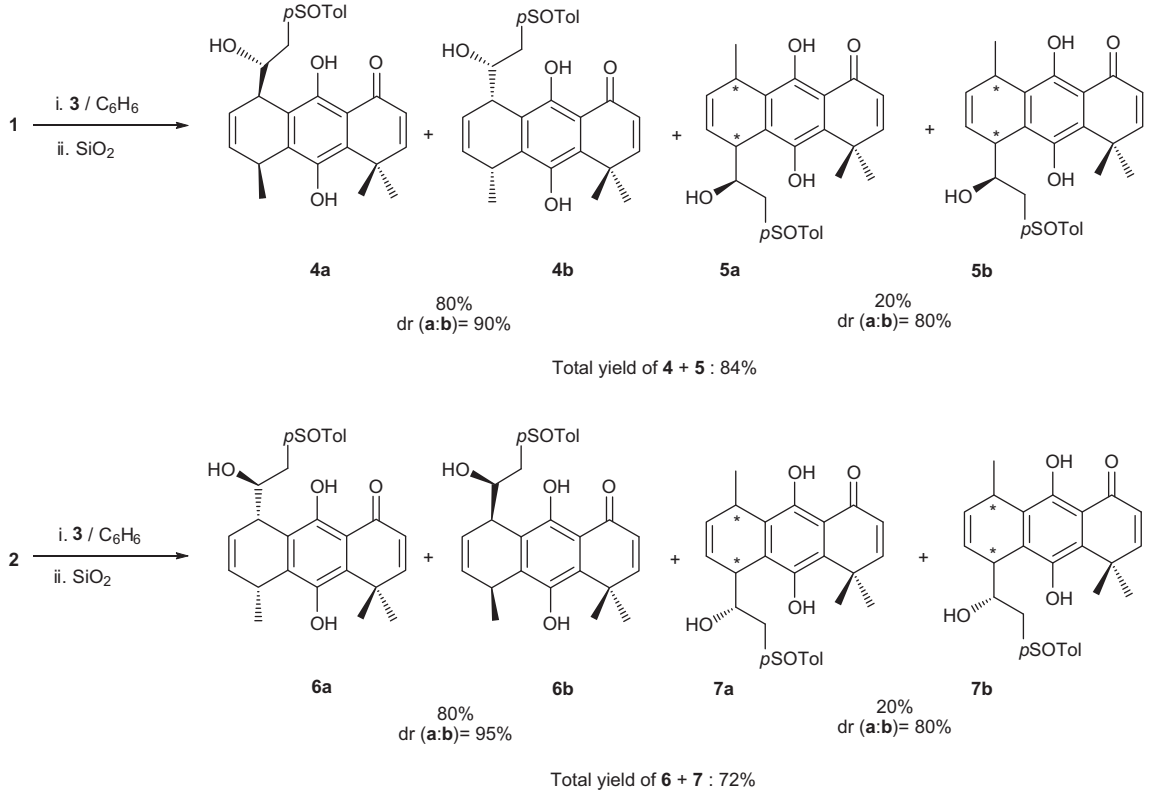
2.1. Characterization of the reaction products

The determination of the regioselectivity in both reactions was achieved by the analysis of the bidimensional NMR spectra (HMQC and HMBC) of each isolated product.

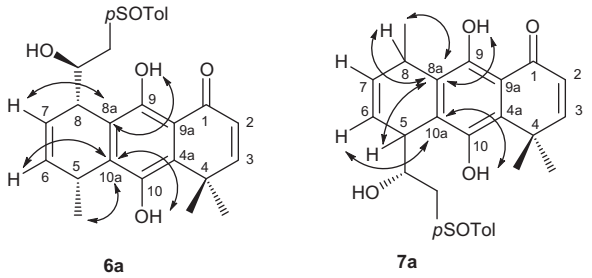
An important feature of this regiochemical assignment was the intramolecular hydrogen-bond between the C9 hydroxyl group and the carbonyl oxygen of C1. This allowed ready differentiation of the phenolic OH groups in the regioisomers **4**/**5** and **6**/**7**.

For example, in the HMBC spectrum of **6a**, the C10 hydroxyl proton at δ 4.73 correlated with a quaternary carbon atom (C10a), which showed another correlation with the methyl protons at δ 1.43 and with *H*-C6 (δ 6.10). In addition, another quaternary carbon (C8a) correlated simultaneously with the chelated hydroxylic proton (δ 13.39) at C9 and with *H*-C7 (δ 5.81) (Scheme 3).

In an analogous way, the regiochemistry of **7a** was established from the observed correlations between the chelated hydroxylic proton (δ 13.18) at C9 and the quaternary carbon C8a, and between the latter carbon atom and the methyl group at C8 (δ 1.37). In addition, the hydroxylic proton at C10 (δ 8.01) also correlated with the quaternary carbon atom C10a, which exhibited a correlation with *H*-C6 (δ 5.67) (Scheme 3).



Scheme 2. Reactions of sulfinyldienols **1** or **2** with naphthoquinone **3** and the corresponding products.



Scheme 3. Most important correlations observed in the HMBC spectra of compounds **6a** and **7a**.

Following a similar analysis, the regiochemistry of compounds **4**/**5** was established from the corresponding bidimensional NMR spectra.

X-ray analysis of compound **4a**, the major product of the reaction of **1** with **3**, led to the assignment of its stereogenic centers (Fig. 1).

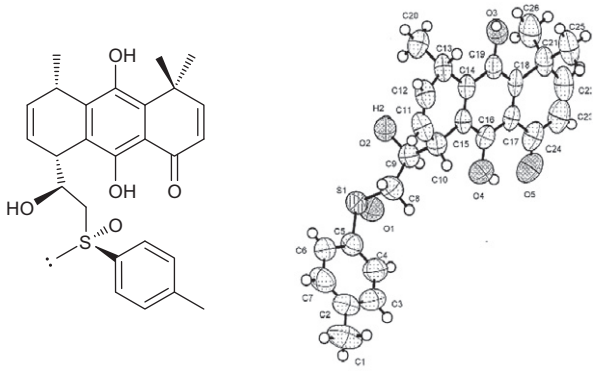


Figure 1. X-ray structure of compound **4a**.

In order to assign the absolute configurations of the stereogenic centers of **6a**, we next oxidized **4a** and **6a** to the corresponding sulfones, thus eliminating the homochiral sulfinyl group in each compound. The resulting sulfones possessed only three stereogenic centers, one of which was the hydroxylic carbon atom, while the other two, carbons C8 and C5, were formed in the Diels–Alder reaction. The requirement of a suprafacial process for the Diels–Alder reaction led to the expectation that these sulfones should be either enantiomers or diastereomers. NMR analysis of their spectra showed that the pair of sulfones were diastereomers, thus leading to the immediate assignment of the absolute configuration of **6a**, as shown in Scheme 2.

The absolute configurations of compounds **4b** and **6b** (Scheme 2) followed from the fact that they were both generated by the addition of naphthoquinone **3** to the other diastereotopic faces of dienes **1** and **2**, respectively.

Due to the fact that regioisomers **5** and **7** constituted only approximately 20% of the product mixture, their absolute configurations were not investigated further. Nevertheless, the relative proportions of the stereoisomeric pairs **5a**/**5b** and **7a**/**7b** could be obtained from analysis of the ^{1}H NMR spectrum of the product mixture, as described below.

2.2. Analysis of the cycloaddition selectivities

From our results, we were able to analyze the facial and regioselectivity of the Diels–Alder cycloaddition. This was based on the product yields, estimated from the integration of the signals assigned to the chelated protons of each compound, readily identified in all spectra (Fig. 2).

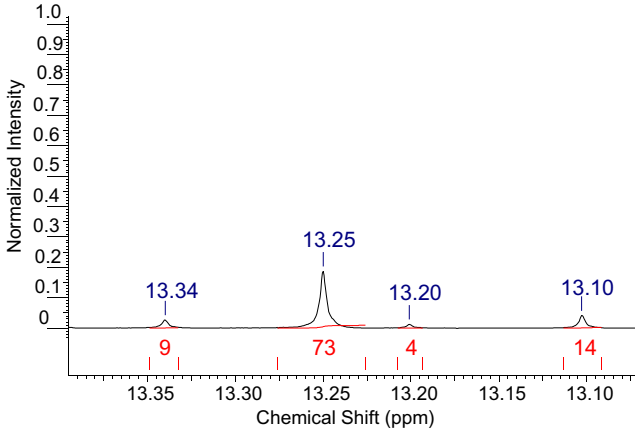


Figure 2. ^{1}H NMR signals assigned to the chelated protons of products **4a**, **4b**, **5a**, **5b** from the enolized reaction mixture of **1** and **3**.

The total yield of the products of the two cycloadditions was high, amounting to 84% for the conversion of **1** + **3** → → **4** + **5** and to 72% for the reaction **2** + **3** → → **6** + **7**. Both dienols **1** and **2** reacted with high regioselectivity, with an approximate proportion of regioisomers of 80:20. In addition, a high π-facial selectivity of the two major regioisomers **4a** and **6a** was observed, amounting to 90–95%.

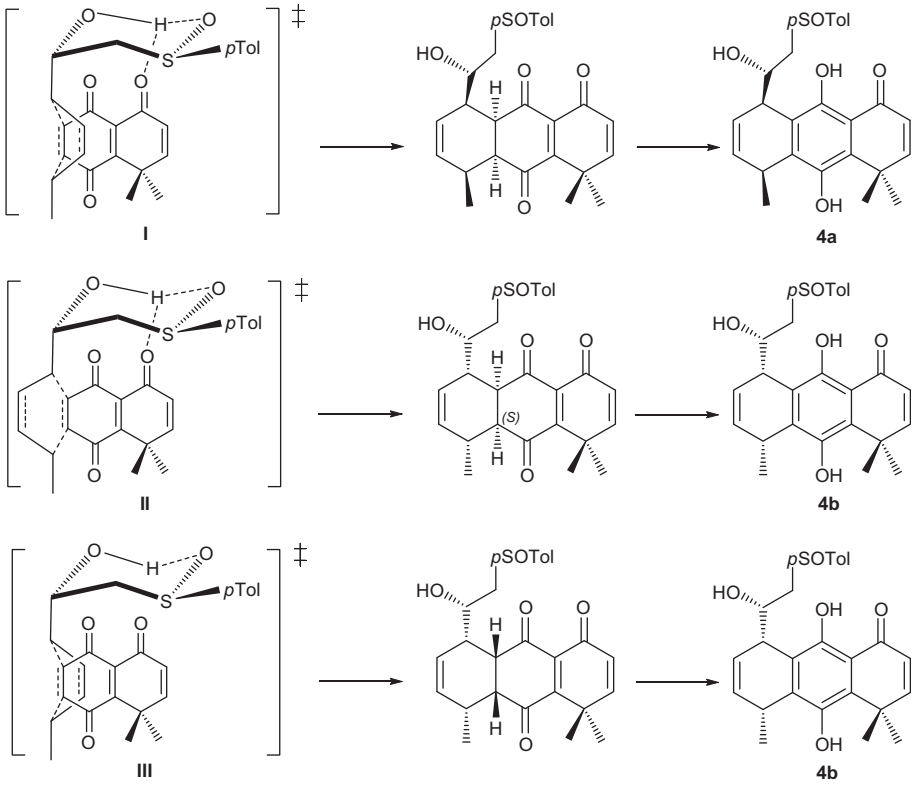
Although we did not determine the absolute configurations of the minor regioisomers **5** and **7**, the integrations of the signals assigned to their chelated protons allowed the estimation of their relative proportion of the pairs **5a**/**5b** and **7a**/**7b** in the mixture. In each pair, the major isomers, **5a** and **7a**, amounted to approximately 80%. Thus, a π-facial selectivity was observed in the formation of all regioisomers **4**/**6** and **5**/**7**. This observation was important in the analysis of the role of the remote sulfinyl group in the stereoselective cycloaddition.

The causes of such high selectivities were next investigated, by an analysis of the probable transition-state geometries of the reaction.

The observation that the major products of these cycloadditions were compounds **4a** and **6a** was consistent with a possible TS geometry where an intermolecular hydrogen-bond between the hydroxyl group of the diene and a carbonyl group of the naphthoquinone governed the approach of the dienophile to the diene. A similar argument had been used for the regioselectivity observed in the cycloaddition of naphthoquinone **3** with a primary dienol.[19] In all cases, the dienophile approaches the diene from the same face of its hydroxyl substituent. This is illustrated in Scheme 4, which describes the reaction of **1** with **3**. Similar arguments can be applied to the reaction of **2** with **3**, as discussed below.

It should be noted that the sulfinyldiene conformation shown in Scheme 4 is less stable than the one with an axial *S*-tolyl group and an equatorial dienyl chain, as proven by the ^{1}H NMR spectrum of compound **1**. Nevertheless, the proposed transition states depict in all cases the less stable conformer, since it allows an intermolecular hydrogen-bond between the diene and dienophile. This effect is absent in the TS's derived from the more stable conformer of **1** (scheme not shown), thus nicely illustrating the Curtin-Hammett principle.

Scheme 4-I depicts a possible geometry for the *endo*-approach of the diene to the dienophile, leading to the major isomer **4a**. It should be noted that the selective formation of this compound is



Scheme 4. Plausible TS geometries of the reaction of **1** with **3**: (I) *endo*-approach of the diene to the dienophile. (II) *exo*-approach of the diene to the dienophile. (III) *endo*-approach of the diene to the dienophile from the more sterically hindered face.

a consequence of two factors: the intermolecular hydrogen-bond between the OH group of the diene and the ketone group of the dienophile, and the presence of the chiral sulfinyl group, which is responsible for the observed high π-facial stereoselectivity. An intramolecular hydrogen bond between the S–O group and the hydroxylic proton has been described before in an NMR study of the preferred conformations of similar compounds.[20] In the case of the studied reaction, this hydrogen bond is responsible for the rather rigid conformations of the dienes **1** and **2**, leading to a high π-facial selectivity by the approaching dienophile, as shown in Scheme 4.

The formation of isomer **4b** in a smaller amount could be ascribed to the *exo*-approach of the diene to the dienophile (Scheme 4-II), a process which is normally less favoured in Diels–Alder cycloadditions. Alternatively, an *endo*-approach of the diene to the dienophile from the more sterically hindered face would also account for the formation of **4b** as the minor product (Scheme 4-III).

The above discussion rationalizes the selectivity in the formation of the major regioisomers **4**/**6**, and suggests two main factors for this result: the intermolecular OH–CO hydrogen-bond and the presence of the sulfinyl group forming an intramolecular hydrogen-bond with the OH group of the diene. The role of the latter in the high π-facial selectivity remains uncertain, because it could be argued that the intermolecular OH–CO bond would be enough to explain the observed selectivities.

Unequivocal evidence for the role played by the sulfinyl group is provided by the observation that the formation of the minor regioisomers **5** and **7** also exhibited a high π-facial selectivity. In this case, the formation of an intermolecular OH–CO bond is no longer possible, leaving the sulfinyl group as the only factor responsible for the observed selectivity.

For the reaction of **2** with **3**, similar arguments could be made to explain the observed selectivities. The most stable conformation of dienol **2** is also the one that allows the least sterically hindered approach of the dienophile, and the formation of an intermolecular hydrogen-bond in the transition state, in a very similar way to that suggested for the reaction of **1** with **3.** The regio- and π-facial selectivities for the reaction of **2** are also dependent on the intermolecular hydrogen-bond and the presence of the neighboring sulfinyl group, aspects which are common to both dienols.

3. Conclusions

Herein we have demonstrated that a sulfinyl group remotely attached to a diene is capable of controlling the stereoselectivity of a Diels–Alder reaction with one naphthoquinone, achieving high regio- and π-facial selectivities in the products. An additional structural requirement is the presence of a hydroxy substituent on the diene, allowing the formation of an intermolecular hydrogen-bond between the diene and dienophile in the transition state.

4. Experimental

4.1. General

Melting points were obtained with a Kofler hot-stage apparatus and are not corrected. IR spectra were recorded with a Nicolet Magna 550 FT-IR spectrometer. ^{1}H and ^{13}C NMR spectra were obtained with a Bruker Avance DRX-300. All chemical shifts in the NMR spectra are reported as ppm downfield from TMS. The following calibrations were used: $CDCl_3$ δ 7.26 and 77.00. Optical rotations were measured on a Perkin–Elmer 241 MC polarimeter. Commercially available starting materials and solvents were used without further purification. Silica gel 60 (70–230 mesh) and alu-Foil 60 F254 were used for column chromatography and analytical TLC, respectively. THF was dried using Na and benzophenone

under a nitrogen atmosphere. *i*-Pr_2NH was distilled from KOH. *n*-BuLi (2.5 M solution in hexanes) was purchased from Aldrich and was titrated with *N*-pivaloyl-*o*-toluidine[21] in THF every time it was used. (*SR*)-1-(*p*-tolylsulfinyl)-3,5-heptadien-2-one and (2*S*,*SR*)-1-(*p*-tolylsulfinyl)-3,5-heptadien-2-ol **1** were prepared as previously described.[17] The X-ray analysis data of compound **4a** were deposited at the Cambridge Crystallographic Data Centre and allocated the deposition number CCDC 898239.

4.2. (2*R*,*SR*)-1-(*p*-Tolylsulfinyl)-3,5-heptadien-2-ol 2

(*SR*)-1-(*p*-Tolylsulfinyl)-3,5-heptadiene-2-one (1.21 mmol) was dissolved in dry THF (5 mL) under nitrogen. A solution of $ZnBr_2$ (1.7 mmol) in dry THF (5 mL) was then added. The mixture was stirred for 30 min at 25 °C. The reaction mixture was then cooled to −78 °C and 3 mL of DIBALH (1.0 M in hexane) was added dropwise. The resulting mixture was stirred at this temperature for 45 min. Methanol (3 mL) was then added, and the reaction mixture was allowed to warm up to 25 °C. The solvent was removed with a rotary evaporator and a saturated aqueous solution of NH_4Cl (5 mL) was added to the residue. The resulting mixture was stirred for 15 min, extracted with ethyl acetate, and the organic extracts were dried over magnesium sulfate. The solvent was eliminated under reduced pressure and the residue was purified by column chromatography (AcOEt:Hex, 1:0.7). Yield: 62%, with 90%de $[\alpha]_D^{20} = +132$ (*c* 1.8, acetone); Mp: 85 °C. IR (KBr) (cm^{-1}): 3328, 3008, 2962, 2916, 2871, 1653, 1006, 812. ^1H NMR δ ($CDCl_3$ 300.13 MHz): 1.75 (d, 3H, *J* = 6.7 Hz), 2.42 (s, 3H), 2.80 (dd, 1H, *J* = 13.1 Hz, *J* = 2.9 Hz) 3.03 (dd, 1H, *J* = 13.1 Hz, *J* = 9.3 Hz); 3.65 (s, 1H), 4.81 (m, 1H), 5.53 (dd, 1H, *J* = 15.1 Hz, *J* = 6.4 Hz) 5.74 (m, 1H), 6.01 (dd, 1H, *J* = 15.0 Hz, *J* = 10.5 Hz), 6.28 (dd, 1H, *J* = 15.2 Hz, *J* = 10.4 Hz), 7.34 (d, 2H, *J* = 8.1 Hz), 7.55 (d, 2H, *J* = 8.2 Hz). ^{13}C NMR δ ($CDCl_3$, 75 MHz): 18.10, 21.40, 62.63, 69.22, 123.99, 129.67, 130.09, 130.30, 131.22, 131.95, 140.45, 141.96. HRMS (EI). Anal. Calcd for $C_{14}H_{17}OS$ (M-OH) 233.1000, found 233.0991.

4.3. Diels–Alder cycloadditions

General procedure: A solution of sulfinyldienol **1** or **2** (0.128 mmol) and dienophile **3** (0.128 mmol) in benzene (5 mL) was allowed to react at room temperature in the absence of light for one week. The course of the reaction was followed by TLC. Evaporation of the solvent left a residue, which did not contain any starting material, as shown by its ^1H NMR spectrum in $CDCl_3$. The residue was redissolved in benzene, after which silica gel (60 mg) was added, and the mixture was stirred overnight. The mixture was then filtered and the silica gel residue was washed with methanol. The combined filtrates were evaporated to yield a mixture of anthracenones, which underwent separation by semi-preparative thin-layer chromatography (AcOEt:Hex 1:2 as eluent). In this way, pure compounds **4a**, **4b**, **5a**, from sulfinyldienol **1,** and **6a**, **6b**, **7a** from sulfinyldienol **2,** were obtained. In addition minor products **5b,** from sulfinyldienol **1,** and **7b** from sulfinyldienol **2**, were also isolated with some contamination, which did not preclude identification by their ^1H NMR spectra. These products were characterized by their IR, ^1H and ^{13}C NMR spectra as follows.

4.3.1. (5*S*,8*R*)-9,10-Dihydroxy-8-{(1*S*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 4a

Mp: 234–236 °C. IR (KBr) (cm^{-1}): 3431, 2925, 1598, 1423. ^1H NMR δ ($CDCl_3$, 300.13 MHz): 1.35 (d, 3H, *J* = 7.0 Hz), 1.58 (s, 3H), 1.64 (s, 3H), 2.42 (s, 3H), 2.86 (dd, 1H, *J* = 2.0 Hz, *J* = 13.0 Hz), 3.18 (dd, 1H, *J* = 10.0 Hz, *J* = 13.0 Hz), 3.42 (m, 2H), 3.82 (m, 1H), 4.52 (m, 1H), 4.61 (m, 1H), 5.94 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 6.12 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 6.23 (d, 1H, *J* = 10.0 Hz), 6.82 (d, 1H, *J* = 10.0 Hz), 7.32 (d, 2H, *J* = 8.0 Hz), 7.51 (d, 2H, *J* = 8.0 Hz), 13.25 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz): 21.56, 25.06, 25.27, 30.45, 38.18, 40.56, 60.45, 68.36, 113.07, 121.60, 123.21, 123.94, 124.15, 129.97, 130.00, 132.95, 133.17, 137.69, 141.50, 142.80, 154.7, 161.14, 191.13. Anal. Calcd for $C_{26}H_{28}O_5S$: C, 69.00; H, 6.24; S, 7.08. Found C, 68.25; H, 6.41; S, 6.39.

4.3.2. (5*S*,8*R*)-9,10-Dihydroxy-8-{(1*S*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 4b

^1H NMR δ ($CDCl_3$, 300.13 MHz): 1.38 (d, 3H, *J* = 7.0 Hz), 1.57 (s, 3H), 1.63 (s, 3H), 2.35 (s, 1H), 2.38 (s, 3H), 2.67 (dd, 1H, *J* = 1.0 Hz, *J* = 13.0 Hz), 3.08 (dd, 1H, *J* = 11.0 Hz, *J* = 13.0 Hz), 3.45 (m, 1H), 3.94 (m, 1H), 4.66 (m, 1H), 5.92 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 6.12 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 6.21 (d, 1H, *J* = 10.0 Hz), 6.84 (d, 1H, *J* = 10.0 Hz), 7.34 (d, 2H, *J* = 8.0 Hz), 7.39 (d, 2H, *J* = 8.0 Hz), 13.34 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz): 21.36, 21.80, 25.14, 25.23, 30.40, 38.17, 60.95, 69.52, 113.05, 121.59, 123.68, 123.89, 124.50, 129.83, 131.84, 133.62, 136.43, 139.85, 141.23, 143.12, 154.32, 161.20, 190.95.

4.3.3. 9,10-Dihydroxy-5-{(1*S*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 5a

Mp: 198–201 °C. IR (KBr) (cm^{-1}): 3418, 2924, 1651, 1601.^1H NMR δ ($CDCl_3$, 300.13 MHz): 0.74 (d, 3H, *J* = 7.0 Hz), 1.58 (s, 3H), 1.65 (s, 3H), 2.40 (s, 1H), 2.80 (d, 1H, *J* = 14.0 Hz), 3.53 (d, 1H, *J* = 14.0 Hz), 3.65 (m, 1H), 3.87 (m, 2H), 5.70 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 6.04 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 6.15 (s, 1H), 6.23 (dd, 1H, *J* = 1.0 Hz, *J* = 10.0 Hz), 6.84 (dd, 1H, *J* = 1.0 Hz, *J* = *J* = 10.0 Hz), 7.33 (d, 2H, *J* = 8.0 Hz), 7.40 (d, 2H, *J* = 8.0 Hz), 7.99 (s, 1H), 13.15 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz):21.35, 21.43, 25.02, 25.45, 29.45, 38.44, 41.65, 55.06, 76.36, 113.53, 122.62, 124.01, 130.26, 134.36, 134.84, 136.20, 136.78, 142.04, 144.95, 153.98, 161.72, 191.57. Anal. Calcd for $C_{26}H_{28}O_5S$: C, 69.00; H, 6.24; S, 7.08. Found: C, 68.14; H, 6.61; S, 6.53.

4.3.4. 9,10-Dihydroxy-5-{(1*S*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 5b

^1H NMR δ ($CDCl_3$, 300.13 MHz): 1.32 (d, 3H, *J* = 7.0 Hz), 1.56 (s, 3H), 1.68 (s, 3H), 2.47 (s, 3H), 2.61 (d, 1H, *J* = 14.0 Hz), 2.93 (dd, 1H, *J* = 11.0 Hz, *J* = 14.0 Hz), 3.65 (m, 1H), 4.02 (m, 1H), 4.40 (d, 1H, *J* = 11.0 Hz), 5.36 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 5.91 (dd, 1H, *J* = 5.0 Hz, *J* = 10.0 Hz), 6.23 (d, 1H, *J* = 10.0 Hz), 6.66 (s, 1H), 6.85 (d, 1H, *J* = 10.0 Hz), 7.40 (d, 2H, *J* = 8.0 Hz), 7.45 (d, 2H, *J* = 8.0 Hz), 9.23 (s, 1H), 13.21 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz):20.73, 21.50, 24.99, 25.23, 29.63, 38.54, 42.66, 52.63, 72.49, 113.96, 122.23, 123.81, 124.16, 127.49, 130.08, 130.37, 133.91, 134.26, 136.78, 142.18, 145.41, 153.99, 161.99, 191.61.

4.3.5. (5*R*,8*S*)-9,10-Dihydroxy-8-{(1*R*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 6a

$[\alpha]_D^{20} = +84$ (*c* 1.79, acetone) Mp: 144–147 °C. IR (KBr) (cm^{-1}) 3416, 3020, 2959, 2937, 1651, 1597, 1029, 809. ^1H NMR δ ($CDCl_3$, 300.13 MHz): 1.43 (d, 3H, *J* = 7.0 Hz), 1.58 (s, 3H), 1.63 (s, 3H), 2.42 (s, 3H), 2.98(dd, 1H, *J* = 12.9 Hz, *J* = 2.1 Hz), 3.17 (dd, 1H, *J* = 12.9 Hz, *J* = 10.4 Hz), 3.45(m, 1H), 3.56 (d, 1H, *J* = 4.1 Hz), 3.82 (m, 1H), 4.59 (m, 1H), 4.73 (s, 1H), 5.81 (dd, 1H, *J* = 9.9 Hz, *J* = 5.0 Hz), 6.10 (dd, 1H, *J* = 10.1 Hz, *J* = 5 Hz), 6.23 (d, 1H, *J* = 10.0 Hz), 6.82 (d, 1H, *J* = 10.1 Hz), 7.33 (d, 2H, *J* = 8.2 Hz), 7.56 (d, 2H, *J* = 8.3 Hz), 13.39 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz): 21.45, 21.51, 25.03, 25.28, 30.44, 38.19, 40.95, 62.00, 69.75,

113.08, 121.94, 122.92, 123.85, 124.26, 130.09, 133.35, 133.40, 137.10, 140.32, 140.02, 142.98, 154.14, 161.27, 191.22. HRMS (ESI-MS): Anal. clacd. for $C_{26}H_{29}O_5S$ $(M+H)^+$ 453.1711 found 453.1711.

4.3.6. (5*S*,8*R*)-9,10-Dihydroxy-8-{(1*R*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 6b

Mp: 99 °C (dec). IR (KBr) (cm^{-1}): 3411, 3260, 3040, 2960, 2927, 1655, 1598, 1034, 809. ^1H NMR δ ($CDCl_3$, 300.13 MHz): 1.18 (d, 3H, J = 7.2 Hz), 1.58 (s, 3H), 1.64 (s, 3H), 2.38 (s, 3H), 2.81(dd, 1H, J = 12.8 Hz, J = 1.7 Hz), 3.20 (dd, 1H, J = 12.8 Hz, J = 9.3 Hz), 3.43 (m, 1H), 4.10 (m, 1H), 4.22 (m, 2H), 4.60 (s, 1H), 5.99 (dd, 1H, J = 9.8 Hz, J = 4.3 Hz), 6.03 (dd, 1H, J = 9.9 Hz, J = 4.2 Hz), 6.26 (d, 1H, J = 10.1 Hz), 6.85 (d, 1H, J = 10.1 Hz), 7.27 (d, 2H, J = 8.2 Hz), 7.51 (d, 2H, J = 8.2 Hz), 13.58 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz): 21.42, 21.78, 25.07, 25.25, 30.34, 38.18, 40.52, 62.39, 72.27, 113.22, 122.04, 123.91, 124.33, 124.83, 129.95, 131.73, 133.64, 136.36, 140.54, 141.78, 143.16, 154.35, 161.25, 191.12. HRMS (ESI-MS): Anal. Calcd for $C_{26}H_{28}O_5NaS$ $(M+Na)^+$ 475.1549, found 475.1538.

4.3.7. 9,10-Dihydroxy-5-{(1*R*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 7a

Mp: 248 °C. IR (KBr) (cm^{-1}): 3377, 3020, 2925, 2854, 1655, 1599, 1077, 804.^1H NMR δ ($CDCl_3$, 300.13 MHz): 1.37 (d, 3H, J = 7 Hz), 1.57 (s, 3H), 1.65 (s, 3H), 2.45 (s, 3H), 3.09 (dd, 1H J = 13.1 Hz, J = 9.5 Hz), 3.14 (dd, 1H, J = 12.9 Hz, J = 2.0 Hz), 3.80 (m, 2H), 4.32 (ddd, 1H, J = 9.6 Hz, J = 9.6 Hz, J = 1.9 Hz), 5.67 (dd, 1H, J = J = 9.7 Hz, J = 5.5 Hz), 6.02 (s, 1H), 6.22 (d, 1H, J = 10.1 Hz), 6.24 (dd, 1H, J = 9.6 Hz, J = 5.5 Hz), 6.82 (d, 1H, J = 10.0 Hz), 7.39 (d, 2H, J = 8.2 Hz), 7.60 (d, 2H, J = 8.2 Hz), 8.01 (s, 1H), 13.18 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz): 21.51, 22.37, 25.04, 25.47, 29.82, 38.42, 42.12, 59.14, 78.34, 113.61, 122.62, 123.90, 123.93, 127.68, 130.46, 134.32, 134.42, 136.83, 139.90, 142.81, 145.00, 154.13, 161.61, 191.52. HRMS (ESI-MS): Anal. Calcd for $C_{26}H_{28}O_5NaS$ $(M+Na)^+$ 475.1549, found 475.1547.

4.3.8. 9,10-Dihydroxy-5-{(1*R*)-1-hydroxy-2-[(4-methylphenyl)-(*R*)-sulfinyl]ethyl}-4,4,5-trimethyl-5,8-dihydro-1(4*H*)-anthracenone 7b

Mp: 199–202 °C. IR (KBr) (cm^{-1}): 3421, 3072, 2956, 2929, 1656, 1596, 1066, 813. ^1H NMR δ ($CDCl_3$, 300.13 MHz): 1.17 (d, 3H, J = 7.0 Hz), 1.55 (s, 3H), 1.64 (s, 3H), 2.37 (s, 3H), 2.40 (dd, 1H, J = 13.0 Hz, J = 10.7 Hz), 2.94 (dd, 1H, J = 13.0 Hz, J = 0.8 Hz), 3.65 (m, 1H), 4.20 (m, 1H), 4.79 (m, 1H), 5.78 (ddd, 1H, J = 9.9 Hz, J = 4.5 Hz, J = 0.8 Hz), 5.96 (s, 1H), 6.08 (ddd, 1H, J = 9.8 Hz, J = 5.0 Hz, J = 1.0 Hz), 6.19 (d, 1H, J = 9.9 Hz), 6.82 (d, 1H, J = 10.1 Hz), 7.28 (d, 2H, J = 8.1 Hz), 7.38 (d, 2H, J = 8.2 Hz), 9.10 (s, 1H), 13.13 (s, 1H). ^{13}C NMR δ ($CDCl_3$, 75 MHz): 20.64, 21.41, 24.86, 25.19, 29.67, 38.48, 42.45, 56.22, 74.54, 113.95, 122.57, 123.40, 123.73, 127.50, 129.56, 130.40, 133.85, 134.87, 139.23, 142.48, 145.30, 153.84, 161.96, 191.55. HRMS (ESI-MS): Anal. Calcd for $C_{26}H_{28}O_5NaS$ $(M+Na)^+$ 475.1549, found 475.1545.

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