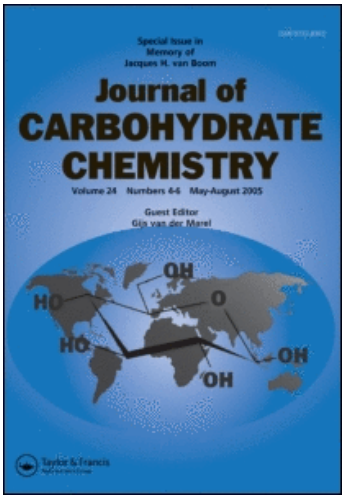

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Selective Oxidation of Glycosyl Sulfides to Sulfoxides with Sodium Hypochlorite and Catalyzed by Metalloporphyrins

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Selective Oxidation of Glycosyl Sulfides to Sulfoxides with Sodium Hypochlorite and Catalyzed by Metalloporphyrins

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An efficient and selective method for oxidation of glycosyl sulfides to the corresponding glycosyl sulfoxides with metalloporphyrins as catalysts and sodium hypochlorite as oxidant was achieved under mild conditions. High chemoselectivity and diastereomeric excesses were obtained. Both acid-labile protected groups and carbon–carbon double bonds of allyl groups tolerated under these conditions.

Keywords Oxidation; Glycosyl sulfide; Glycosyl sulfoxide; Sodium hypochlorite; Metalloporphyrin

INTRODUCTION

Sulfoxides are versatile synthetic intermediates in stereocontrol chemistry.[1] They can be used to prepare chemically and biologically significant molecules,[2] including therapeutic agents such as antiulcer (proton pump inhibitor),[3] antibacterial,[4] antifungal,[5] antiatherosclerotic,[6] antihypertensive,[7] cardiotonic,[8] psychotropic,[9] and vasodilator agents.[10] In carbohydrate chemistry, glycosyl sulfoxides have been extensively used as important glycosyl donors, which were commonly activated by Tf_2O in acid scavengers

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such as 2,6-di-*tert*-butyl-4-methylpyridine (DTBMP).[11] This glycosylation method has been developed as an important strategy for the preparation of oligosaccharides[12] and glycoconjugates,[13] owing to its noticeable advantages including mild reaction conditions, high donor activity, and excellent anomeric stereocontrol.[14] The glycosylation with glycosyl sulfoxides as donors could readily take place at low temperature, even in the presence of electron-withdrawing protecting groups.[14a,14b] They could be applied not only for the solution-phase synthesis,[11–15] but also for the solid-phase synthesis of oligosaccharides.[16] Besides being used as glycosyl donors, glycosyl sulfoxides could also be converted to glycosyl carbanions, which are very useful in the stereospecific construction of C-glycosides, via sulfinyl-lithium exchange.[17]

The versatility of sulfoxides as organic reagents[18] and the high activity of glycosyl sulfoxides as donors[11–15] continually motivate the development of efficient synthesis methods for sulfoxides and glycosyl sulfoxides.[11] Although many methods for the synthesis of sulfoxides have been investigated, selective oxidation of glycosyl sulfides to glycosyl sulfoxides still remains a challenging task.[19] As one of the most successful methods, the oxidation of glycosyl sulfides to sulfoxides was primarily achieved with *m*-CPBA (*m*-chloroperbenzoic acid) in CH_2Cl_2.[19] However, this method suffers from some shortcomings, such as the application of very low temperature to avoid overoxidation of sulfoxides to sulfones and insolubility of *m*-CPBA in the reaction medium. In addition, it is difficult to completely remove the byproduct *m*-chlorobenzoic acid from sulfoxides. Therefore, new oxidation protocols with mild reaction conditions and convenient workup are needed. In recent years, some efficient methods have been developed to meet these requirements, such as $H_2O_2/Ac_2O/SiO_2$ in CH_2Cl_2,[19d] H_2O_2 in hexafluoro-2-propanol (HFIP) under neutral conditions,[19c] silica gel-supported oxone,[19a] *tert*-butyl hydroperoxide (TBHP),[20] and magnesium monoperoxyphthalate (MMPP) as an oxidant under microwave irradiation.[19b] Ultrasound was also used to enhance the rate and selectivity of the oxidation toward sulfoxides.[21]

Metalloporphyrins have been widely used as biomimetic catalysts for oxidation during the past decades,[22] combining with various oxygen sources, such as PhIO, NaOCl, H_2O_2, ROOH, $KHSO_5$, O_2, and electrons.[23] Fe- and Mn-porphyrin complexes were developed to be effective catalysts for the transfer of oxygen atoms with the formation of sulfoxides from sulfides.[24] Drago and coworkers have demonstrated that manganese tetrakis(phenyl)porphyrin (MnTPPCl) is capable of catalyzing the oxidation of *n*-butyl sulfide to corresponding sulfoxide by NaOCl in a biphasic system.[25] The addition of MnTPPCl led to the complete conversion of *n*-butyl sulfide and made a sixfold increase in initial rate. However, in addition to *n*-butyl sulfide and MnTPPCl, other sulfides and metalloporphyrins have not been investigated. Recently, iron tetrakis(pentafluorophenyl)porphyrin has been used as a catalyst for the oxidation of sulfides with hydrogen peroxide, for which high yields and

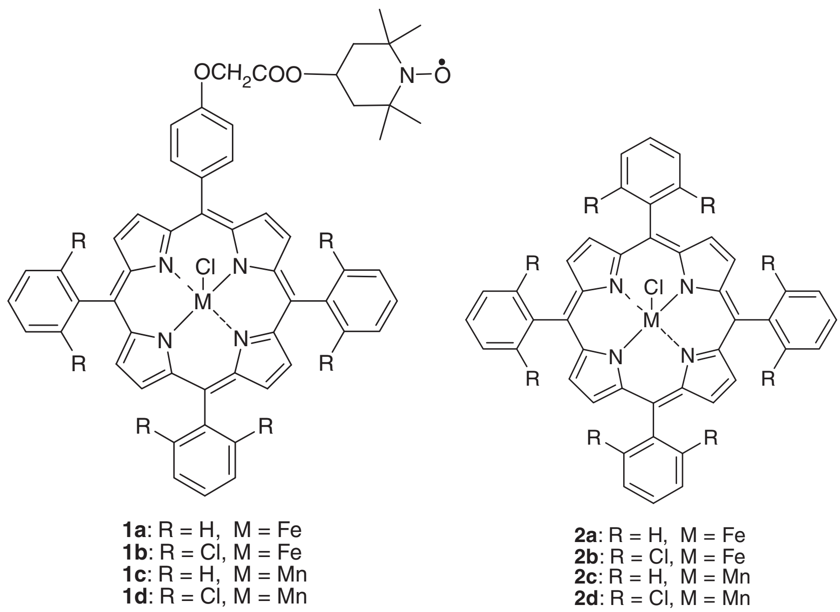


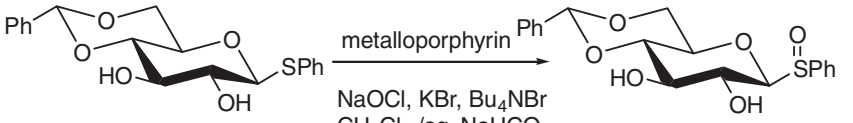
Figure 1: TEMPO-linked porphyrins and porphyrin complexes.

chemoselectivities were obtained.[24] Our group has reported the selective oxidation of alcohols and sulfides with TEMPO-linked metalloporphyrins (Fig. 1) as efficient catalysts using NaOCl as oxidant.[26] In view of the continual interest in glycosyl sulfoxides,[11] it is worthwhile to carry out the further work extension of the metalloporphyrin-catalyzed oxidation methodology to the oxidation of glycosyl sulfides. Best of all, compared with reported approaches, this method let the reaction system be homogeneous and almost neutral. Herein, we report the detailed investigation on the selective oxidation of a variety of sensitive functional group-containing glycosyl sulfides to glycosyl sulfoxides with metalloporphyrins as catalysts using NaOCl as oxidant.

RESULTS AND DISCUSSION

Initially glycosyl sulfide **3a** was chosen as the model substrate. Reactions were carried out in a two-phase system (dichloromethane/saturated aq. $NaHCO_3$) in the presence of metalloporphyrins, tetrabutylammonium bromide, and potassium bromide at 0°C to 25°C for 1.5 h. Oxidation of glycosyl sulfide **3a** afforded the corresponding sulfoxide **4a** and all metalloporphyrins gave the same anomeric isomer ratio (10:1) (Table 1, entry 1). As shown in Table 1, commercially available Mn-porphyrin complexes, such as MnTPPCl and Mn(TDCPP)Cl (Fig. 1), exhibited high catalytic activities for selective

Table 1: Metalloporphyrin-catalyzed oxidation of sulfide **3** with NaOCl[a].



3a **4a**

(isomer ratio = 10 : 1)

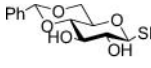
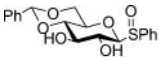
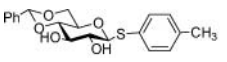
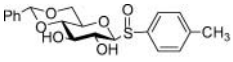
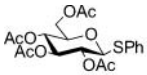
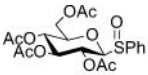
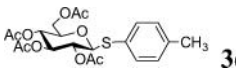
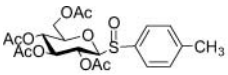
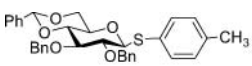
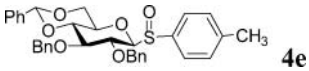
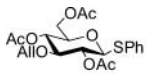
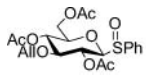
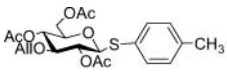
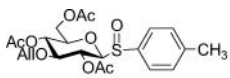
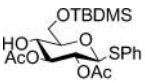
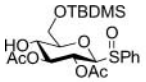
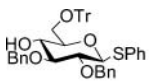
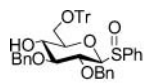
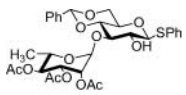
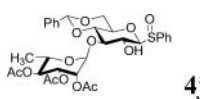
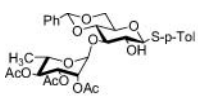
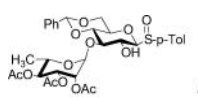
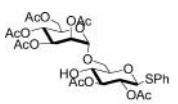
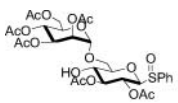
Entry	Catalyst	Catalyst (mol%)	Yield (%)[b,c]
1	**1a**	1	50
2	**1b**	1	62
3	**1c**	1	81
4	**1d**	1	86
5	Mn(TPP)Cl	1	78
6	Mn(TDCPP)Cl	0.1	83
7	Mn(TDCPP)Cl	0.5	87
8	Mn(TDCPP)Cl	1	84
9	Mn(TDCPP)Cl	3	74 (6)
10	Fe(TPP)Cl	0.5	70
11	Fe(TDCPP)Cl	0.5	79
12	None	—	15

[a]Compound **3a** (1 mmol) was oxidized by NaOCl (1.25 mmol) in the presence of metalloporphyrins, KBr (10 mol%), and Bu_4NBr (5 mol%) in CH_2Cl_2/saturated aq. $NaHCO_3$ = 1:1 (10 mL) at 0°C for 1 h.
[b]Isolated yields.
[c]The yield of sulfone is in parentheses.

oxidation of sulfides as well as TEMPO-linked Mn-porphyrins and TEMPO-linked Fe-porphyrins (Fig. 1), which were synthesized according to the published method.[26] The complexes of chlorinated porphyrin ligand and TEMPO-linked Mn-porphyrins have higher catalytic activity, while the Fe complexes with porphyrin and TEMPO-linked porphyrin ligands gave lower yields (Table 1, entries 1, 2, 10, and 11) than the corresponding Mn complexes (Table 1, entries 3–9). The amount of catalyst was also examined (Table 1, entries 6–9). When the amount of Mn(TDCPP)Cl was increased from 0.1 mol% to 0.5 mol%, a slightly higher yield was given, whereas further increasing the amount of catalyst from 0.5 mol% to 1 mol% led to a slight reduction in yield. When the catalyst was increased to 3 mol%, a part of sulfide was overoxidated to sulfone and a lower yield was given (Table 1, entry 9).

The other glycosyl sulfides with various types of protecting groups were further investigated to examine the generality of this oxidation protocol. Although TEMPO-linked Mn-porphyrins were efficient catalysts as was Mn(TDCPP)Cl (Table 1, entries 3, 4, and 7–9), Mn(TDCPP)Cl was used for the oxidation of these glycosyl sulfides because it is much easier to be prepared. The results are shown in Table 2. Glycosyl sulfides were observed to undergo

Table 2: Oxidation of glycosyl sulfides to sulfoxides[a].

Entry	Substrate	Sulfoxide	Yield (%)[b,c]	Time (min)[d]
1	 **3a**	 **4a**	87 (10:1)	70
2	 **3b**	 **4b**	89 (1:0)	70
3	 **3c**	 **4c**	89 (1:0)	90
4	 **3d**	 **4d**	93 (1:0)	90
5	 **3e**	 **4e**	97 (7:1)	75
6	 **3f**	 **4f**	84 (1:0)	90
7	 **3g**	 **4g**	87 (1:0)	90
8	 **3h**	 **4h**	80 (1:0)	75
9	 **3i**	 **4i**	85 (1:0)	60
10	 **3j**	 **4j**	80 (1:0)	75
11	 **3k**	 **4k**	83 (1:0)	75
12	 **3l**	 **4l**	81 (1:0)	75

[a]Different sulfide (1 mmol) was oxidized by NaOCl (1.25 mmol) in the presence of Mn(TDCPP)Cl (0.5 mol%), KBr (10 mol%), and Bu_4NBr (5 mol%) in CH_2Cl_2/saturated aq. $NaHCO_3$ = 1:1 (10 mL) at 0°C for 1 h.
[b]Isolated yields.
[c]The diastereomer ratios of glycosyl sulfoxides are in parentheses.
[d]By monitoring the disappearance of the starting material glycosyl sulfides with TLC.

smooth oxidation to the corresponding sulfoxides, with yields of over 80%. For all of these sulfides no overoxidation to sulfone was found. Various protecting groups and hydroxyl groups were not affected during the procedure. Compared with the method using *m*-CPBA as oxidant, acid-labile protecting groups, such as TBDMS, Tr, and benzylidene, were stable under the reaction conditions (Table 2, entries 1, 2, 5, and 8–11). Interestingly, by monitoring the disappearance of the starting material glycosyl sulfides with TLC during oxidation procedure, polar substrates underwent faster oxidation (Table 2, entries 1, 2, and 8–12), which may be due to their higher solubility in water. The electronic effect of the protecting groups on the C-2 of the glycosyl sulfides also influenced the reaction rates. Electron-donating groups (e.g., ethers) on C-2 resulted in much higher reaction rates than electron-withdrawing groups (e.g., ester). In the case of benzyl sulfides (Table 2, entries 5 and 9), no oxidation was observed at the benzylic C—H bonds. The carbon-carbon double bonds in the allyl group also tolerated the oxidation of NaOCl (Table 2, entries 6 and 7). It was noted that the yields for *p*-methyl-phenyl glycosyl sulfoxides were higher than for phenyl glycosyl sulfoxides due to the electron-donating effect of methyl. This protocol was applied for the oxidation of disaccharide sulfides (Table 2, entries 10–12). Good chemoselectivities and yields were obtained.

The oxidation of glycosyl sulfides may lead to two diastereoisomeric products because the prochiral sulfur center could accept the oxygen from two different sides.[12] And these diastereoisomeric glycosyl sulfoxides may have an impact on further glycosylation due to steric hindrance. It is interesting that the metalloporphyrin-catalyzed oxidation method gave high diastereomeric excesses of the corresponding glycosyl sulfoxides. For most of glycosyl sulfides, only one isomer was observed. Oxidation of glycosyl sulfides **3a** and **3e** gave high diastereomeric ratios, 10:1 (Table 2, entry 1) and 7:1 (Table 2, entry 5), respectively. It has been reported that **3g** was oxidized to glycosyl sulfoxide **4g** with 1:1 diastereomeric ratio when magnesium monoperoxyphthalate (MMPP) was used as oxidant.[19b] Here only one configuration of **4g** was obtained (Table 2, entry 7). It is reasonable to assume that the oxidation proceeds through the metal-oxo species and the bulky porphyrin leads to the high diastereomeric excesses.

CONCLUSION

We developed an efficient and selective method for oxidation of glycosyl sulfides to the corresponding glycosyl sulfoxides with metalloporphyrins as catalysts and sodium hypochlorite as oxidant. The oxidation was achieved in high yields and various *O*-protecting groups were not affected under these reaction conditions. Using this protocol, the overoxidation to sulfone can be prevented and high diastereoisomeric excesses were obtained.

EXPERIMENTAL

All reagents were purchased from commercial suppliers and used as received. Disaccharide sulfides were prepared according to the published procedures.[27] NMR spectra were recorded on a Bruker Advance DMX 500 spectrophotometer or Varian Unity INOVA-400 spectrophotometer using the deuterated solvent as the lock and the residual solvent or TMS as the internal reference. Low-resolution electrospray ionization mass spectra (ESI-MS) were recorded on a Bruker Esquire 3000 Plus spectrometer (Bruker-Franzen Analytik GmbH Bremen, Germany) equipped with an ESI interface and ion trap analyzer. High-resolution mass spectra (HRMS) were obtained on a Bruker 7-tesla FT-ICRMS equipped with an electrospray source (Billerica, MA, USA).

General Procedure for the Oxidation of Sulfides to Sulfoxides

To a stirred solution of the sulfides (1.0 mmol) and the catalyst metalloporphyrins (0.005 mmol) in CH_2Cl_2 (8 mL), Bu_4NBr (0.05 mmol) and a saturated aqueous $NaHCO_3$ (5 mL) containing KBr (0.1 mmol) were added. Then, to this cooled (0°C) and well-stirred mixture, a solution of 0.73 M NaOCl (0.91 mL, 1.25 mmol) in saturated aq. $NaHCO_3$ was added dropwise over a period of 10 min. The mixture was stirred for a further 1 h at 0°C and 0.5 h at rt, and the organic phase was separated. The aqueous phase was extracted with CH_2Cl_2 (3×5 mL) and the organic solution was combined, washed with H_2O, brine, dried over anhydrous Na_2SO_4, and filtered. The solvent was removed in vacuo and the residue was purified by chromatography on silica gel with ethyl acetate/hexane as an eluent to afford the pure products.

4a[26]

White solid, mp: 90–92°C; ^{1}H NMR (400 MHz, $CDCl_3$): δ 7.78–7.70 (m, 2H), 7.59–7.48 (m, 3H), 7.48–7.41 (m, 2H), 7.32–7.20 (m, 3H), 5.55 (s, 1H), 4.31 (s, 1H), 4.28–4.19 (m, 2H), 4.12 (d, $J = 9.4$ Hz, 1H), 3.92 (t, $J = 9.6$ Hz, 1H), 3.75 (t, $J = 10.3$ Hz, 1H), 3.62 (t, $J = 9.4$ Hz, 1H), 3.45–3.30 (m, 1H), 3.02 (s, 1 H); ^{13}C NMR (125 MHz, $CDCl_3$): δ 68.3, 71.0, 73.4, 74.4, 79.7, 93.8, 102.2, 124.8, 126.5, 128.6, 129.5, 129.6, 132.3, 136.9, 141.6; ESI-MS: $m/z = 399$ ($[M + Na]^+$), 775 ($[2M + Na]^+$). Isomer, white solid, mp: 94–96°C; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.95–7.93 (d, $J = 7.6$ Hz, 2H), 7.74 (t, $J = 7.5$ Hz, 1H), 7.63–7.60 (m, 2H), 7.45–7.43 (m, 2H), 7.35–7.34 (m, 3H), 5.48 (s, 1H), 4.41 (d, $J = 9.4$ Hz, 1H), 4.25 (dd, $J = 3.5$, 10.1 Hz, 1H), 3.98–3.88 (m, 2H), 3.74 (s, 1H), 3.73–3.65 (m, 1H), 3.48–3.46 (m, 2H), 2.96 (s, 1H); ESI-MS: $m/z = 399$ ($[M + Na]^+$), 775 ($[2M + Na]^+$).

4b[19b]

White solid, mp: 160–162°C; ^{1}H NMR (500 MHz, $CDCl_3$): δ 7.60 (d, J = 8.4 Hz, 2H), 7.46 (d, J = 8.4 Hz, 2H), 7.37–7.34 (m, 5H), 5.53 (s, 1H), 4.43 (s, 1H), 4.26–4.23 (m, 1H), 4.49–4.15 (m, 2H), 3.85 (t, J = 8.4 Hz, 1H), 3.72 (t, J = 10.2 Hz, 1H), 3.59 (t, J = 9.3 Hz, 1H), 3.41–3.38 (m, 1H), 3.29 (s, 1H), 2.45 (s, 3H, CH_3); ^{13}C NMR (125 MHz, $CDCl_3$): δ 143.0, 138.2, 136.9, 130.3, 129.5, 128.5, 126.5, 125.0, 102.2, 93.8, 79.7, 74.3, 73.3, 70.9, 68.3, 21.8; ESI-MS: m/z = 413 ($[M + Na]^+$), 803 ($[2M + Na]^+$).

4c[19b]

White solid, mp: 54–56°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.72–7.53 (m, 5H), 5.35–5.21 (m, 2H), 5.02–4.92 (m, 1H), 4.45 (dd, J = 9.4, 9.2 Hz, 1H), 4.28 (d, J = 9.6 Hz, 1H), 3.73–3.68 (m, 2H), 2.12 (s, 3H), 2.06 (s, 3H), 1.96 (s, 3H), 1.95 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.3, 170.1, 169.3, 169.2, 138.9, 131.6, 128.8, 125.7, 92.2, 76.2, 73.5, 67.7, 67.4, 61.3, 20.6, 20.5, 20.45, 20.43; ESI-MS: m/z = 457 ($[M + Na]^+$).

4d[19a]

White solid, mp: 120–122°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.49 (d, J = 8.0 Hz, 2H), 7.25 (d, J = 7.6 Hz, 2H), 5.20–5.11 (m, 2H), 4.87 (t, J = 10.0 Hz, 1H), 4.34 (d, J = 9.6 Hz, 1H), 4.10–4.02 (m, 2H), 3.65–3.61 (m, 1H), 2.35 (s, 3H), 1.93 (s, 3H), 1.92 (s, 3H), 1.91 (s, 3H), 1.87 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.3, 170.0, 169.3, 169.2, 142.2, 135.4, 129.5, 125.9, 91.9, 76.1, 73.5, 67.5, 67.4, 61.2, 21.4, 20.5 (2 × C), 20.43, 20.40; ESI-MS: m/z = 493 ($[M + Na]^+$), 509 ($[M + K]^+$).

4e

White solid, mp: 138–141°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.45–7.27 (m, 16H), 7.19–7.12 (m, 4H), 5.53 (s, 1H), 4.90 (t, J = 10.8 Hz, 2H), 4.72 (t, J = 10.8 Hz, 2H), 4.58 (d, J = 8.8 Hz, 1H), 4.42 (d, J = 8.4 Hz, 1H), 3.93 (s, 1H), 3.77–3.70 (m, 2H), 3.57–3.56 (m, 2H), 2.35 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 141.7, 137.9, 137.6, 137.0, 136.2, 129.5, 129.0, 128.5, 128.4, 128.2, 128.1, 128.0, 127.8, 127.5, 125.9, 125.5, 101.2, 95.3, 83.0, 81.0, 75.2, 74.9, 74.0, 70.0, 68.3, 21.3; ESI-MS: m/z = 593 ($[M + Na]^+$); HRMS(ESI): m/z calcd for $C_{34}H_{35}O_6S$ $[M + H]^+$ 571.2154, found 571.2166. Isomer, white solid, mp: 139–142°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.52–7.50 (m, 2H), 7.44–7.43 (m, 2H), 7.38–7.27 (m, 15H), 5.54 (s, 1H), 5.03 (t, J = 10.0 Hz, 1H), 4.98 (d, J = 4.0 Hz, 1H), 4.94–4.92 (m, 0.5H), 4.90–4.87 (m, 0.5H), 4.84–4.81 (m, 1H), 4.75–4.69 (m, 0.5H), 4.60–4.58 (m, 0.5H), 4.17–4.12 (m, 1H), 4.06 (dd, J = 5.2, 10.4 Hz, 1H), 4.99 (d, J = 10.0 Hz, 1H), 3.82–3.75 (m, 2H), 3.33–3.27 (m, 1H), 2.43

(s, 3H); ESI-MS: $m/z = 593$ ($[M + Na]^+$); HRMS(ESI): m/z calcd for $C_{34}H_{35}O_6S$ $[M + H]^+$ 571.2154, found 571.2167, error 2.2 ppm.

4f

White solid, mp: 134–137°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.72–7.71 (m, 2H), 7.514–7.510 (m, 3H), 5.78–5.70 (m, 1H), 5.22–5.12 (m, 2H), 4.86 (t, $J = 9.6$ Hz, 1H), 4.29–4.26 (m, 1H), 4.11–4.00 (m, 4H), 3.70–3.55 (m, 3H), 2.07 (s, 3H), 2.04 (s, 3H), 1.94 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.4, 169.4, 169.1, 138.8, 133.8, 131.6, 128.7, 126.2, 117.3, 92.5, 80.5, 76.4, 73.3, 69.2, 68.8, 61.6, 20.9, 20.7, 20.6; ESI-MS: $m/z = 477$ ($[M + Na]^+$), 493 ($[M + K]^+$), 931 ($[2M + Na]^+$), 947 ($[2M + K]^+$); HRMS(ESI): m/z calcd for $C_{21}H_{27}O_9S$ $[M + H]^+$ 455.1376, found 455.1370, error 1.3 ppm.

4g

White solid, mp: 140–143°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.60 (d, $J =$ 8.0 Hz, 2H), 7.32–7.26 (m, 2H), 5.79–5.70 (m, 1H), 5.21–5.10 (m, 2H), 4.85 (t, $J = 9.6$ Hz, 1H), 4.26 (d, $J = 9.6$ Hz, 1H), 4.09–3.99 (m, 4H), 3.70–3.54 (m, 3H), 2.41 (s, 3H), 2.08 (s, 3H), 2.04 (s, 3H), 1.95 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.4, 169.4, 169.1, 142.2, 135.4, 133.9, 129.5, 126.3, 117.3, 92.3, 80.5, 76.4, 73.4, 69.3, 68.8, 61.7, 21.4, 20.9, 20.7, 20.5; ESI-MS: $m/z = 491$($[M + Na]^+$), 507 ($[M + K]^+$); HRMS(ESI): m/z calcd for $C_{22}H_{29}O_9S$ $[M + H]^+$ 469.1532, found 469.1539, error 1.5 ppm.

4h

White solid, mp: 78–80°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.65–7.63 (m, 2H), 7.51–7.50 (m, 3H), 5.21 (t, $J = 9.6$ Hz, 1H), 5.12 (t, $J = 9.2$ Hz, 1H), 4.47 (d, $J =$ 9.2 Hz, 1H), 3.93 (dd, $J = 4.4$, 10.4 Hz, 1H), 3.74 (dd, $J = 5.6$, 10.8 Hz, 1H), 3.68 (t, $J = 8.8$ Hz, 1H), 3.48–3.43 (m, 1H), 3.19 (s, 3H), 2.06 (s, 3H), 1.82 (s, 3H), 0.89 (s, 9H), 0.07 (s, 3H), 0.06 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.1, 169.5, 132.6, 132.3, 128.9, 128.0, 85.8, 78.5, 77.2, 71.2, 70.0, 64.3, 25.8, 20.8, 20.7, 18.2, –0.04, –5.52; ESI-MS: $m/z = 509$ ($[M + Na]^+$), 995 ($[2M + Na]^+$); HRMS(ESI): m/z calcd for $C_{22}H_{35}O_8SSi$ $[M + H]^+$ 487.1822, found 487.1827, error 1.0 ppm.

4i

White solid, mp: 119–123°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.65–7.63 (m, 2H), 7.41–7.38 (m, 8H), 7.32–7.25 (m, 20H), 4.87 (s, 2H), 4.79 (s, 2H), 4.51 (d, $J = 9.2$ Hz, 1H), 3.71–3.59 (m, 3H), 3.51–3.47 (m, 1H), 3.43–3.39 (m, 1H), 3.30 (dd, $J = 3.6$, 10.0 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 146.8, 143.5, 138.0, 137.6, 137.5, 131.3, 131.2, 128.8, 128.7, 128.69, 128.61, 128.55, 128.54, 128.0,

127.9, 127.8, 127.7, 127.5, 127.2, 127.1, 126.9, 125.6, 95.1, 95.0, 86.7, 86.2, 82.0, 76.3, 75.4, 69.9, 62.2; ESI-MS: m/z = 733 ($[M + Na]^+$), 749 ($[M + K]^+$); HRMS(ESI): m/z calcd for $C_{45}H_{43}O_6S$ $[M + H]^+$ 711.2780, found 711.2766, error 1.9 ppm.

4j

White solid, mp: 134–136°C; ^{1}H NMR (400 MHz, $CDCl_3$,): δ 7.63–7.61 (m, 2H), 7.50–7.48 (m, 3H), 7.38–7.36 (m, 2H), 7.25–7.23 (m, 3H), 5.48 (s, 1H), 5.31–5.30 (m, 1H), 5.22 (dd, J = 3.6, 10.4 Hz, 1H), 5.16 (d, J = 1.2 Hz, 1H), 4.89 (t, J = 10.4 Hz, 1H), 4.19 (dd, J = 5.2, 10.4 Hz, 1H), 4.11–4.07 (m, 2H), 3.85 (t, J = 9.6 Hz, 1H), 3.68 (t, J = 10.4 Hz, 1H), 3.59 (t, J = 9.6 Hz, 1H), 3.40–3.31 (m, 1H), 2.04 (s, 3H), 1.91 (s, 3H), 1.87 (s, 3H), 0.75 (d, J = 6.0 Hz, 3H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.1, 170.0, 169.8, 141.5, 136.8, 131.9, 129.3, 129.0, 128.0, 126.1, 124.4, 101.6, 97.8, 93.8, 77.8, 77.0, 73.7, 71.1, 71.0, 69.5, 69.1, 68.0, 66.0, 20.8, 20.7, 20.6, 16.7; ESI-MS: m/z = 671 ($[M + Na]^+$); HRMS(ESI): m/z calcd for $C_{31}H_{37}O_{13}S$ $[M + H]^+$ 649.1955, found 649.1950, error 0.8 ppm.

4k

White solid, mp: 146–148°C; ^{1}H NMR (500 MHz, $CDCl_3$,): δ 7.58 (d, J = 8.1 Hz, 2H), 7.46–7.44 (m, 2H), 7.36 (d, J = 8.1 Hz, 2H), 7.33–7.31 (m, 3H), 5.56 (s, 1H), 5.39–5.38 (m, 1H), 5.30 (dd, J = 3.5, 10.1 Hz, 1H), 5.25 (d, J = 0.6 Hz, 1H), 4.97 (t, J = 10.0 Hz, 1H), 4.19 (t, J = 8.2 Hz, 1H), 4.26 (dd, J = 4.9, 10.4 Hz, 1H), 4.20–4.16 (m, 2H), 4.11 (d, J = 9.5 Hz, 1H), 3.93 (t, J = 9.4 Hz, 1H), 3.75 (t, J = 10.4 Hz, 1H), 3.67 (t, J = 9.5 Hz, 1H), 3.43–3.39 (m, 1H), 2.45 (s, 3H), 2.13 (s, 3H), 1.99 (s, 3H), 1.95 (s, 3H), 0.83 (d, J = 6.2 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 170.4, 170.3, 170.1, 143.0, 138.6, 137.1, 130.4, 129.3, 128.3, 126.4, 124.8, 101.9, 98.1, 94.0, 78.2, 77.3, 74.3, 71.4, 71.3, 69.8, 69.4, 68.3, 66.3, 21.8, 21.2, 21.0, 20.9, 17.0; ESI-MS: m/z = 685 ($[M + Na]^+$); HRMS(ESI): m/z calcd for $C_{32}H_{39}O_{13}S$ $[M + H]^+$ 663.2111, found 663.2099, error 1.8 ppm.

4l

White solid, mp: 127–127°C; ^{1}H NMR (500 MHz, $CDCl_3$,): δ 7.62–7.59 (m, 2H), 7.49–7.43 (m, 3H), 5.19–5.12 (m, 4H), 5.03–4.98 (m, 1H), 4.69 (d, J = 2.0 Hz, 1H), 4.43 (d, J = 10.0 Hz, 1H), 4.19 (dd, J = 5.2 Hz, 12.4 Hz, 1H), 4.07–4.02 (m, 2H), 3.95–3.90 (m, 1H), 3.82 (dd, J = 3.6 Hz, 11.6 Hz, 1H); ^{13}C NMR (100 MHz, $CDCl_3$): δ 171.2, 170.6, 169.8, 169.7, 169.5, 169.2, 138.9, 131.4, 128.8, 125.2, 97.5, 92.5, 78.9, 69.1, 68.8, 68.3, 67.7, 66.8, 66.0, 65.9, 62.3, 60.2, 20.9, 20.7, 20.6, 20.58, 20.52, 20.4; ESI-MS: m/z = 725 ($[M + Na]^+$); HRMS(ESI): m/z calcd for $C_{30}H_{39}O_{17}S$ $[M + H]^+$ 703.1908, found 703.1923, error 2.1 ppm.

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