Photoinitiated Thiol−Ene Reactions of Various 2,3-Unsaturated *O*-, *C*- *S*- and *N*-Glycosides – Scope and Limitations Study

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Abstract: The photoinitiated thiol−ene addition reaction is a highly stereo- and regioselective, and environmentally friendly reaction proceeding under mild conditions, hence it is ideally suited for the synthesis of carbohydrate mimetics. A comprehensive study on UV-light-induced reactions of 2,3-unsaturated *O*-, *C*-, *S*- and *N*-glycosides with various thiols was performed. The effect of experimental parameters and structural variations of the alkenes and thiols on the efficacy and regio- and stereoselectivity of the reactions was systematically studied and optimized. The type of anomeric heteroatom was found to profoundly affect the reactivity of 2,3-unsaturated sugars in the thiol−ene couplings. Hydrothiolation of 2,3-dideoxy *O*-glycosyl enosides efficiently produced the axially C2-*S*-substituted addition products with high to complete regioselectivity. Moderate efficacy and varying regio- and stereoselectivity were observed with 2,3-unsaturated *N*-glycosides and no addition occurred onto the endocyclic double bond of *C*-glycosides. Upon hydrothiolation of 2,3-unsaturated *S*-glycosides, the addition of thiyl radicals was followed by elimination of the thiyl aglycone resulting in 3-*S*-substituted glycals.

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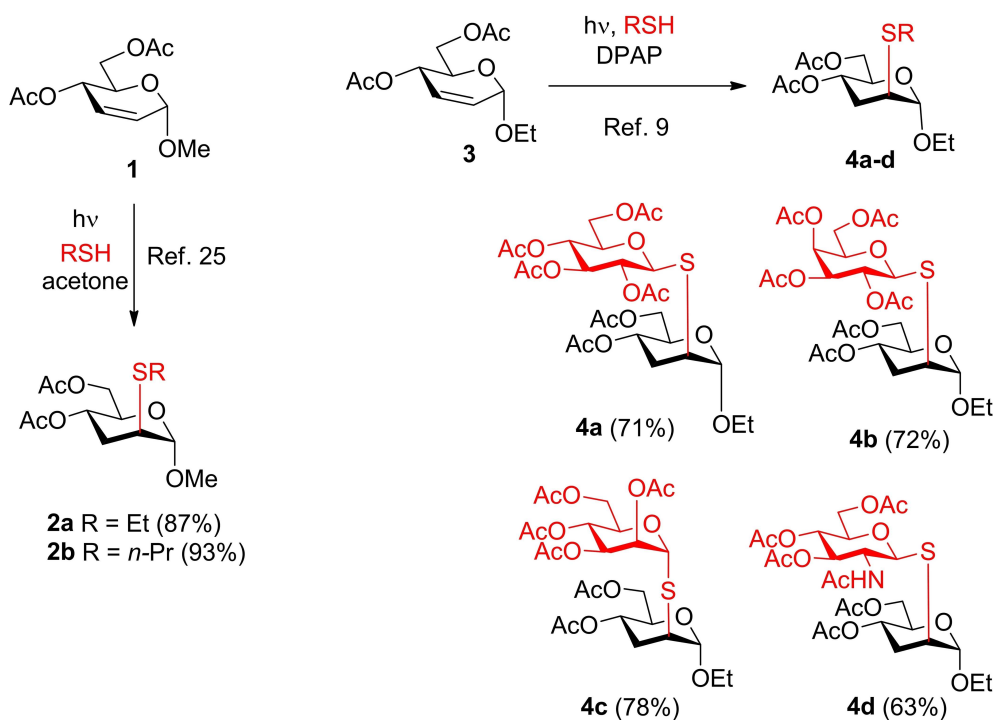H-4032 Debrecen (Hungary)

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Introduction

Carbohydrates, in the form of oligosaccharides, polysaccharides and glycoconjugates, play a crucial role in cell surface binding events, protein stability and immunology, and represent a highly important class of biomolecules.[1] In spite of their central role in biology, carbohydrates remain less exploited compared to proteins and nucleic acids, and are only rarely considered for drug discovery. A major problem with the application of oligosaccharides as biological probes or drug candidates is the sensitivity of the glycosidic bond to enzymatic hydrolysis.[2] Stable mimetics have been designed to tackle this problem and the replacement of the interglycosidic oxygen by a sulfur atom to form *S*-glycosides is one common tactic to generate stable analogs of native oligosaccharides and glycoconjugates.[3–5]

For the synthesis of thio-linked carbohydrate mimetics, the exocyclic sulfur atom can be efficiently introduced into the sugar backbone *via* the photoinduced thiol−ene "click" (TEC) reaction using unsaturated pyranoses or furanoses as acceptor substrates.[6] The thiol−ene reaction proceeds *via* a two-step radical process in mild conditions and often quantitative yields and shows tolerance to a wide range of functional groups.[7] This reaction has already been used to couple various thiols to a broad range of unsaturated sugars including glycals,[8] 1- and 2-substituted glycals,[9–14] exoglycals[15–18] and pyranosyl and furanosyl exomethylene derivatives.[10,19–21]

2,3-Unsaturated glycosides are useful chiral substrates for further manipulations in organic synthesis and are easily accessible by Ferrier rearrangement of commercially available tri-*O*-acetyl glycals.[22–24] Surprisingly, these types of glycosides were scarcely applied as alkene substrates in the thiol−ene coupling reactions.[9,25] Kushida and coworkers reported that acetone-sensitized photochemical addition of ethanethiol and 1-propanethiol to methyl 4,6-di-*O*-acetyl-2,3-dideoxy-α-D-eryth-

Scheme 1. Literature results on hydrothiolation of 2,3-unsaturated pyranosides. DPAP: 2,2-dimethoxy-2-phenylacetophenone.

ro-hex-2-enopyranoside **1** occurred with high stereo- and regioselectivity giving the corresponding D-*arabino*-configured 3-deoxy-2-*S*-alkyl-2-thio-hexopyranosides **2a** and **2b** in high yields (Scheme 1).[25] We have demonstrated that UV-initiated addition of various acetylated 1-thiosugars to 2,3-unsaturated ethyl glycoside **3** using 2,2-dimethoxy-2-phenylacetophenone (DPAP) as the initiator also proceeded with high efficacy and selectivity, providing an easy access to 3-deoxy-2-*S*-disacchar- ides (Scheme 1, **4a**–**4d**).[9] Hence, 2,3-unsaturated glycosides can be regarded as very useful yet underexploited acceptor substrates for rapid and stereoselective synthesis of stable analogs of biorelevant sugars such as, among others, 1,2-α- mannobiosides.[26,27]

To obtain a better view on the scope and limitations of the TEC reaction on unsaturated sugar skeletons, we decided to carry out a detailed study on radical mediated additions of various thiols onto a broad range of 2,3-unsaturated sugars including *O*-glycosides with D-*erythro* (**3**, **5**–**7**) and D-*threo* configuration (**8**) and bearing a C2-substituent (**9**, **10**), as well as *C*- (**11**), *S*- (**12**, **13**), and *N*-glycosides (**14**) (Figure 1).

Results and Discussion

In the first set of experiments, we investigated the effect of the anomeric substituent of enosides on the thiol–ene couplings (Table 1). Therefore, some easily available 2,3-unsaturated sugars such as ethyl glycoside **3**, 2-bromoethyl glycoside **5**, and phenyl glycoside **6** were reacted with 1-thiosugars (**15** and **18**) and functionalized alkyl thiols (**16** and **17**). In the case of addition of 1-thioglucose **15** to ethyl glycoside **3**, the efficacy of
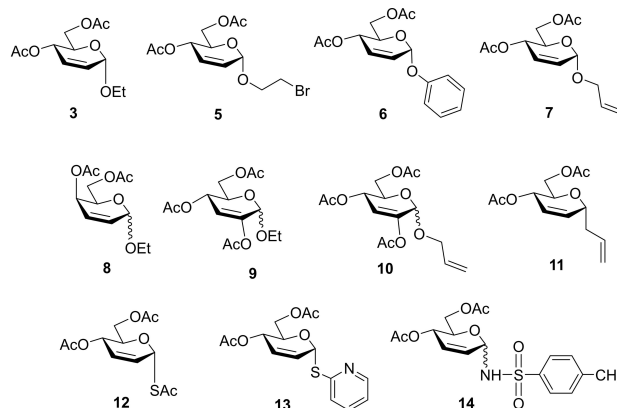

Figure 1. 2,3-Unsaturated glycosides used as alkene reactants.

various initiation conditions was also studied (Table 1, en- tries 1–4). In our previous work, **3** and **15** were reacted at room temperature upon photoinitiation to give **4a** as the sole product with 71% yield (Scheme 1).[9] Recently, we have found in the case of 2-acetoxy glycals that the reaction temperature is a crucial factor in terms of efficacy of the thiol–ene coupling, the cooling promotes while the heating inhibits the addition reactions.[12,13] We were curious how cooling and heating affect the conversion of **3**. The low-temperature photoinduced reaction was performed by the previously established standard conditions,[12] irradiating at $\lambda_{max} = 365$ nm for 3×15 min in the presence of the cleavable photoinitiator 2,2-dimethoxy-2- phenylacetophenone (DPAP) (Table 1, Entries 1 and 2). Cooling to 0 °C was beneficial to the conversion, yielding 75% of **4a**, and an even higher, 82% yield was achieved by running the
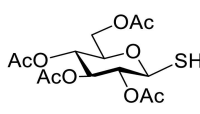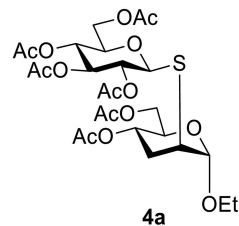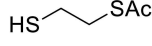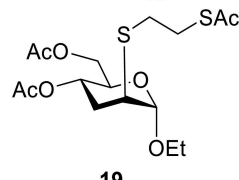
Table 1. Hydrothiolation reactions of 2,3-unsaturated *O*-glycosides **3**, **5** and **6** under various conditions.
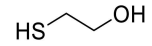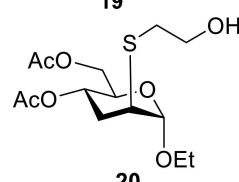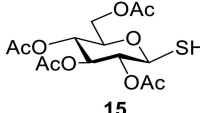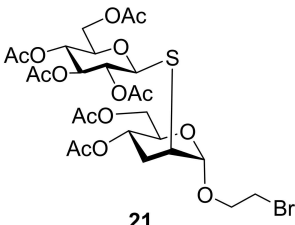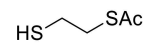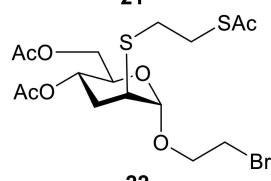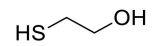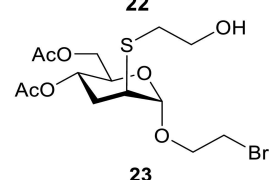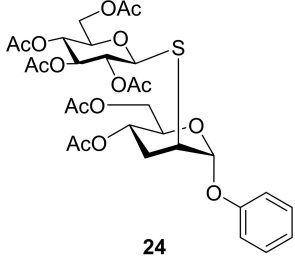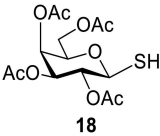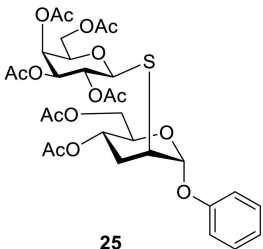
Entry	Solvent	Alkene	Thiol [equiv.]	Conditions[a]	Product	Isolated yield [%][b]
1	toluene	**3**		0 °C, DPAP, hν		75
2	toluene	**3**	**15** (1.2 equiv)	−80 °C, DPAP, hν	**4a**	82
3	toluene	**3**		120 °C, AIBN		11
4	CH₂Cl₂	**3**		rt, Et₃B, catechol		67
5	toluene	**3**	**16** (3.0 equiv)	0 °C, DPAP, hν	**19**	69
6	toluene	**3**		−80 °C, DPAP, hν		23
7	toluene	**3**	**17** (2.0 equiv)	0 °C, DPAP, hν	**20**	46
8	toluene	**3**		−80 °C, DPAP, hν		68
9	toluene	**5**	**15** (1.2 equiv)	−40 °C/−80 °C, DPAP, hν	**21**	95
10	toluene	**5**	**16** (3.0 equiv)	0 °C, DPAP, hν	**22**	72
11	toluene	**5**	**17** (2.0 equiv)	0 °C, DPAP, hν	**23**	32
12		**5**		−80 °C, DPAP, hν		64
13	toluene	**6**		rt, DPAP, hν		55
14	toluene	**6**	**15** (1.2 equiv)	0 °C, DPAP, hν	**24**	56
15	toluene	**6**		−40 °C, DPAP, hν		68
16	toluene	**6**		−80 °C, DPAP, hν		74

Table 1. continued

Entry	Solvent	Alkene	Thiol [equiv.]	Conditions[a]	Product	Isolated yield [%][b]
17 18	toluene	6	18 (1.2 equiv)	rt, DPAP, hν −80 °C, DPAP, hν	25	69 78

[a] The reaction time was 3×15 min for the photoinduced reactions, 6 h for the AIBN mediated reaction and 3 days for the Et₃B mediated reaction. [b] By-product formation was not observed, the low/moderate yields are the results of the low/moderate conversions of the alkenes.

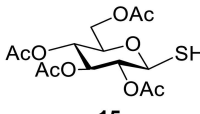reaction at −80 °C. Changing the method of initiation to thermal activation using azobisisobutyronitrile (AIBN)[18] as the radical initiator at 120 °C proved to be detrimental to the reaction, yielding only 11% of **4a**. Recently, Renaud and co-workers reported that triethylborane in combination with catechol represents a very efficient initiator system for radical hydrothiolation of allylic double bonds.[28] Using Et₃B and catechol to initiate a reaction between **3** and **15**, the conversion and isolated yield was close to the one observed in the case of photoinitiation at rt; however, the reaction required 3 days instead of 45 min. In view of these results, the most optimal initiation method for completing the thio-click reaction was the UV irradiaton in the presence of DPAP. Hence, further reactions were performed using photoinitiation.

Compound **3** was hydrothiolated with ethane dithiol monoacetate **16** as well at two different temperatures. While the reaction afforded the expected axially 2-S-alkylated **19** as the sole product with 69% yield at 0 °C, very low conversion of **3** occurred at −80 °C (entries 5–6). When **3** was reacted with 2-mercaptoethanol **17** at the above two temperatures, the lower temperature led to the more efficient addition reaction to give **20** in 68% yield (entries 7 and 8).

Next, the compatibility of functionalized aglycone on the thiol–ene coupling was examined. It was observed that the bromoethyl glycoside was compatible with the thio-click reaction. Upon reacting **5** with 1-thioglucose **15** at either −40 °C or −80 °C the reaction completed with an excellent 95% yield of thiodisaccharide **21**. Addition of thiol **16** onto **5** at 0 °C afforded **22** with a good 72% yield, the lower conversion being attributed to the lower reactivity of thiol **16**. When 2-mercaptoethanol **17** was reacted with **5** at the same conditions, the yield of **23** was only 32%, which could be successfully increased to 64% by conducting the reaction at −80 °C.

We also studied how changing the alkyl aglycone into an aryl one affects the efficacy of the reaction. Reacting phenyl glycoside **6** to thiol **15** at rt afforded the expected thiodisaccharide **24** with a satisfactory 55% yield. Cooling the reaction to 0 °C showed no significant difference in the conversion, however, cooling to −40 °C increased the yield to 68% and further cooling to −80 °C gave the best results, an excellent 74% yield. Hydrothiolation of compound **6** with 1-thiogalactose **18** gave **25** with 69% yield at rt and an increased 78% yield at

−80 °C. Although changing the alkyl aglycone to an aryl one slightly decreases the conversion of the alkene at rt, efficient additions could be elicited with 1-thiosugars at lower temperature.

We have found that each reaction showed complete regio- and stereoselectivity, however, the reactivity of the thiols proved to be a crucial factor for the conversion and overall yield. Cooling was beneficial to the reactions of carbohydrate thiols and 2-mercaptoethanol. We assume that in these cases the low temperature stabilizes the intermediate carbon-centered radical, which is formed in the reversible thiyl addition step, thereby allowing it to react with a thiol in the hydrogen abstraction step.[12,13] In contrast, cooling was detrimental to the reactivity of alkyl thiol **16**. These observations are in line with our recent results on hydrothiolation of 2-acetoxy-glycals[13] and furanose exomethylenes.[20,21] These studies revealed that thiols bearing electron withdrawing substituents, e.g. peracetylated 1-thiosugars, show high reactivity in the thiol–ene reactions at the −40 to −80 °C temperature interval, while the reactivity of simple alkyl thiols and the thio-substituted derivative **16** decreased significantly by the excessive cooling, probably because the hydrogen abstraction step is inhibited at such a low temperature due to the less abstractable hydrogen of alkyl thiols.

A chemoselectivity study was carried out on allyl glycoside **7** bearing double bonds both internally and terminally (Scheme 2). The terminal double bond is more reactive than the internal one, offering the possibility to introduce different thiol moieties to the pyranose ring and the aglycone. Reacting **7** with 1.0 equiv. of 1-thiogalactose **18** at −80 °C we observed exclusive addition onto the allyl moiety affording the thiogalactosylated **26** with 81% yield. Reacting this isolated **26** with 1.2 equiv. of 1-thioglucose **15** at 0 °C efficient addition occurred onto the internal double bond providing pseudotrisaccharide **27** with an excellent 88% yield. Directly coupling 2.5 equivalents of the β-1-thiomannose derivative **28** to carbohydrate **7** resulted in the formation of the expected **29** with a good 75% yield, while less than 5% of **30** was also detected. Performing the reaction at −80 °C the yield of **29** reached 83%. It has been concluded that the terminal unsaturated bond is indeed more reactive, allowing hydrothiolation of the terminal double bond with complete chemoselectivity while the internal double bond
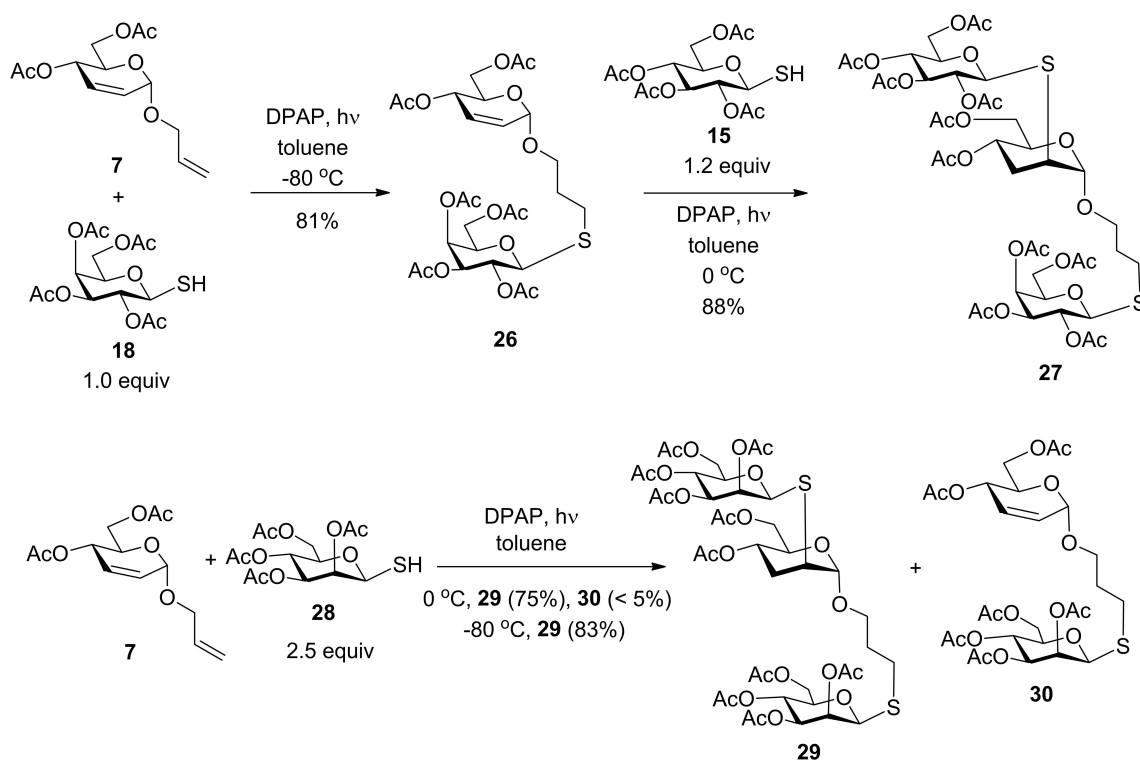
Scheme 2. Chemoselectivity study – homo- and heterodithioglycosylation of the 2,3-unsaturated allyl glycoside **7** using different thiol–alkene ratios.

remains intact. Hence, this reaction offers a rapid access to various pseudotrisaccharides or multivalent oligosaccharides.

Next, the impact of the enose configuration was studied. The reactions were performed with an inseparable 5:1 α:β mixture of ethyl 4,6-di-O-acetyl-2,3-dideoxy-D-threo-hex-2-eno-pyranoside **8** (Scheme 3). Hydrothiolation of the anomeric mixture of **8** with 1-thioglucose **15** at different temperatures gave two regioisomers, compounds **31** and **32**. At rt the overall yield was 78% with isomeric ratio of **31**:**32** ~ 3:1. Cooling the

reaction to −80 °C increased the overall yield to 80% and increased the regioselectivity in favor of the C-2 thiolated product to reach a **31**:**32** = 5:1 ratio. The structure of the crystalline major product **31** was confirmed by X-ray measurements (Figure 2). The constitution and stereochemistry of the minor product was determined on the basis of NMR spectra, and the C3 configuration was confirmed by cross-peak detected between the H-3 and H-1 atoms in the ROESY NMR spectrum of **32** (See Figure S1).
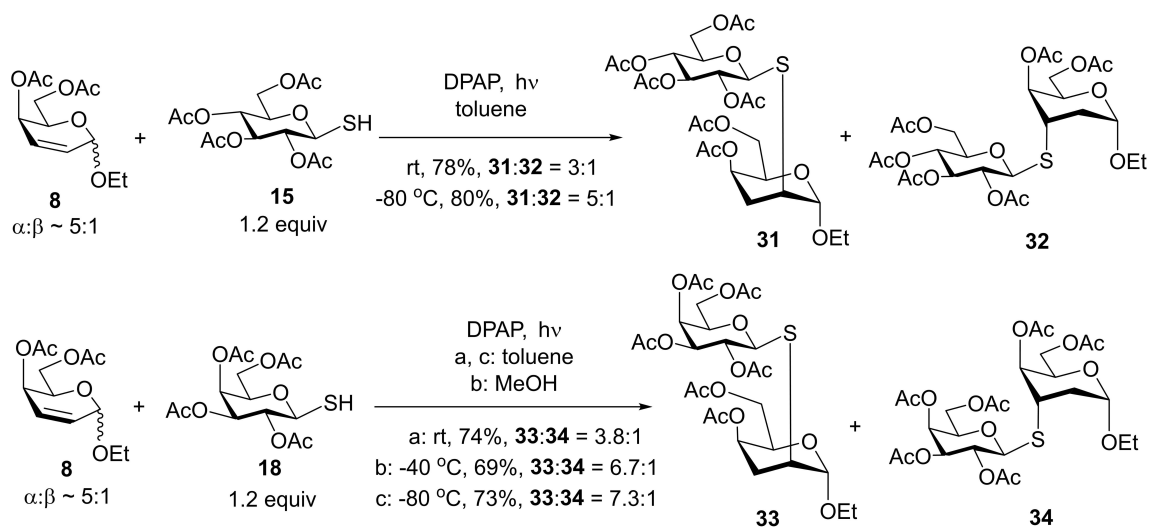
Scheme 3. The effect of alkene-configuration on the regioselectivity of thiol–ene reactions.

Figure 2. ORTEP view of thiodisaccharide **31**; hydrogen atoms are omitted for clarity.

Reacting the unsaturated carbohydrate **8** with the D-*galacto* configured thiol **18** in toluene also showed incomplete regioselectivity. At rt the **33:34** ratio was 3.8:1 with a satisfactory 74% yield. Next the solvent was changed to methanol and the temperature was lowered to −40 °C. We observed that the overall yield decreased slig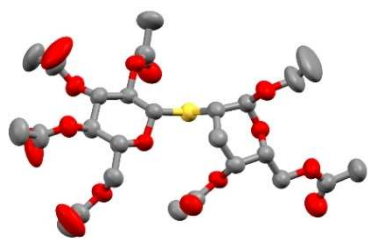htly to 69%, however, the regioselectivity increased to 6.7:1 in favor of the 2-thiolated product **33**. Further cooling the reaction to −80 °C in toluene the ratio of **33:34** reached 7.3:1 with 73% combined yield.

The regioselectivity of the thiol–ene reactions can be explained by the enhanced stability of the intermediate carbon-centered radical upon addition of the thiyl radical to the less substituted olefinic carbon atom.[29,30] Although the C2 and C3 carbons are equally substituted in enosides **3** and **5**–**8** studied above, the addition reactions proceed preferably or exclusively through the C3 centered radical intermediate due to its higher stability. The spatial arrangement of the C4 substituent proved to have a crucial effect on the regio- and stereochemical outcome of the reactions. In the D-*erythro* cases, as it is shown in Figure 3 on the example of **3**, the stable $^4C_1$ conformer of the C3-centered radical intermediate (**3-C3R**) can readily form by upper-face attack of the thiyl radical to C2 of the $^OH_5$ conformational form of the starting enosides leading to exclusive formation of the C2-thiolated products. In the case of the D-*threo*-configured **8**, the axial 4-OAc group exerts a shielding effect on the β-side of the double bond, inhibiting the attack of
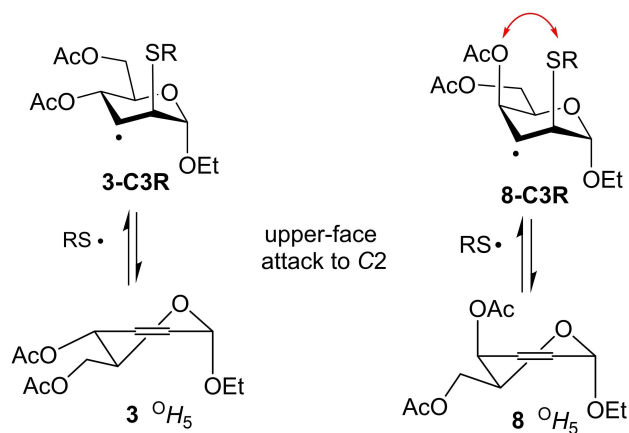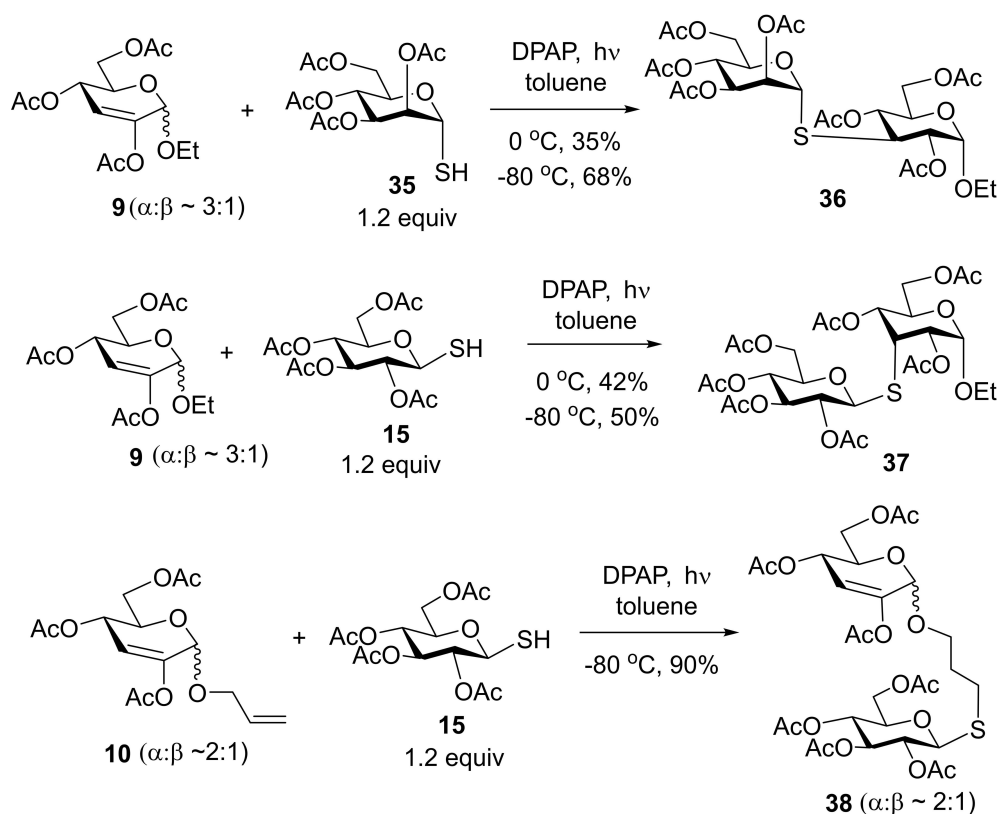
thiyl radicals on the upper-face and opening up the way for a bottom-face attack onto C3. Moreover, the 1,3-*syn*-diaxial repulsion between substituents at C-2 and *C*-4 decreases the stability of the resulting radical intermediate **8-C3R**. We assume that these factors result in a lower level of selectivity of the thiol–ene reactions of **8**. Although cooling the reactions promotes the formation of the 3-deoxy-2-*S*-disaccharides **31** and **33** the regioselectivity was incomplete even at −80 °C.

Importantly, the addition proceeded with complete stereo-selectivity at both the C2 and C3 positions providing solely the axially linked 2-thio-D-*lyxo* (**31** and **33**) and the axially linked 3-thio-D-*xylo* (**32** and **34**) disaccharides, which is in line with the literature results. It was demonstrated in the case of substituted cyclohexenes,[30,31] as well as 1- and 2-substituted glycals[9–13] that the addition occurs preferentially in an anti fashion as the result of a kinetically favored axial attack of the thiyl radical onto the cyclic alkene in its half-chair conformation together with a stereoselective hydrogen abstraction from the thiol into an axial position.

Next, we studied the hydrothiolation of 2-substituted 2,3-unsaturated glycosides to learn the impact of the C2-substituent on the regio- and stereoselectivity and efficacy of the addition (Scheme 4). In this case the starting glycosides **9** and **10** were inseparable anomeric mixtures. Reacting ethyl glycoside **9** with α-1-thiomannose **35** at rt moderate conversion occurred to give **36** with 35% yield. Cooling the reaction to −80 °C however increased the isolated yield of **36** to 68%. The D-*gluco* configuration of the ethyl glycoside unit was determined by NMR measurements on the basis of the $^3J_{H2,H3} =$ 11.8 Hz and $^3J_{H3,H4} = 11.3$ Hz coupling constants and the cross-peak detected between the H-3 and H-5 atoms in the ROESY NMR spectrum of **36**. Reacting carbohydrate **9** with β-1-thioglucose **15** at 0 °C gave **37** with 42% yield. In this case the cooling did not improve the conversion significantly, the reaction repeated at −80 °C gave **37** with 50% yield. Although the isolated **37** contained stereoisomeric impurities, the D-*allo* configuration of the major component could be undoubtedly determined by the ¹H NMR coupling constants of H-3 ($^3J_{H2,H3} =$ $^3J_{H3,H4}$ 4.7 Hz) and the ROESY connectivities detected between the H2, H3 and H4 protons of the ethyl glycoside unit (See Figure S1). It can be seen that the regioselectivity of the reaction can be controlled *via* substitution of position 2 and the hydrothiolation proceeded with full regio- and high stereo-selectivity. However, surprisingly, the efficacy and the stereo-chemical result of the reactions strongly depended on the configuration of the thiol. The different stereochemical outcome of the reactions with the different thiosugars can be explained by double stereodifferentiation of the donor and acceptor compounds, which phenomenon is well-documented in the field of chemical glycosylation.[32–34] Moreover, the results demonstrate that the α anomer of the starting enoside **9** was more reactive than the β one, as we could not detect any thiodisaccharide products bearing β-ethyl aglycone. (However, it is possible that products were formed from the minor, β-anomer of **9** in such low amounts that they remained undetected in the reaction mixture.) Upon hydrothiolation of allyl glycoside **10** with 1.2 equiv. of thiol **15** the addition

Figure 3. Formation of carbon-centered radical intermediates upon thiol–ene reactions of enosides **3** and **8**.

Scheme 4. Hydrothiolation of 3-deoxy-2,3-unsaturated glycosides – the impact of the C2-substituent on the addition.

occurred exclusively on the terminal unsaturated bond with an outstanding 90% yield while retaining the anomeric ratio of $\alpha:\beta \sim 2:1$ at the *O*-glycoside unit.

Following the successful hydrothiolations of *O*-allyl glycosides, our focus turned to *C*-allyl ones (Scheme 5). The first attempts to selectively couple thiol **15** to the terminal unsaturated bond of **11** were successful, at rt compound **39** was isolated with 40% yield, and increasing the thiol excess to

2.5 equiv. while lowering the temperature to $-80\,^\circ$C raised the yield to 48%. However, attempted hydrothiolations of the internal unsaturated bond of **39** with 8 equivalents of 1-propanethiol and excess of thiol **15** (2 equiv.) were unsuccessful. Traces of addition product (**40**) could be detected by MS analysis of the reaction mixtures, however, only unreacted **39** was recovered and no product could be isolated in either case. Afterwards, compound **11** was reacted with 3 equiv. of thiol **15**,
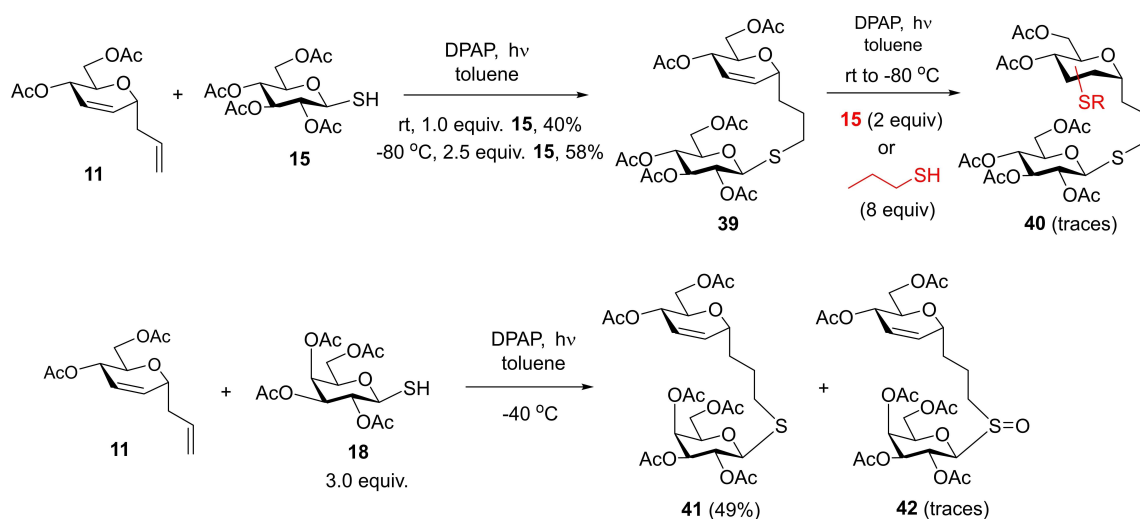
Scheme 5. Hydrothiolation of the 2,3-unsaturated allyl *C*-glycoside **11**.

however, still only compound **39** was isolated. Hydrothiolation of **11** with 3 equiv. of thiol **18** resulted in the exclusive formation of compound **41** along with sulfoxide derivative **42** which was detected in the reaction mixture by MS, and no reaction occurred on the internal unsaturated bond. We have concluded that although the thioladdition can be performed on the more reactive terminal double bond, the conversion is significantly lower than the ones experienced with *O*-glycosides, and the internal double bond practically proved intact in the thiol–ene reaction.

Next, hydrothiolation of 2,3-unsaturated *S*-glycosides was taken into focus (Scheme 6). Surprisingly, when 1-acetylthio derivative **12** was reacted with thiol **35** at rt, the expected addition product could not be detected. Instead, moderate conversion of the starting compounds and formation of a complex mixture were observed from which the 3-thio-substituted glycals **43** and **44** along with disulfide **45** were isolated. We tested whether the allyl rearrangement of **12** producing **43** can be elicited by UV-light irradiation without any thiol, however, no reaction occurred. Afterwards, thioacetic acid was reacted with 1-thioenose **12**, and compound **43** was isolated again as the sole product. Subjecting the arylthio enoside **13** to hydrothiolation with thiol **35**, only allyl rearrangement and formation of disulfide were observed again to give 3-thioglycosylated glycal **44** (40%) and disulfide **45**.

The proposed mechanism of this rearrangement is shown on Scheme 7. After addition of the thiyl radical, the formed 1,3-dithio C2-centered radical **II** rapidly decomposes either by homolytic cleavage of the C3–SR^2 bond to give the starting enoside and thiyl radical or by homolytic cleavage of the C1–SR^1 bond resulting in glycal **III** and the aglycone-derived thiyl radical (R^{1}S radical). Addition of the latter R^{1}S radical onto enoside **I** leads to glycal **V** *via* intramolecular decomposition of

the 1,3-dithio C2-centered radical intermediate **IV**. Similar failure of radical mediated hydrothiolation of *S*-allyl cysteine derivative has been reported previously by Dondoni, Marra and co-workers.[35]

Finally, thiol–ene coupling reactions of the 2,3-unsaturated *N*-glycoside **14** was studied (Scheme 8). Compound **14** consisted of an inseparable anomeric mixture of $\alpha : \beta \sim 3 : 1$ which posed difficulties in the purification of the addition products. Reacting compound **14** with thiol **15** at rt and 0 °C no reaction was detected. Running the reaction at −40 °C resulted in the formation of a multicomponent mixture, of which only compound **46** could be isolated and the starting compound was also recovered mainly in α-anomeric form. Reacting **14** with 1-thioxylose **47** also resulted in a multicomponent mixture consisting of compounds **48** and **49** as the major components. Interestingly enough, only hydrothiolation products arisen from the β-anomer of **14** have been isolated from the reactions above. It is known that the addition of thiyl radicals requires electron-rich double bonds. The results suggest that the electron density of the double bond might be significantly different in the α and β anomers of the starting enoside. The electron withdrawing effect of the sulfonyl group might be more pronounced in the α anomer leading to its decreased reactivity in the thiol–ene coupling reaction. Similarly to the thiol–ene couplings of 2-acetoxy-2,3-unsaturated-*O*-glycosides, the stereochemical outcome of the reactions was controlled by the configuration of the thiols.

Conclusions

The effect of the anomeric heteroatom of enosides on the radical-mediated thiol–ene coupling reactions was studied for
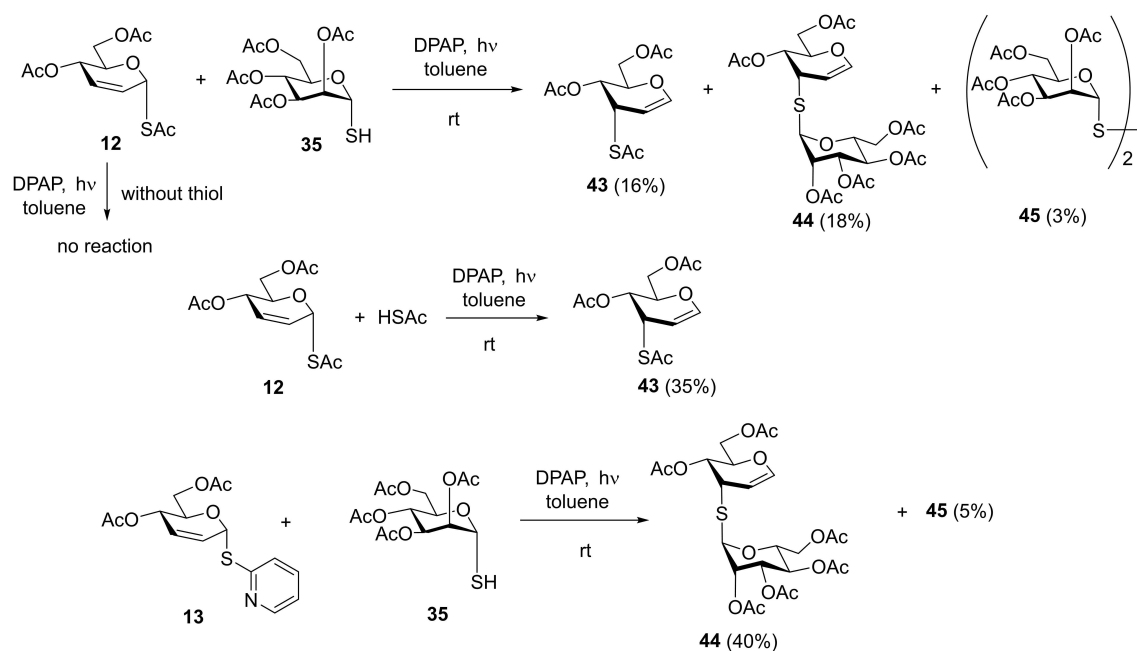
Scheme 6. Thiol–ene coupling reactions of 2,3-unsaturated *S*-glycosides.
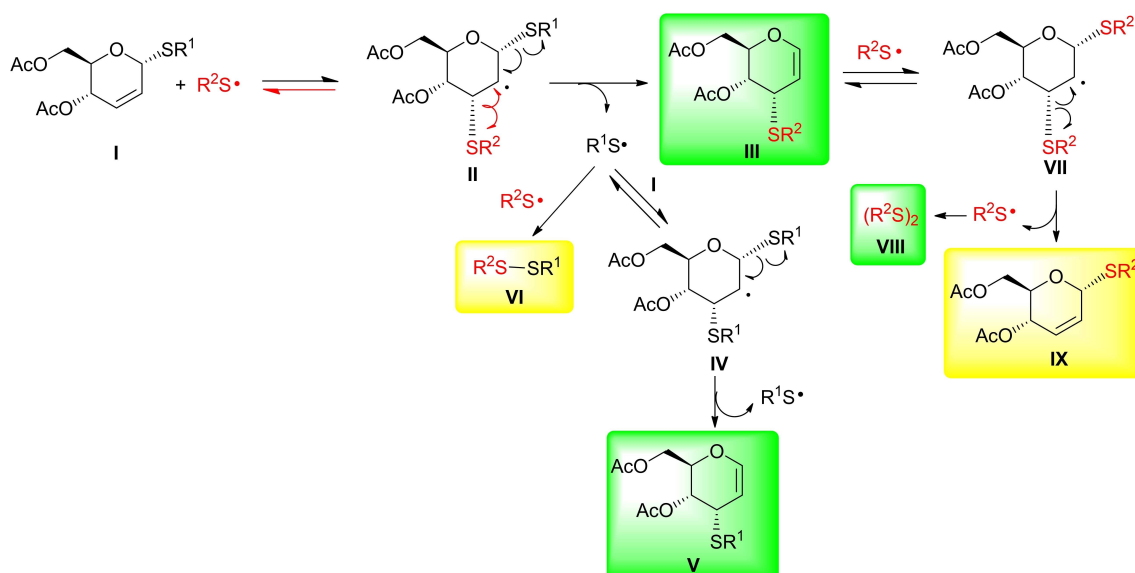
Scheme 7. Proposed mechanism for hydrothiolation of 2,3-unsaturated thioglycosides (Structure of products observed are highlighted in green, further possible products are highlighted in yellow).
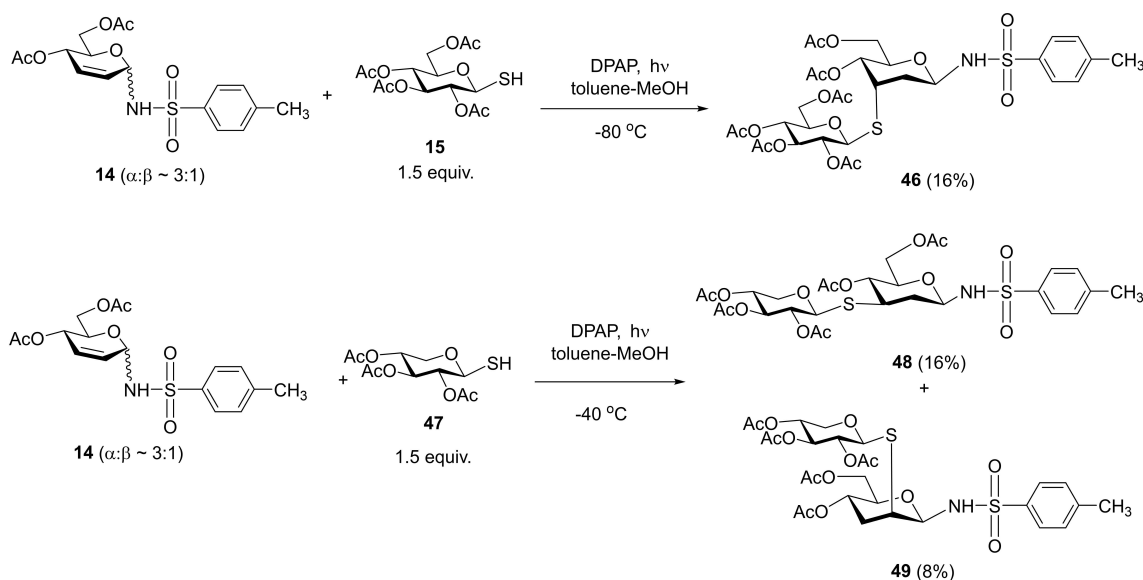
Scheme 8. Hydrothiolation of 2,3-unsaturated *N*-glycoside **14**.

the first time. It has been demonstrated that photoinitiated thiol–ene additions of 2,3-unsaturated-*O*-glycosides proceed with high to complete regioselectivity and stereoselectivity in favor of the C-2-axially-linked products. Additions onto D-*erythro*-configured 2,3-dideoxy-2,3-unsaturated-*O*-glycosides occurred with exclusive regio- and stereoselectivity to afford the D-*arabino*-configured C-2 thioalkylated or thioglycosylated products. The photoinduced thiol–ene coupling proved to be compatible with the 2-bromoethyl aglycone of **5**, and proceeded efficiently both with alkyl and aryl glycosides. Cooling the reaction mixture was generally beneficial to the conversion, however, lower conversions were observed at low temperature with thiol **16**. Hydrothiolation reactions of the D-*threo*-config-

ured glycoside **8** led to a mixture of the C-2-thio and C-3-thio products revealing that the regioselectivity of additions can be modified by changing the configuration of the unsaturated glycosides, and the level of regioselectivity was also found to be controlled by the configuration of the thiols. We have found that the addition occurred with complete axial stereoselectivity at both the C2 and C3 positions, moreover, both the yields and regioselectivity could be effectively increased by cooling. Substitution at C2 position of **9** led to reversed regioselectivity and slightly decreased reactivity, probably due to steric congestion. In this case the stereochemistry of the reaction seems to be unpredictable: addition of α-1-thiomannose

occurred with D-*gluco* selectivity while addition of β-1-thioglucose provided the D-*allo* configured product.

Changing the glycosidic oxygen to carbon, sulfur and nitrogen profoundly affects the reactivity of the C2–C3 double bond. In the case of the *C*-allyl glycoside, the lack of anomeric oxygen slightly decreases the reactivity of the terminal double bond and completely inhibits the radical hydrothiolation of the internal one. The *S*-allyl derivatives are not useful alkenes in thiol–ene reactions, as they suffer allyl rearrangement upon hydrothiolation due to the high lability of the forming 1,3-dithio carbon-centered radical intermediate.

The reactivity of the unsaturated *N*-glycoside **14** and the 2-substituted *O*-glycoside **9** proved to be highly dependent on the anomeric configuration of the enosides and also on the stereochemistry of thiols.

If only moderate/low yields were observed in the thiol–ene reactions, it was the result of moderate/low conversion of the alkene. In these cases, a disulfide by-product was always formed from the thiol but not in significant amounts, and the unreacted thiol and alkene could be recovered from the reaction mixture.

Our results demonstrate that the photoinduced addition of thiols to 2,3-unsaturated *O*-glycosides is a mild, atom economic and efficient method for the synthesis of carbohydrate mimetics with diverse regio- and stereoselectivity. Hydrothiolation reactions of *N*-glycosides are worth further studying because they provide an opportunity to synthesize valuable glycomimetics.

Experimental Section

General method for photoinitiated free radical thioladdition

Ethyl 4,6-di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranoside **3**,[36] 2-bromoethyl 4,6-di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranoside **5**,[37] phenyl 4,6-di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranoside **6**,[36] allyl 4,6-di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranoside **7**,[38] ethyl 4,6-di-*O*-acetyl-2,3-dideoxy-α,β-D-*threo*-hex-2-enopyranoside **8**,[39] ethyl 2,4,6-tri-*O*-acetyl-3-deoxy-α,β-D-*erythro*-hex-2-enopyranoside **9**,[40,41] allyl 2,4,6-tri-*O*-acetyl-3-deoxy-α,β-D-*erythro*-hex-2-enopyranoside **10**,[41] 3-(4,6-Di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranosyl)-1-propene **11**[42] 4,6-di-*O*-acetyl-2,3-dideoxy-1-thio-1-*S*-acetyl-α-D-*erythro*-hex-2-enopyranose **12**,[43] pyperidin-2-yl 4,6-di-*O*-acetyl-2,3-dideoxy-1-thio-α-D-*erythro*-hex-2-enopyranoside **13**,[44] *N*-(4,6-di-*O*-acetyl-2,3-dideoxy-α,β-D-*erythro*-hex-2-enopyranosyl) *p*-toluenesulfonamide **14**,[45] 2,3,4,6-tetra-*O*-acetyl-1-thio-β-D-glucopyranose **15**,[46] mono-*S*-acetyl-ethanedithiol **16**,[47] 2,3,4,6-tetra-*O*-acetyl-1-thio-β-D-galactopyranose **18**,[48] 2,3,4,6-tetra-*O*-acetyl-1-thio-β-D-mannopyranose **28**,[49] 2,3,4,6-tetra-*O*-acetyl-1-thio-α-D-mannopyranose **35**[50] and 2,3,4-tri-*O*-acetyl-1-thio-β-D-xylopyranose **47**[51] were prepared according to the literature procedures. 2-Mercaptoethanol (**17**) and initiator 2,2-dimethoxy-2-phenylacetophenone (DPAP) were purchased from Sigma Aldrich Chemical Co. Optical rotations were measured at room temperature with a Perkin-Elmer 241 automatic polarimeter. TLC was performed on Kieselgel 60 F$_{254}$ (Merck) with detection by UV-light (254 nm) and immersing into sulfuric acidic ammonium–molibdenate solution or 5% ethanolic sulfuric acid followed by heating. Flash column chromatography was performed on Silica gel 60 (Merck 0.040–0.063 mm), column chromatography was performed on Silica gel 60 (Merck 0.063–0.200 mm). Organic solutions were dried over Na$_2$SO$_4$ or MgSO$_4$, and concentrated in

vacuum. One- and two-dimensional ^{1}H, ^{13}C, COSY and HSQC spectra were recorded with Bruker DRX-360 (^{1}H: 360 MHz; ^{13}C: 90 MHz), Bruker DRX-400 (1H: 400 MHz; ^{13}C: 100 MHz) and Avance II 500 (^{1}H: 500.13 MHz; ^{13}C: 125.76 MHz) spectrometers at 25 °C. Chemical shifts are referenced to Me$_4$Si (0.00 ppm for ^{1}H) and to the residual solvent signals (CDCl$_3$: 77.1, CD$_3$OD: 49.3 for ^{13}C). MALDI-TOF MS analyses of the compounds were carried out in the positive reflectron mode using a BIFLEX III mass spectrometer (Bruker, Germany) equipped with delayed-ion extraction. 2,5-Dihydroxybenzoic acid (DHB) was used as matrix and F$_3$CCOONa as cationising agent in DMF. ESI-TOF HRMS spectra were recorded by a microTOF–Q type QqTOFMS mass spectrometer (Bruker) in the positive ion mode using MeOH as the solvent. CCDC deposition number for compound **31**: 1941430.

The photocatalytic reactions were carried out in a borosilicate vessel by irradiation with a 75 W Hg-lamp giving maximum emission at 365 nm. The mercury lamp was placed in a water-cooled immersion mantle. The samples to be irradiated were placed in a 25–50 mL borosilicate flask located ~2 cm away from the lamp. The samples were not purged to remove the oxygen and were not stirred during the reaction. In case of low-temperature reactions, the reaction flask was submerged in a cooling bath (acetone-liquid nitrogen mixture in a Dewar flask). During irradiation, the entire set-up was covered in aluminum foil. The corresponding alkene, thiol and DPAP (DPAP, 0.1 equiv./alkene) were dissolved in the given solvent. The reaction mixture was cooled to the given temperature and was irradiated with UV-light for 15 min. After irradiation another 0.1 equiv. of DPAP dissolved in the given solvent, was added to the reaction mixture and the irradiation continued for another 15 min. The addition of 0.1 equiv. of DPAP and the irradiation was repeated one more time. The solvent was evaporated in vacuo and the crude product was purified by column chromatography or flash column chromatography.

Ethyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-thio-α-D-*arabino*-hexopyranoside (4a)[9]

A: Compound **3** (0.3 mmol, 86 mg) in toluene (2.0 mL) was reacted with thiol **15** (0.36 mmol, 131 mg, 1.2 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 75 : 25) to give compound **4a** (141 mg, 75%) as colourless foam. The reaction was performed in the same scale at −80 °C to **4a** with 82% yield.

B: Compound **3** (0.3 mmol, 86 mg), thiol **15** (0.36 mmol, 131 mg, 1.2 equiv.) and AIBN (0.03 mmol, 5 mg, 0.1 equiv) were dissolved in dry toluene (3.0 mL). The reaction mixture was put in a pressure cylinder and was heated to 120 °C for 6 hours. Afterwards the solvent was evaporated in vacuo. The crude product was purified by flash chromatography to give compound **4a** (21 mg, 11%).

C: Compound **3** (1.0 mmol, 258 mg), thiol **15** (1.2 mmol, 438 mg, 1.2 equiv.), triethylborane solution (15% in *n*-hexane) (1.2 mmol, 0.784 mL, 1.2 equiv) and catechol (1.2 mmol, 132 mg, 1.2 equiv) were dissolved in dry dichloromethane (2.0 mL). The reaction mixture was stirred at room temperature for three days. Afterwards the solvent was evaporated in vacuo. The crude product was purified by flash chromatography to give compound **4a** (420 mg, 67%). $[\alpha]_D^{20}$ + 10.6 (*c* 1.18, CHCl$_3$, lit. [9] $[\alpha]_D^{20}$ + 10.5.

Ethyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2-acetylthioethyl)-2-thio-α-D-*arabino*-hexopyranoside (19)

A: Compound **3** (0.5 mmol, 129 mg) in toluene (3 mL) was reacted with thiol **16** (1.5 mmol, 0.204 mg, 3.0 equiv.) at 0 °C according to the general method. The crude product was purified by flash

chromatography (*n*-hexane/acetone 8:2) to give compound **19** (123 mg, 69%) as yellow syrup.

B: The reaction was repeated at −80 °C with 3.0 equiv. of thiol **16** to give compound **19** with 23% yield. $[\alpha]_D^{20}$ + 76.4 (*c* 0.25, CHCl$_3$); R_f = 0.48 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.05 (dd, *J* = 8.7 Hz, *J* = 15.2 Hz, 1H, H-4), 4.82 (s, 1H, H-1), 4.21 (dd, *J* = 5.6 Hz, *J* = 11.9 Hz, 1H, H-6a), 4.15 (d, *J* = 10.6 Hz, 1H, H-6b), 3.98–3.94 (m, 1H, H-5), 3.80–3.72 (m, 1H, OC*H*$_{2a}$–CH$_3$), 3.59–3.51 (m, 1H, OC*H*$_{2b}$–CH$_3$), 3.07 (dd, *J* = 6.7 Hz, *J* = 8.9 Hz, 3H, H-2, C*H*$_2$–SAc), 2.77–2.73 (m, 2H, SC*H*$_2$), 2.20–2.18 (m, 2H, H-3a,b), 2.35, 2.09, 2.05 (3 × s, 9H, 3 × Ac–CH$_3$), 1.25 (t, *J* = 6.9 Hz, 3H, OCH$_2$–C*H*$_3$) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 195.3 (1C, SCOCH$_3$), 170.9, 169.8 (2C, 2 × OCOCH$_3$), 99.2 (1C, C-1), 69.0 (1C, C-5), 65.4 (1C, C-4), 63.3 (1C, OCH$_2$–CH$_3$), 63.2 (1C, C-6), 44.2 (1C, C-2), 31.8 (1C, SCH$_2$), 30.7, (2C, C-3, SAc–CH$_3$), 29.3 (CH$_2$–SAc), 21.1, 20.8 (2C, 2 × Ac–CH$_3$), 15.1 (1C, OCH$_2$–CH$_3$) ppm; MALDI-TOF HRMS: *m/z* calcd for C$_{16}$H$_{26}$NaO$_7$S$_2$ [M + Na]$^+$ 417.1018, found 417.1014.

Ethyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2-hydroxyethyl)-2-thio-α-D-*arabino*-hexopyranoside (20)

A: Compound **3** (0.5 mmol, 129 mg) in toluene (3 mL) was reacted with thiol **17** (1.0 mmol, 0.078 mL, 2.0 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 8:2) to give compound **20** (78 mg, 46%) as yellow syrup.

B: The reaction was repeated at −80 °C under the same conditions to give compound **20** (116 mg, 68%) as yellow syrup. $[\alpha]_D^{20}$ + 60.0 (*c* 0.14, CHCl$_3$); R_f = 0.19 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.07 (dd, *J* = 7.4 Hz, *J* = 16.6 Hz, 1H, H-4), 4.82 (d, *J* = 1.5 Hz, 1H, H-1), 4.21 (dd, *J* = 5.5 Hz, *J* = 12.0 Hz, 1H, H-6a), 4.16 (dd, *J* = 2.6 Hz, *J* = 11.9 Hz, 1H, H-6b), 3.98–3.95 (m, 1H, H-5), 3.80–3.72 (m, 3H, OC*H*$_{2a,b}$, OC*H*$_{2a}$–CH$_3$), 3.58–3.52 (m, 1H, OC*H*$_{2b}$–CH$_3$), 3.03 (d, *J* = 1.7 Hz, 1H, H-2), 2.83–2.76 (m, 2H, SC*H*$_2$), 2.43 (s, 1H, O*H*), 2.18 (dd, *J* = 4.4 Hz, *J* = 7.2 Hz, 2H, H-3a,b), 2.09, 2.05 (2 × s, 6H, 2 × Ac–CH$_3$), 1.25 (t, *J* = 7.1 Hz, 3H, OCH$_2$–C*H*$_3$) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 171.0, 170.0 (2C, 2 × COCH$_3$), 99.4 (1C, C-1), 69.1 (1C, C-5), 65.6 (1C, C-4), 63.4 (1C, OCH$_2$–CH$_3$), 63.2 (1C, C-6), 61.1 (1C, CH$_2$OH), 44.3 (1C, C-2), 35.5 (1C, SCH$_2$), 30.2, (1C, C-3), 21.1, 20.9 (2C, 2 × Ac–CH$_3$), 15.1 (1C, OCH$_2$–CH$_3$) ppm; MALDI-TOF MS: *m/z* calcd for C$_{14}$H$_{24}$NaO$_7$S [M + Na]$^+$ 359.114, found 359.167.

2-Bromoethyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-thio-α-D-*arabino*-hexopyranoside (21)

Compound **5** (0.57 mmol, 192 mg) in toluene (2.0 mL) was reacted with thiol **15** (0.68 mmol, 249 mg, 1.2 equiv.) at −80 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 75:25) to give compound **21** (378 mg, 95%) as white powder. $[\alpha]_D^{20}$ + 14.1 (*c* 0.29, CHCl$_3$); R_f = 0.18 (*n*-hexane/acetone 7:3); M.p.: 124–126 °C; ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.23 (t, *J* = 9.3 Hz, 1H, H-3′), 5.07 (dd, *J* = 10.0 Hz, *J* = 20.1 Hz, 2H, H-2′, H-4′), 4.92 (s, 1H, H-1), 4.88 (dd, *J* = 5.1 Hz, *J* = 9.3 Hz, 1H, H-4), 4.65 (d, *J* = 10.0 Hz, 1H, H-1′), 4.27 (dd, *J* = 4.8 Hz, *J* = 12.3 Hz, 1H, H-6′a), 4.21–4.11 (m, 3H, H-6a,b, H-6′b), 4.03–3.97 (m, 2H, H-5, OC*H*$_{2a}$), 3.86 (dt, *J* = 5.8 Hz, *J* = 11.3 Hz, 1H, OC*H*$_{2b}$), 3.74–3.72 (m, 1H, H-5′), 3.55 (t, *J* = 5.8 Hz, 2H, C*H*$_2$–Br), 3.30 (s, 1H, H-2), 2.28–2.21 (m, 1H, H-3a), 2.14–2.10 (m, 1H, H-3b), 2.10, 2.09, 2.07, 2.05, 2.03, 2.01 (6 × s, 18H, 6 × Ac–CH$_3$) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.9, 170.6, 170.2, 169.7, 169.5, 169.4 (6C, 6 × COCH$_3$), 100.5 (1C, C-1′), 82.8 (1C, C-1′), 76.2 (1C, C-5′), 73.7 (1C, C-3′), 69.5 (1C, C-2′), 69.4 (1C, C-5), 68.2 (1C, C-4′), 68.0, (1C, OCH$_2$), 65.1 (1C, C-4), 63.0 (1C, C-6), 62.0 (1C, C-6′), 41.8 (1C, C-2), 30.5 (1C, C-3), 30.4

(1C, CH$_2$–Br), 21.1, 20.9, 20.8, 20.7, 20.6 (6C, 6 × Ac–CH$_3$) ppm; ESI-HRMS: *m/z* calcd for C$_{26}$H$_{37}$BrNaO$_{15}$S [M + Na]$^+$ 723.0934, found 723.0910.

2-Bromoethyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2-acetylthioethyl)-2-thio-α-D-*arabino*-hexopyranoside (22)

Compound **5** (0.6 mmol, 202 mg) in toluene (2.0 mL) was reacted with thiol **16** (1.8 mmol, 0.245 mg, 3.0 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 85:15) to give compound **22** (204 mg, 72%) as yellow syrup. R_f = 0.16 (*n*-hexane/acetone 85:15); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.04 (td, *J* = 8.9 Hz, *J* = 6.0 Hz, 1H, H-4), 4.88 (d, *J* = 2.1 Hz, 1H, H-1), 4.18 (d, *J* = 4.2 Hz, 2H), 4.07–3.97 (m, 2H), 3.94–3.83 (m, 1H), 3.54 (t, *J* = 6.0 Hz, 2H C*H*$_2$–Br), 3.15 (td, *J* = 4.3 Hz, *J* = 2.0 Hz, 1H, H-2), 3.11–3.04 (m, 2H), 2.79–2.73 (m, 2H), 2.35 (s, 3H, CH$_3$), 2.23–2.17 (m, 2H, H-3a,b), 2.09 (s, 3H, CH$_3$), 2.06 (s, 3H, CH$_3$) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 195.3 (1C, SCOCH$_3$), 170.8, 169.8 (2C, 2 × OCOCH$_3$), 99.8 (1C, C-1), 69.5 (1C, C-5), 67.9 (1C, OCH$_2$), 65.3 (1C, C-4), 63.1 (1C, C-6), 43.8 (1C, C-2), 31.8 (1C, SCH$_2$), 30.7 (1C, SAc–CH$_3$), 30.4, 29.9, 29.3 (3C, 2 × SCH$_2$ and CH$_2$–Br), 21.1, 20.9 (2C, 2 × OAc–CH$_3$) ppm; MALDI-TOF MS: *m/z* calcd for C$_{16}$H$_{25}$BrNaO$_7$S$_2$ [M + Na]$^+$ 495.012, found 495.08.

2-Bromoethyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2-hydroxyethyl)-2-thio-α-D-*arabino*-hexopyranoside (23)

A: Compound **5** (0.92 mmol, 309 mg) in toluene (2.0 mL) was reacted with thiol **17** (1.84 mmol, 0.128 mL, 2.0 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 8:2) to give compound **23** (115 mg, 32%) as yellow syrup.

B: The reaction was repeated at the same scale at −80 °C to give **23** with 64% yield. $[\alpha]_D^{20}$ + 59.3 (*c* 0.27, CHCl$_3$); R_f = 0.25 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.14–4.99 (m, 1H, H-4), 4.88 (d, *J* = 2.1 Hz, 1H, H-1), 4.18 (d, *J* = 4.2 Hz, 2H), 4.07–3.98 (m, 1H), 3.90–3.83 (m, 1H), 3.76 (t, *J* = 6.0 Hz, 2H, OCH$_2$), 3.54 (t, *J* = 5.9 Hz, 2H, C*H*$_2$–Br), 3.15–3.06 (m, 1H, H-2), 2.81 (t, *J* = 6.0 Hz, 2H), 2.21–2.16 (m, 2H, H-3a,b), 2.12 (d, *J* = 4.9 Hz, 1H), 2.09 (d, *J* = 3.1 Hz, 3H, CH$_3$), 2.06 (s, 3H, CH$_3$), 1.26 (s, 1H) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.8, 170.0 (2C, 2 × COCH$_3$), 99.9 (1C, C-1), 69.5 (1C, C-5), 67.8 (1C, OCH$_2$), 65.3 (1C, C-4), 63.1 (1C, C-6) 61.1 (1C, OCH$_2$), 43.9 (1C, C-2), 35.3 (1C, OCH$_2$), 30.4, 30.0 (2C, SCH$_2$ and CH$_2$–Br), 21.1, 20.8 (2C, 2 × Ac–CH$_3$) ppm; MALDI-TOF MS: *m/z* calcd for C$_{14}$H$_{23}$BrNaO$_7$S [M + Na]$^+$ 437.025, found 437.121.

Phenyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-thio-α-D-*arabino*-hexopyranoside (24)

A: Compound **6** (0.435 mmol, 133 mg) in toluene (2.0 mL) was reacted with thiol **15** (0.522 mmol, 190 mg, 1.2 equiv.) at rt according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 75:25) to give compound **24** (150 mg, 55%) as yellow syrup.

B: The reaction was repeated at 0 °C, to give **24** with 56% yield **C**: The reaction was repeated at −40 °C, the yield of **24** was 68%.

D: The reaction was repeated at −80 °C, the yield of **24** was 74%. $[\alpha]_D^{20}$ −12.7 (*c* 0.33, CHCl$_3$); R_f = 0.25 (n-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.39–7.21 (m, 2H, arom), 7.09–7.00 (m, 3H, arom), 5.63 (s, 1H, H-1), 5.23 (t, *J* = 9.4 Hz, 1H), 5.17–5.03 (m, 2H), 4.95 (td, *J* = 10.3 Hz, *J* = 4.8 Hz, 1H), 4.62 (d, *J* = 9.8 Hz, 1H, H-1′), 4.17 (dt, *J* = 12.4 Hz, *J* = 4.8 Hz, 2H), 4.10 (dd, *J* = 7.8 Hz, *J* = 2.4 Hz, 1H), 3.99 (ddd, *J* = 9.8 Hz, *J* = 5.6 Hz, *J* = 2.4 Hz, 1H), 3.73 (ddd, *J* =

10.0 Hz, $J = 4.1$ Hz, $J = 2.3$ Hz, 1H), 3.59–3.44 (m, 1H), 2.46 (ddd, $J = 13.0$ Hz, $J = 10.7$ Hz, $J = 4.6$ Hz, 1H, H-3a), 2.24 (dt, $J = 13.1$ Hz, $J = 4.3$ Hz, 1H, H-3b), 2.08 (s, 3H, Ac–CH_3), 2.07–2.05 (m, 1H, H-2), 2.04 (s, 3H, Ac–CH_3), 2.00 (s, 6H, 2×Ac–CH_3), 1.98 (s, 3H, Ac–CH_3), 1.78 (s, 3H, Ac–CH_3) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.6, 170.5, 170.0, 169.5, 169.4, 169.3 (6C, 6×COCH$_3$), 156.1 (1C, CAr–O), 129.5, 129.4, 122.4, 116.4 (5C, arom), 97.9 (1C, C-1), 82.5 (1C, C-1′), 76.1, 73.6, 69.5, 69.1, 67.9, 64.7 (6C, skeleton carbons), 62.6, 61.6 (2C, C-6, C-6′), 41.9 (1C, C-2), 30.4 (1C, C-3), 20.9, 20.7, 20.5, 20.5, 20.2 (6C, 6×Ac–CH_3) ppm; ESI-HRMS: m/z calcd for C$_{30}$H$_{38}$NaO$_{15}$S [M + Na]$^+$ 693.1829, found 693.1819.

Phenyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2,3,4,6-tetra-*O*-acetyl-β-D-galactopyranosyl)-2-thio-α-D-*arabino*-hexopyranoside (25)

A: Compound **6** (0.36 mmol, 110 mg) in toluene (2.0 mL) was reacted with thiol **18** (0.432 mmol, 157 mg, 1.2 equiv.) at rt according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 75:25) to give compound **25** (166 mg, 69%) as colourless syrup. **B**: The reaction was repeated at −80 °C to give **25** with 78% yield. [α]$_D^{20}$ + 30.8 (*c* 0.13, CHCl$_3$); $R_f = 0.29$ (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 7.36–7.23 (m, 1H), 7.13–7.00 (m, 3H, arom), 5.64 (s, 1H, H-1), 5.41 (d, $J = 3.3$ Hz, 1H), 5.30 (t, $J = 9.9$ Hz, 1H), 5.05 (dd, $J = 10.0$ Hz, $J = 3.3$ Hz, 1H), 4.98 (td, $J = 10.0$ Hz, $J = 4.7$ Hz, 1H), 4.63 (d, $J = 10.0$ Hz, 1H, H-1′), 4.18–4.00 (m, 4H), 3.94 (t, $J = 6.6$ Hz, 1H), 2.51–2.40 (m, 1H), 2.33–2.22 (m, 1H), 2.19–2.12 (m, 1H), 2.08, 2.05, 2.04, 2.00, 1.99, 1.98 (6 s, 6×3H, 6×Ac–CH_3) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.7, 170.3, 170.1, 169.9, 169.7, 169.6 (6C, COCH$_3$), 156.3 (1C, CAr–O), 129.6, 129.5, 122.6, 117.1, 116.5 (5C, arom), 98.3 (1C, C-1), 83.5 (1C, C-1′), 74.8, 71.8, 69.6, 67.2, 66.6, 64.8 (6C, skeleton carbons), 62.7, 61.4 (2C, C-6), 42.4 (1C, C2), 30.4 (1C, C-3), 21.0, 20.8, 20.7, 20.6, 20.6, 20.5 (6C, 6×Ac–CH_3) ppm; ESI-HRMS: m/z calcd for C$_{30}$H$_{38}$NaO$_{15}$S [M + Na]$^+$ 693.1829, found 693.1814.

3-(2,3,4,6-Tetra-*O*-acetyl-1-thio-β-D-galactopyranosyl)-*n*-propyl 4,6-di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranoside (26)

Compound **7** (0.75 mmol, 200 mg) in toluene (2.0 mL) was reacted with thiol **18** (0.75 mmol, 273 mg, 1.0 equiv.) at −80 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 75:25) to give compound **26** (385 mg, 81%) as yellow syrup. [α]$_D^{20}$ + 28.9 (*c* 0.26, CHCl$_3$); $R_f = 0.1$ (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.96–5.79 (m, 2H, CH=CH), 5.43 (d, $J = 3.3$ Hz, 1H, H-1), 5.31 (dd, $J = 9.7$ Hz, $J = 1.5$ Hz, 1H), 5.23 (t, $J = 10.0$ Hz, 1H), 5.07–5.03 (m, 2H), 4.50 (d, $J = 9.9$ Hz, 1H, H-1′), 4.26 (dd, $J = 12.1$ Hz, $J = 5.3$ Hz, 1H), 4.20 (d, $J = 2.5$ Hz, 1H, H1-S), 4.18–4.11 (m, 2H), 4.12–4.04 (m, 1H), 3.95 (t, $J = 6.7$ Hz, 1H), 3.87 (dt, $J = 9.8$ Hz, $J = 6.1$ Hz, 1H, CH_2O), 3.59 (dt, $J = 9.8$ Hz, $J = 6.1$ Hz, 1H, CH_2O), 2.80 (qt, $J = 12.8$ Hz, $J = 7.2$ Hz, 2H, CH_2S), 2.16 (s, 3H, CH_3), 2.11 (s, 3H, CH_3), 2.09 (s, 3H, CH_3), 2.07 (s, 3H, CH_3), 2.04 (s, 3H, CH_3), 2.00–1.90 (m, 2H, CH_2) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.8, 170.4, 170.3, 170.2, 170.1, 169.5 (6C, 6×COCH$_3$), 129.2, 127.8, (2C CH=CH) 94.5 (1C, C-1), 84.3 (1C, C-1′), 74.5, 71.9, 67.3, 67.2 (4C, skeleton carbons), 67.0 (1C, CH_2O) 67.0, 65.3 (2C, skeleton carbons), 63.0, 61.5 (2C, 2C-6, C-6′), 30.0 (1C, CH_2S), 27.1 (1C, CH_2), 21.0, 20.8, 20.7, 20.6 (6C, 6×Ac–CH_3) ppm; ESI-HRMS: m/z calcd for C$_{27}$H$_{38}$NaO$_{15}$S [M + Na]$^+$ 657.1829, found 657.1829.

3-(2,3,4,6-Tetra-*O*-acetyl-1-thio-β-D-galactopyranosyl)-*n*-propyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-2-thio-α-D-*arabino*-hexopyranoside (27)

Compound **26** (0.55 mmol, 353 mg) in toluene (2.0 mL) was reacted with thiol **15** (0.66 mmol, 240 mg, 1.2 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 7:3) to give compound **27** (482 mg, 88%) as white crystals. [α]$_D^{20}$ + 5.5 (*c* 0.29, CHCl$_3$); $R_f = 0.19$ (*n*-hexane/acetone 7:3); M.p.: 54–57 °C; ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.41 (dd, $J = 3.4$ Hz, $J = 1.2$ Hz, 1H, H-1), 5.20 (td, $J = 9.7$ Hz, $J = 6.2$ Hz, 2H), 5.06 (d, $J = 7.2$ Hz, 1H), 5.05–5.00 (m, 2H), 4.88 (td, $J = 9.8$ Hz, $J = 5.2$ Hz, 1H), 4.80 (d, $J = 1.8$ Hz, 1H), 4.60 (d, $J = 10.0$ Hz, 1H), 4.49 (d, $J = 9.9$ Hz, 1H), 4.40–4.02 (m, 6H), 3.93 (td, $J = 6.7$ Hz, $J = 1.2$ Hz, 1H), 3.85 (ddd, $J = 9.5$ Hz, $J = 5.3$ Hz, $J = 2.7$ Hz, 1H), 3.77–3.73 (m, 1H), 3.70 (ddd, $J = 10.0$ Hz, $J = 5.0$ Hz, $J = 2.4$ Hz, 1H), 3.51 (dt, $J = 9.7$ Hz, $J = 6.1$ Hz, 1H), 3.21 (td, $J = 4.1$ Hz, $J = 1.8$ Hz, 1H), 2.88–2.69 (m, 2H), 2.20–2.10 (m. 2 H), 2.14 (s, 3H, Ac–CH_3), 2.07 (s, 3H, Ac–CH_3), 2.05 (s, 6H, 2×Ac–CH_3), 2.04 (s, 3H, Ac–CH_3), 2.02 (s, 3H, Ac–CH_3), 2.01 (s, 3H, Ac–CH_3), 2.00 (s, 3H, Ac–CH_3), 1.98 (s, 3H, Ac–CH_3), 1.96 (s, 3H, Ac–CH_3), 1.95–1.88 (m, 2H) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.9, 170.5, 170.4, 170.2, 170.1, 170.1, 169.6, 169.6, 169.5, 169.4 (10C, 10×COCH$_3$), 99.9 (1C, C-1), 84.2, 83.1 (2C, C-1′, C-1″), 76.1, 74.4, 73.7, 71.9, 69.6, 69.1, 68.3, 67.3, 67.2, 65.0 (10C, skeleton carbons), 66.1 (1C, OCH$_2$), 63.0, 62.0, 61.3 (3C, C-6, C-6, C-6″), 42.5 (1C, C-2), 30.7, 29.7, 27.0 (3C, C-3 and 2×CH$_2$), 21.0, 20.8, 20.8, 20.7, 20.6 (10C, 10×Ac–CH_3) ppm; ESI-HRMS: m/z calcd for C$_{41}$H$_{58}$NaO$_{24}$S$_2$ [M + Na]$^+$ 1021.2657, found 1021.2663.

3-(2,3,4,6-Tetra-*O*-acetyl-1-thio-β-D-mannopyranosyl)-*n*-propyl 4,6-di-*O*-acetyl-3-deoxy-2-*S*-(2,3,4,6-tetra-*O*-acetyl-β-D-manno-pyranosyl)-2-thio-α-D-*arabino*-hexopyranoside (29) and 3-(2,3,4,6-tetra-*O*-acetyl-1-thio-β-D-mannopyranosyl)-*n*-propyl 4,6-di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranoside (30)

A: Compound **7** (0.6 mmol, 162 mg) in toluene (3.0 mL) was reacted with thiol **28** (1.5 mmol, 546 mg, 2.5 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 65:35) to give compound **29** (448 mg, 75%) as colourless syrup. Compound **30** was detected in MS but could not be isolated in pure form.

B: The reaction was repeated at −80 °C to give **29** with 83% yield.

Data for compound **29**:

[α]$_D^{20}$ + 107.5 (*c* 0.20, CHCl$_3$); $R_f = 0.18$ (*n*-hexane/acetone 65:35); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.38–5.21 (m, 7H), 5.01 (td, $J = 9.8$, 5.4 Hz, 1H), 4.82 (s, 1H), 4.39–4.06 (m, 9H), 3.89 (ddd, $J = 9.9$ Hz, $J = 4.7$ Hz, $J = 3.3$ Hz, 1H), 3.79 (dt, $J = 9.7$ Hz, $J = 6.2$ Hz, 1H), 3.52 (dt, $J = 9.7$ Hz, $J = 5.8$ Hz, 1H), 3.20 (td, $J = 3.8$ Hz, $J = 1.5$ Hz, 1H), 2.79–2.66 (m, 2H), 2.24–2.20 (m 2H, H-3a,b), 2.17 (s, 6H, 2×Ac–CH_3), 2.12 (s, 3H, Ac–CH_3), 2.10 (s, 3H, Ac–CH_3), 2.09 (s, 3H, Ac–CH_3), 2.06 (s, 9H, 3×Ac–CH_3), 2.01 (s, 6H, 2×Ac–CH_3), 1.95 (t, $J = 6.7$ Hz, 2H CH_2) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.8, 170.5, 170.0, 169.8, 169.8, 169.7, 169.7, 169.6 (10C, 10×COCH$_3$), 98.8 (1C, C-1), 82.6, 82.6 (2C, C-1′, C-1″), 71.1, 70.9, 69.4, 69.4, 69.3, 69.2, 69.1, 66.2, 66.0, 64.8, (10C, skeleton carbons), 66.0 (1C, OCH$_2$), 63.0, 62.4, 62.3 (3C, C-6, C-6′, C-6″), 44.9 (1C, C-2), 29.3, 28.2 (2C, 2×CH$_2$), 21.0, 20.9, 20.9, 20.7, 20.7, 20.6 (10C, 10×Ac–CH_3) ppm; ESI-HRMS: m/z calcd for C$_{41}$H$_{58}$NaO$_{24}$S$_2$ [M + Na]$^+$ 1021.2657, found 1021.2664.

Ethyl 4,6-di-O-acetyl-3-deoxy-2-S-(2,3,4,6-tetra-O-acetyl-β-D-glucopyranosyl)-2-thio-α-D-*lyxo*-hexopyranoside (31) and ethyl 4,6-di-O-acetyl-2-deoxy-3-S-(2,3,4,6-tetra-O-acetyl-β-D-glucopyranosyl)-2-thio-α-D-*xylo*-hexopyranoside (32)

A: Compound **8** (1.0 mmol, 258 mg) in toluene (2.0 mL) was reacted with thiol **15** (437 mg, 1.2 mmol, 1.2 equiv) at rt according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 8:2) to give compounds **31** (354 mg, 58%) as white crystals and **32** (124 mg, 20%) as colourless syrup.

B: The reaction was repeated at −80 °C to give **31** and **32** in a 5:1 ratio with 80% combined yield.

Data for compound **31**:

$[\alpha]_D^{20}$ + 103.5 (*c* 0.17, CHCl$_3$); R_f = 0.17 (*n*-hexane/acetone 7:3); M.p: 147–149 °C; ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.22 (t, *J* = 9.4 Hz, 1H, H-3′), 5.07 (dt, *J* = 1.9 Hz, *J* = 9.8 Hz, 2H, H-2′, H-4′), 4.95 (s, 1H, H-1), 4.86 (s, 1H, H-4), 4.44 (d, *J* = 10.0 Hz, 1H, H-1′), 4.27 (dd, *J* = 4.8 Hz, *J* = 12.4 Hz, 1H, H-6′a), 4.16–4.08 (m, 4H, H-5, H-6a,b, H-6′b), 3.78–3.69 (m, 2H, H-5′, OCH_{2a}–CH$_3$), 3.58–3.50 (m, 1H, OCH_{2b}–CH$_3$), 3.08 (dd, *J* = 1.2 Hz, *J* = 2.9 Hz, 1H, H-2), 2.47 (ddd, *J* = 3.2 Hz, *J* = 5.3 Hz, *J* = 15.2 Hz, 1H, H-3a), 2.14–2.08 (m, 1H, H-3b), 2.09, 2.08, 2.05, 2.03, 2.01 (5×s, 18H, 6×Ac–CH_3), 1.25 (t, *J* = 7.1 Hz, 3H, −OCH$_2$–CH_3) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.6, 170.5, 170.3, 170.1, 169.5, 169.3 (6C, 6×COCH$_3$), 100.5 (1C, C-1, $^1J_{C1,H1}$ = 172.7 Hz), 83.2 (1C, C-1′, $^1J_{C1′,H1′}$ = 152.6 Hz), 76.3 (1C, C-5′), 73.7 (1C, C-3′), 69.0 (1C, C-2′), 68.3 (1C, C-4′), 66.5 (1C, C-5), 65.8 (1C, C-4), 63.3, (1C, OCH$_2$–CH$_3$), 63.2 (1C, C-6), 62.0 (1C, C-6′), 38.5 (1C, C-2), 28.4 (1C, C-3), 21.3, 20.8, 20.7, 20.6 (6C, 6×Ac–CH$_3$), 15.1 (1C, OCH$_2$–CH$_3$) ppm; ESI-HRMS: *m/z* calcd for C$_{26}$H$_{38}$NaO$_{15}$S [M + Na]$^+$ 645.1829, found 645.1832.

Data for compound **32**:

$[\alpha]_D^{20}$ −12.0 (*c* 0.40, CHCl$_3$); R_f = 0.18 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.27 (t, *J* = 9.3 Hz, 1H, H-3′), 5.15 (t, *J* = 9.7 Hz, 1H, H-4′), 5.08 (t, *J* = 9.7 Hz, 1H, H-2′), 4.88 (d, *J* = 3.0 Hz, 1H, H-1), 4.83 (s, 1H, H-4), 4.65 (d, *J* = 10.1 Hz, 1H, H-1′), 4.52 (t, *J* = 6.4 Hz, 1H, H-5), 4.25 (dd, *J* = 4.5 Hz, *J* = 12.4 Hz, 1H, H-6′a), 4.19–4.10 (m, 3H, H-6a,b, H-6′b), 3.74 (ddd, *J* = 2.2 Hz, *J* = 4.3 Hz, *J* = 9.8 Hz, 1H, H-5′), 3.71–3.65 (m, 1H, OCH_{2a}–CH$_3$), 3.50–3.42 (m, 2H, H-3, OCH_{2b}–CH$_3$), 2.35 (ddd, *J* = 3.7 Hz, *J* = 6.1 Hz, *J* = 14.7 Hz, 1H, H-2a), 2.12, 2.08, 2.06, 2.03, 2.02 (6×s, 18H, 6×Ac–CH_3), 1.78 (d, *J* = 14.3 Hz, 1H, H-2b), 1.21 (t, *J* = 7.1 Hz, 3H, −OCH$_2$–CH_3) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.8, 170.7, 170.5, 170.4, 169.5, 169.4 (6C, 6×COCH$_3$), 95.6 (1C, C-1, $^1J_{C1,H1}$ = 165.5 Hz), 82.9 (1C, C-1′, $^1J_{C1′,H1′}$ = 154.2 Hz), 76.3 (1C, C-5′), 74.1 (1C, C-3′), 70.2 (1C, C-4), 69.4 (1C, C-2′), 68.4 (1C, C-4′), 63.7 (1C, C-6), 62.9, (1C, OCH$_2$–CH$_3$), 62.7 (1C, C-5), 62.1 (1C, C-6′), 36.4 (1C, C-3), 29.9 (1C, C-2), 21.1, 20.9, 20.8, 20.7 (6C, 6×Ac–CH$_3$), 15.1 (1C, OCH$_2$–CH$_3$) ppm; ESI-HRMS: *m/z* calcd for C$_{26}$H$_{38}$NaO$_{15}$S [M + Na]$^+$ 645.1829, found 645.1826.

Ethyl 4,6-di-O-acetyl-3-deoxy-2-S-(2,3,4,6-tetra-O-acetyl-β-D-galactopyranosyl)-2-thio-α-D-*lyxo*-hexopyranoside (33) and ethyl 4,6-di-O-acetyl-2-deoxy-3-S-(2,3,4,6-tetra-O-acetyl-β-D-galactopyranosyl)-2-thio-α-D-*xylo*-hexopyranoside (34)

A: Compound **8** (0.79 mmol, 203 mg) in toluene (2.0 mL) was reacted with thiol **18** (350 mg, 0.96 mmol, 1.2 equiv) at rt according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 8:2) to give compounds **33** (291 mg, 59%) as colourless syrup and **34** (77 mg, 15%) as colourless syrup.

B: The reaction was repeated at −40 °C in methanol to give compounds **33** and **34** with 69% overall yield, **33** to **34** ratio was 6.7:1.

C: The reaction was repeated at −80 °C to give compounds **33** and **34** with 73% overall yield, **33** to **34** ratio was 7.3:1.

Data for compound **33**:

$[\alpha]_D^{20}$ + 25.2 (*c* 0.31, CHCl$_3$); R_f = 0.26 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.43 (d, *J* = 2.2 Hz, 1H, H-4′), 5.27 (t, *J* = 10.0 Hz, 1H, H-2′), 5.05 (dd, *J* = 3.3 Hz, *J* = 10.0 Hz, 1H, H-3′), 4.96 (s, 1H, H-1), 4.87 (s, 1H, H-4), 4.44 (d, *J* = 9.9 Hz, 1H, H-1′), 4.17–4.05 (m, 5H, H-5, H-6a,b, H-6′a,b), 3.96 (t, *J* = 6.4 Hz, 1H, H-5′), 3.78–3.72 (m, 1H, OCH_{2a}–CH$_3$), 3.60–3.54 (m, 1H, OCH_{2b}–CH$_3$), 3.13 (dd, *J* = 1.0 Hz, *J* = 3.2 Hz, 1H, H-2), 2.48 (ddd, *J* = 3.1 Hz, *J* = 5.3 Hz, *J* = 15.2 Hz, 1H, H-3a), 2.21–2.15 (m, 1H, H-3b), 2.18, 2.16, 2.10, 2.06, 2.05, 1.99 (6×s, 18H, 6×Ac–CH_3), 1.25 (t, *J* = 7.0 Hz, 3H, OCH$_2$–CH_3) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.7, 170.4, 170.3, 170.2, 170.1, 169.6 (6C, 6×Ac–CO), 100.4 (1C, C-1, $^1J_{C1,H1}$ = 171.9 Hz), 83.7 (1C, C-1′, $^1J_{C1′,H1′}$ = 153.5 Hz), 74.7 (1C, C-5′), 71.8 (1C, C-3′), 67.3 (1C, C-4′), 66.5 (1C, C-5), 66.4 (1C, C-2′), 65.8 (1C, C-4), 63.3, (1C, OCH$_2$–CH$_3$), 63.2 (1C, C-6), 61.4 (1C, C-6′), 38.5 (1C, C-2), 28.4 (1C, C-3), 21.3, 20.8, 20.7, 20.6 (6C, 6×Ac–CH$_3$), 15.1 (1C, −OCH$_2$–CH$_3$) ppm; ESI-HRMS: *m/z* calcd for C$_{26}$H$_{38}$NaO$_{15}$S [M + Na]$^+$ 645.1829, found 645.1832.

Data for compound **34**:

$[\alpha]_D^{20}$ −41.7 (*c* 0.06, CHCl$_3$); R_f = 0.27 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.44 (t, *J* = 2.9 Hz, 1H, H-4′), 5.27 (t, *J* = 10.0 Hz, 1H, H-2′), 5.09 (dd, *J* = 3.2 Hz, *J* = 9.9 Hz, 1H, H-3′), 4.88 (s, 2H, H-1, H-4), 4.60 (d, *J* = 10.0 Hz, 1H, H-1′), 4.52 (t, *J* = 6.2 Hz, 1H, H-5), 4.20–4.09 (m, 4H, H-6a,b, H-6′a,b), 3.95 (t, *J* = 6.6 Hz, 1H, H-5′), 3.72–3.65 (m, 1H, OCH_{2a}–CH$_3$), 3.48–3.44 (m, 1H, OCH_{2b}–CH$_3$), 3.41–3.39 (m, 1H, H-3), 2.38 (ddd, *J* = 3.5 Hz, *J* = 5.6 Hz, *J* = 14.6 Hz, 1H, H-2a), 2.15, 2.12, 2.08, 2.04, 1.99 (5×s, 18H, 6×Ac–CH_3), 1.82 (d, *J* = 14.5 Hz, 1H, H-2b), 1.22 (t, *J* = 7.0 Hz, 3H, OCH$_2$–CH_3) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.7, 170.4, 170.1, 169.6 (6C, 6×COCH$_3$), 95.7 (1C, C-1, $^1J_{C1,H1}$ = 167.1 Hz), 83.5 (1C, C-1′, $^1J_{C1′,H1′}$ = 154.0 Hz), 74.8 (1C, C-5′), 72.0 (1C, C-3′), 70.1 (1C, C-4), 67.3 (1C, C-4′), 66.8 (1C, C-2′), 63.6 (1C, C-6), 62.8 (1C, OCH$_2$–CH$_3$), 62.7 (1C, C-5), 61.3 (1C, C-6′), 36.7 (1C, C-3), 30.0 (1C, C-2), 21.1, 20.9, 20.8, 20.7 (6C, 6×Ac–CH$_3$), 15.1 (1C, −OCH$_2$–CH$_3$) ppm; ESI-HRMS: *m/z* calcd for C$_{26}$H$_{38}$NaO$_{15}$S [M + Na]$^+$ 645.1829, found 645.1837.

Ethyl 2,3,6-tri-O-acetyl-3-S-(2,3,4,6-tetra-O-acetyl-α-D-mannopyranosyl)-3-thio-α-D-glucopyranoside (36)

A: Compound **9** (0.5 mmol, 158 mg) in toluene (2.0 mL) was reacted with thiol **35** (0.6 mmol, 218 mg, 1.2 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 8:2) to give compound **36** (119 mg, 35%) as colourless syrup.

B: The reaction was repeated at −80 °C to give **36** with 68% yield. $[\alpha]_D^{20}$ + 93.9 (*c* 0.23, CHCl$_3$); R_f = 0.31 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.40 (s, 1H, H-1′), 5.33 (t, *J* = 9.5 Hz, 1H, H-4′), 5.21–5.18 (m, 2H, H-2′, H-3′), 5.04 (t, *J* = 10.4 Hz, 1H, H-4), 5.01 (d, *J* = 3.3 Hz, 1H, H-1), 4.79 (dd, *J* = 3.4 Hz, *J* = 11.8 Hz, 1H, H-2), 4.40–4.30 (m, 2H, H-5′, H-6′a), 4.19–4.10 (m, 2H, H-6a, H-6′b), 4.04 (dd, *J* = 2.5 Hz, *J* = 12.3 Hz, 1H, H-6b), 3.90 (ddd, *J* = 2.6 Hz, *J* = 4.7 Hz, *J* = 9.7 Hz, 1H, H-5), 3.76–3.68 (m, 1H, OCH_{2a}–CH$_3$), 3.57–3.49 (m, 1H, OCH_{2b}–CH$_3$), 3.46 (t, *J* = 11.3 Hz, 1H, H-3), 2.16, 2.14, 2.12, 2.08, 2.05, 2.00 (6×s, 21H, 7×Ac–CH_3), 1.21 (t, *J* = 7.1 Hz, 3H, OCH$_2$–CH_3) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.8, 170.0, 169.9, 169.7, 169.6 (7C, 7×COCH$_3$), 95.1 (1C, C-1, $^1J_{C1,H1}$ = 171.9 Hz), 82.6 (1C, C-1′, $^1J_{C1′,H1′}$ = 172.5 Hz), 71.5 (1C, C-2′), 70.3 (2C, C-2, C-4), 69.6 (1C, C-5′), 69.1 (1C, C-3′), 68.7 (1C, C-5), 66.2 (1C, C-4′), 63.9, (1C, OCH$_2$–CH$_3$), 62.5 (1C, C-

6), 62.1 (1C, C-6′), 46.2 (1C, C-3), 21.0, 20.8, 20.7, 20.6 (7C, 7×Ac–CH$_3$), 15.0 (1C, –OCH$_2$–CH$_3$) ppm; MALDI-TOF HRMS: *m/z* calcd for C$_{28}$H$_{40}$NaO$_{17}$S [M+Na]$^+$ 703.1884, found 703.1793.

Ethyl 2,3,6-tri-*O*-acetyl-3-*S*-(2,3,4,6-tetra-*O*-acetyl-α-D-glucopyranosyl)-3-thio-α-D-allopyranoside (37)

A: Compound **9** (0.5 mmol, 158 mg) in toluene (2.0 mL) was reacted with thiol **15** (0.6 mmol, 218 mg, 1.2 equiv.) at 0 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 8:2) to give compound **37** (140 mg, 42%) as colourless syrup.

B: The reaction was repeated at −80 °C to give **37** with 50% yield. [α]$_D^{20}$+30.8 (*c* 0.49, CHCl$_3$); R_f=0.27 (*n*-hexane/acetone 7:3); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.13 (t, *J*=9.3 Hz, 1H, H-3′), 5.04–4.97 (m, 3H, H-2, H-4, H-4′), 4.39 (t, *J*=9.6 Hz, 1H, H-2′), 4.84 (d, *J*=3.4 Hz, 1H, H-1), 4.32 (dd, *J*=4.6 Hz, *J*=12.0 Hz, 1H, H-6′a), 4.25 (dd, *J*=4.9 Hz, *J*=12.3 Hz, 1H, H-6a), 4.15 (dd, *J*=2.2 Hz, *J*=11.4 Hz, 1H, H-6′b), 4.13 (d, *J*=7.5 Hz, 1H, H-5′), 4.03 (dd, *J*=1.5 Hz, *J*=12.4 Hz, 1H, H-6b), 3.95 (t, *J*=4.7 Hz, 1H, H-3), 3.75–3.71 (m, 1H, OCH$_2$a), 3.61–3.55 (m, 2H, OCH$_2$b, H-5), 2.16, 2.12, 2.09, 2.08, 2.01, 2.00 (6×s, 21H, 7×Ac–CH$_3$), 1.26 (t, J=7.0 Hz, 3H, CH$_3$) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.7, 170.2, 170.0, 169.8, 169.4, 169.0 (7C, 7×COCH$_3$), 95.5 (1C, C-1, $^1J_{C1,H1}$=169.0 Hz), 85.9 (1C, C-1′, $^1J_{C1',H1'}$=156.4 Hz), 75.8 (1C, C-5), 73.9 (1C, C-3′), 70.6 (1C, C-2′), 68.0, 67.9 (2C, C-2, C-4), 67.3 (1C, C-4′), 64.6 (1C, C-5′), 63.8 (1C, –OCH$_2$), 62.3 (1C, C-6′), 61.9 (1C, C-6), 46.5 (1C, C-3), 20.8, 20.7, 20.6, 20.5 (7C, 7×Ac–CH$_3$), 14.8 (1C, CH$_3$), ppm; MALDI-TOF MS: *m/z* calcd for C$_{28}$H$_{40}$NaO$_{17}$S [M+Na]$^+$ 703.188, found 703.215.

3-(2,3,4,6-Tetra-*O*-acetyl-1-thio-β-D-glucopyranosyl)-*n*-propyl 2,4,6-tri-*O*-acetyl-3-deoxy-α,β-D-*erythro*-hex-2-enopyranoside (38)

Compound **10** (0.5 mmol, 164 mg) in toluene (2.0 mL) was reacted with thiol **15** (0.6 mmol, 218 mg, 1.2 equiv.) at −80 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/ethyl acetate 55:45) to give compound **38** (314 mg, 90%) as colourless syrup, with anomeric ratio α:β= 2:1. R_f=0.39 (*n*-hexane/acetone 7:3).

NMR data for the anomers from the spectrum of the anomeric mixture.

Data for compound **38α** given from the spectrum of the anomeric mixture:

^{1}H NMR (400 MHz, CDCl$_3$) δ 5.72 (d, *J*=1.9 Hz, 1H, H-3), 5.46 (dd, *J*=1.2 Hz, *J*=9.4 Hz, 1H, H-4), 5.25–5.20 (m, 1H, H-3′), 5.11–5.00 (m, 3H, H-1, H-2′, H-4′), 4.51 (d, *J*=10.0 Hz, 1H, H-1′), 4.27–4.20 (m, 3H, H-6a,b, H-6′a), 4.15–4.10 (m, 2H, H-5, H-6′b), 3.86 (dt, *J*=6.0 Hz, *J*=12.0 Hz, 1H, OCH$_2$a), 3.74–3.71 (m, 1H, H-5′), 3.64–3.59 (m, 1H, OCH$_2$b), 2.83–2.69 (m, 2H, SCH$_2$), 2.18, 2.11, 2.08, 2.06, 2.03, 2.01 (6×s, 21H, 7×CH$_3$), 1.92 (ddd, *J*=6.8 Hz, J=13.6 Hz, J=16.5 Hz, 2H, CH$_2$) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.7, 170.6, 170.3, 170.2, 170.1, 169.5, 168.2 (7C, 7×COCH$_3$), 146.3 (1C, C-2), 115.4 (1C, C-3), 94.1 (1C, C-1), 83.6 (1C, C-1′), 75.9 (1C, C-5′), 73.8 (1C, C-3′), 69.8 (1C, C-2′), 68.3 (1C, C-4′), 67.3 (1C, OCH$_2$), 67.2 (1C, C-5), 65.3 (1C, C-4), 62.6 (1C, C-6), 62.1 (1C, C-6′), 29.8, (1C, SCH$_2$), 26.7 (1C, CH$_2$), 21.0, 20.9, 20.8, 20.7, 20.6 (7C, 7×CH$_3$) ppm.

Data for compound **38β** given from the spectrum of the anomeric mixture:

^{1}H NMR (400 MHz, CDCl$_3$) δ 5.78 (d, *J*=4.5 Hz, 1H, H-3), 5.33 (t, *J*=4.3 Hz, 1H, H-4), 5.25–5.20 (m, 2H, H-1, H-3′), 5.11–5.00 (m, 2H, H-2′, H-4′), 4.51 (d, *J*=10.0 Hz, 1H, H-1′), 4.27–4.20 (m, 3H, H-6a,b, H-6′a), 4.15–4.10 (m, 2H, H-5, H-6′b), 3.86 (dt, *J*=6.0 Hz, *J*=12.0 Hz, 1H, OCH$_2$a), 3.74–3.71 (m, 1H, H-5′), 3.64–3.59 (m, 1H, OCH$_2$b), 2.83–2.69 (m, 2H, SCH$_2$), 2.18, 2.10, 2.08, 2.06, 2.03, 2.01 (6×s, 21H, 7×CH$_3$), 1.92 (ddd, *J*=6.8 Hz, J=13.6 Hz, J=16.5 Hz, 2H, CH$_2$) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.7, 170.6, 170.3, 170.2, 170.1, 169.5, 168.2 (7C, 7×COCH$_3$), 148.1 (1C, C-2), 112.5 (1C, C-3), 93.9 (1C, C-1), 84.0 (1C, C-1′), 75.8 (1C, C-5′), 73.8 (1C, C-3′), 72.7 (1C, C-5), 69.9 (1C, C-2′), 68.3 (1C, C-4′), 66.9 (1C, OCH$_2$), 65.6 (1C, C-4), 63.1 (1C, C-6), 62.2 (1C, C-6′), 29.8, (1C, SCH$_2$), 27.1 (1C, CH$_2$), 21.0, 20.9, 20.8, 20.7, 20.6 (7C, 7×CH$_3$) ppm.

ESI-HRMS: *m/z* calcd for C$_{29}$H$_{40}$NaO$_{17}$S [M+Na]$^+$ 715.1884, found 715.1870.

3-(4,6-Di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranosyl)-propyl 2,3,4,6-tetra-*O*-acetyl-1-thio-β-D-glucopyranoside (39)

A: Compound **11** (0.86 mmol, 220 mg) in toluene (7.0 mL) was reacted with thiol **15** (0.86 mmol, 313 mg, 1.0 equiv.) at rt according to the general method. The crude product was purified by flash chromatography (CH$_2$Cl$_2$/acetone 95:5) to give compound **39** (213 mg, 40%) as colourless syrup.

B: The reaction was repeated with 2.5 equiv. of thiol **15** (2.15 mmol, 782 mg) at −80 °C to give compound **39** (308 mg, 58%) as colourless syrup. R_f=0.48 (*n*-hexane/acetone 6:4); ^{1}H NMR (400 MHz, CDCl$_3$) δ 5.90 (ddd, J_{gem}=10.4 Hz, *J*=2.5 Hz, J_{gem}=1.5 Hz, 1H, CH=CH), 5.78 (ddd, *J*=10.4 Hz, *J*=3.0 Hz, *J*=2.0 Hz, 1H, CH=CH), 5.22 (t, *J*=9.4 Hz, 1H), 5.14–5.11 (m, 1H), 5.11–5.00 (m, 2H), 4.50 (d, *J*=10.0 Hz, 2H, H-1′), 4.29–4.24 (m, 1H), 4.23 (t, *J*=2.1 Hz, 1H), 4.15 (d, *J*=3.0 Hz, 1H), 4.13–4.10 (m, 1H), 3.92 (td, *J*=6.4 Hz, *J*=3.6 Hz, 1H), 3.73 (ddd, *J*=10.0 Hz, *J*=4.8 Hz, *J*=2.4 Hz, 1H), 2.84–2.65 (m, 2H, CH$_2$–S), 2.10, 2.08, 2.08, 2.06, 2.03, 2.01 (6 s, 6×3H, 6 Ac–CH$_3$), 1.84–1.60 (m, 4H CH$_2$–C) ppm; ^{13}C NMR (100 MHz, CDCl$_3$) δ 170.7, 170.5, 170.3, 170.1, 169.3, 169.3 (6C, 6×COCH$_3$), 133.3, 123.5 (2C, C-2, C-3), 83.4 (1C, C-1′), 75.8, 73.8, 71.1, 69.8, 69.7, 68.3, 65.0 (7C, skeleton carbons), 62.7, 62.1 (2C, C-6, C-6′), 31.8, 29.4, 25.8 (3C, 3×CH$_2$ linker), 21.0, 20.8, 20.7, 20.7, 20.5, 20.5 (6C, 6×Ac–CH$_3$) ppm; ESI-HRMS MS: *m/z* calcd for C$_{27}$H$_{38}$NaO$_{14}$S [M+Na]$^+$ 641.1880, found 641.1876.

3-(4,6-Di-*O*-acetyl-2,3-dideoxy-α-D-*erythro*-hex-2-enopyranosyl)-propyl 2,3,4,6-tetra-*O*-acetyl-1-thio-β-D-galactopyranoside (41)

Compound **11** (1.0 mmol, 254 mg) in toluene (3.0 mL) was reacted with thiol **18** (3.0 mmol, 1.09 g, 3.0 equiv.) at −40 °C according to the general method. The crude product was purified by flash chromatography (*n*-hexane/acetone 7:3) to give compound **41** (301 mg, 49%) as yellow syrup. Compound **42**, sulfoxide derivative of **41**, was detected from the reaction mixture by MS. [α]$_D^{20}$+6.43 (*c* 0.14, CHCl$_3$); R_f=0.24 (*n*-hexane/acetone 7:3); ^{1}H NMR (360 MHz, CDCl$_3$) δ 5.90 (dt, J_{gem}=10.3 Hz, *J*=1.7 Hz, 1H, CH=CH), 5.79 (dt, J_{gem}=10.4 Hz, *J*=2.4 Hz, 1H, CH=CH), 5.43 (d, *J*=3.2 Hz, 1H), 5.23 (t, *J*=9.9 Hz, 1H), 5.12 (ddt, *J*=6.5 Hz, *J*=3.2 Hz, *J*=1.7 Hz, 1H), 5.05 (dd, *J*=10.0 Hz, *J*=3.4 Hz, 1H), 4.50 (d, *J*=9.9 Hz, 1H, H-1), 4.23 (tt, *J*=12.3 Hz, *J*=6.4 Hz, 2H), 4.17–4.07 (m, 3H), 4.01–3.80 (m, 2H), 2.88–2.68 (m, 2H, CH$_2$S), 2.16 (s, 4H), 2.13–2.02 (m, 12H, 4×Ac–CH$_3$), 2.01 (s, 3H), 1.75 (dddd, *J*=29.5 Hz, *J*=22.1 Hz, *J*=10.0 Hz, *J*=4.4 Hz, 4H, CH$_2$–CH$_2$) ppm; ^{13}C NMR (90 MHz, CDCl$_3$) δ 170.7, 170.3, 170.3, 170.1, 169.9, 169.5 (6C, 6×COCH$_3$), 133.2, 123.5 (2C, C=C), 83.9 (1C, C-1′), 74.4, 71.8, 71.1, 69.7, 67.2, 67.2, 64.9 (7C, skeleton carbons), 62.7, 61.4 (2C, C-6, C-6′), 31.9, 29.7, 25.8, (3C, 3×CH$_2$ linker), 21.0, 20.8, 20.6, 20.5 (6C, 6×Ac–CH$_3$) ppm; ESI-HRMS: *m/z* calcd for **41**C$_{27}$H$_{38}$NaO$_{14}$S [M+Na]$^+$ 641.1880, found 641.1876.

MALDI-TOF MS m/z calcd for **42**$C_{27}H_{38}NaO_{15}S$ [M+Na]$^+$ 657.182, found 657.010.

4,6-Di-*O*-acetyl-3-*S*-acetyl-3-thio-1,5-anhydro-D-*ribo*-hex-1-en-itol (43), 4,6-di-*O*-acetyl-3-*S*-(2,3,4,6-tetra-*O*-acetyl-α-D-mannopyranosyl)-3-thio-1,5-anhydro-D-*ribo*-hex-1-enitol (44) and bis-(2,3,4,6-tetra-*O*-acetyl-1-thio-α-D-mannopyranosyl)-1,1′-disulfide (45)

Compound **12** (0.6 mmol, 170 mg) in toluene (5.0 mL) was reacted with thiol **35** (0.9 mmol, 322 mg, 1.5 equiv.) at room temperature according to the general method. The crude product was purified by flash chromatography (*n*-hexane/ethyl acetate 7:3) to give compound **43** (27 mg, 16%) as colourless syrup, compound **44** (60 mg, 18%) as colourless syrup, and **45**[11,52] (14 mg, 3%) as white foam.

Compound **44** was also obtained from **13** with 40% yield by reacting **13** and **35** according to the general method.

Data for compound **43**:

$[α]_D^{20}$ +202.9 (*c* 0.13, CHCl₃); R_f=0.31 (*n*-hexane/ethyl acetate 6:4); ¹H NMR (400 MHz, CDCl₃) δ 6.42 (d, *J*=5.9 Hz, 1H, H-1), 5.36 (dd, *J*=9.8 Hz, *J*=4.7 Hz, 1H), 4.79 (t, *J*=5.8 Hz, 1H), 4.50–4.44 (m, 1H), 4.42–4.33 (m, 1H), 4.32–4.28 (m, 1H), 4.19–4.07 (m, 1H), 2.32 (s, 3H, S*Ac*–C*H₃*), 2.09, 1.99 (2 s, 2×3H, 2 O*Ac*–C*H₃*); ¹³C NMR (100 MHz, CDCl₃) δ 170.8, 169.4 (2C, 2×*C*OCH₃), 145.6 (1C, C-1), 97.6 (1C, C-2), 72.2, 66.0 (2C, C-4, C-5), 62.1 (1C, C-6), 39.4 (1C, C-3), 30.2 (1C, S*Ac*–C*H₃*), 20.8, 20.7 (2C, 2×O*Ac*–C*H₃*) ppm; ESI-HRMS: m/z calcd for $C_{12}H_{16}NaO_6S$ [M+Na]$^+$ 311.0565, found 311.0559.

Data for compound **44**:

$[α]_D^{20}$ +311.9 (*c* 0.28, CHCl₃); R_f=0.78 (*n*-hexane/ethyl acetate 6:4); ¹H NMR (400 MHz, CDCl₃) δ 6.45 (d, *J*=6.0 Hz, 1H, H-1), 5.39–5.31 (m, 2H) 5.30–5.26 (m, 1H), 5.16 (dd, *J*=8.8 Hz, *J*=5.0 Hz, 1H), 4.94 (t, *J*=5.7 Hz, 1H), 4.41–4.24 (m, 6H), 4.11 (dd, *J*=9.5 Hz, *J*=4.5 Hz, 1H), 4.06 (d, *J*=4.8 Hz, 1H), 2.18, 2.16, 2.11, 2.10, 2.06, 2.00 (6 s, 6×3H, 6 *Ac*–C*H₃*) ppm; ¹³C NMR (100 MHz, CDCl₃) δ 170.7, 170.1, 170.0, 170.0, 169.8 (6C, 6×*C*OCH₃), 145.3 (1C, *C*-1), 97.9 (1C, *C*-2), 81.0 (1C, *C*-1′), 71.4, 71.2, 69.7, 69.6, 67.7, 66.2, (1C, skeletal, carbons), 62.3, 62.1 (2C, *C*-6, C-6′), 39.8 (1C, *C*-3), 21.1, 20.9, 20.8, 20.7 (6C, 6× *Ac*–C*H₃*) ppm; ESI-HRMS: m/z calcd for, $C_{24}H_{32}NaO_{14}S$ [M+Na]$^+$ 599.1410, found 599.1403.

N-(4,6-Di-*O*-acetyl-2-deoxy-3-thio-3-*S*-(2,3,4,6-tetra-*O*-acetyl-β-D-glucopyranosyl)-β-D-*ribo*-hexopyranosyl) *p*-toluenesulfonamide (46)

Compound **14** (0.5 mmol, 192 mg) in toluene (2.0 mL) and MeOH (1.0 mL) was reacted with thiol **15** (0.75 mmol, 273 mg, 1.5 equiv.) at −80 °C according to the general method. The crude product was purified by flash chromatography (toluene/acetone 9:1) to give compound **46** (62 mg, 16%) as colourless syrup. $[α]_D^{20}$ +57.4 (*c* 0.19, CHCl₃); R_f=0.28 (*n*-hexane/acetone 6:4); ¹H NMR (400 MHz, CDCl₃) δ 7.78–7.25 (m, 4H, arom), 5.49 (d, *J*=9.9 Hz, 1H, N*H*), 5.18 (t, *J*=9.4 Hz, 1H, H-3′), 5.10 (dt, *J*=2.0 Hz, *J*=10.3 Hz, 1H, H-4′), 5.07 (t, *J*=9.7 Hz, 1H, H-1), 4.97 (t, *J*=9.6 Hz, 1H, H-2′), 4.71 (dd, *J*=4.3 Hz, *J*=9.7 Hz, 1H, H-4), 4.53 (d, *J*=10.0 Hz, 1H, H-1′), 4.21–4.11 (m, 2H, H-6′a,b), 4.00 (dd, *J*=4.6 Hz, *J*=12.1 Hz, 1H, H-6a), 3.87–3.81 (m, 3H, H-3, H-5, H-6b), 3.67–3.62 (m, 1H, H-5′), 2.41 (s, 3H, Ph–C*H₃*), 2.32–2.28 (m, 1H, H-2a), 2.12–2.08 (m, 1H, H-2b), 2.10, 2.06, 2.05, 2.03, 2.01, 2.00 (6×s, 18H, 6× *Ac*–C*H₃*) ppm; ¹³C NMR (100 MHz, CDCl₃) δ 170.9, 170.6, 170.3, 169.8, 169.5, 169.4 (6C, 6×*C*OCH₃), 143.7, 138.7 (2C, 2×C$_q$ arom), 129.4, 127.2 (4C, arom), 84.1 (1C, C-1′, $^1J_{C1',H1'}$=153.7 Hz), 79.1 (1C, C-1, $^1J_{C1,H1}$=155.3 Hz), 76.2 (1C, C-5′), 73.8 (1C, C-

3′), 72.1 (1C, C-5) 70.5 (1C, C-2′), 68.5 (1C, C-4), 68.1 (1C, C-4′), 62.7 (1C, C-6), 62.0 (1C, C-6′), 42.9 (1C, C-3), 37.8 (1C, C-2), 21.6 (1C, Ph–C*H₃*), 20.9, 20.8, 20.7, 20.6 (6C, 6×*Ac*–C*H₃*) ppm; MALDI-TOF HRMS: m/z calcd for $C_{31}H_{41}NNaO_{16}S_2$ [M+Na]$^+$ 747.1867, found 747.1859.

N-(4,6-Di-*O*-acetyl-2-deoxy-3-thio-3-*S*-(2,3,4-tri-*O*-acetyl-β-D-xylopyranosyl)-β-D-*arabino*-hexopyranosyl) *p*-toluenesulfonamide (48) and *N*-(4,6-di-*O*-acetyl-3-deoxy-2-thio-2-*S*-(2,3,4-tri-*O*-acetyl-β-D-xylopyranosyl)-β-D-*arabino*-hexopyranosyl) *p*-toluenesulfonamide (49)

Compound **14** (0.5 mmol, 192 mg) in toluene (2.0 mL) and MeOH (1.0 mL) was reacted with thiol **47** (0.75 mmol, 219 mg, 1.5 equiv.) at −40 °C according to the general method. The crude product was purified by flash chromatography (toluene/acetone 9:1) to give compound **48** (54 mg, 16%) as colourless syrup and compound **49** (27 mg, 8%) as colourless syrup.

Data for compound **48**:

$[α]_D^{20}$ −17.1 (*c* 0.24 CHCl₃); R_f=0.24 (toluene/acetone 9:1); ¹H NMR (400 MHz, CDCl₃) δ 7.83–7.27 (m, 4H, arom), 5.48 (d, *J*=10.1 Hz, 1H, N*H*), 5.14 (t, *J*=7.7 Hz, 1H, H-3′), 4.92–4.84 (m, 3H, H-1, H-2′, H-4′), 4.75–4.69 (m, 2H, H-1′, H-4), 4.19 (dd, *J*=4.7 Hz, *J*=11.9 Hz, 1H, H-5′a), 4.01 (dd, *J*=4.6 Hz, *J*=12.3 Hz, 1H, H-6a), 3.75 (dd, *J*=2.3 Hz, *J*=12.2 Hz, 1H, H-6b), 3.52 (ddd, *J*=2.5 Hz, *J*=4.6 Hz, *J*=9.7 Hz, 1H, H-5), 3.40 (dd, *J*=8.1 Hz, *J*=11.9 Hz, 1H, H-5′b), 3.07 (td, *J*=4.3 Hz, *J*=12.6 Hz, 1H, H-3), 2.45–2.41 (m, 1H, H-2a), 2.42 (s, 3H, Ph–C*H₃*), 2.18, 2.07, 2.05, 2.04, 2.01 (5×s, 15H, 5×*Ac*–C*H₃*), 1.81 (td, *J*=11.0 Hz, *J*=13.1 Hz, 1H, H-2b) ppm; ¹³C NMR (100 MHz, CDCl₃) δ 170.7, 169.9, 169.8, 169.4 (5C, 5×*C*OCH₃), 143.9, 138.4 (2C, 2×C$_q$ arom), 129.5, 127.4 (4C, arom), 82.4 (1C, C-1′, $^1J_{C1',H1'}$=161.5 Hz), 81.7 (1C, C-1, $^1J_{C1,H1}$=151.2 Hz), 76.0 (1C, C-5), 71.3 (1C, C-3′), 69.9 (1C, C-2′), 68.3 (1C, C-4′), 67.6 (1C, C-4), 64.6 (1C, C-5′), 62.6 (1C, C-6), 45.3 (1C, C-3), 39.4 (1C, C-2), 21.7 (1C, Ph–C*H₃*), 20.9, 20.8 (5C, 5× *Ac*–C*H₃*) ppm; ESI-HRMS: m/z calcd for $C_{28}H_{37}NNaO_{14}S_2$ [M+Na]$^+$ 698.1553, found 698.1572.

Data for compound **49**:

$[α]_D^{20}$ −44.3 (*c* 0.23, CHCl₃); R_f=0.26 (toluene/acetone 9:1); ¹H NMR (500 MHz, CDCl₃) δ 7.80–7.27 (m, 4H, arom), 6.19 (d, *J*=9.7 Hz, 1H, N*H*), 5.16 (t, *J*=8.6 Hz, 1H, H-3′), 5.02 (dd, *J*=1.7 Hz, *J*=9.7 Hz, 1H, H-1), 4.99–4.94 (m, 1H, H-4′), 4.92 (t, *J*=8.6 Hz, 1H, H-2′), 4.74 (td, *J*=4.8 Hz, *J*=11.0 Hz, 1H, H-4), 4.58 (d, *J*=8.9 Hz, 1H, H-1′), 4.22 (dd, *J*=5.2 Hz, *J*=11.6 Hz, 1H, H-5′a), 3.99 (dd, *J*=5.1 Hz, *J*=12.1 Hz, 1H, H-6a), 3.90 (dd, *J*=2.3 Hz, *J*=12.1 Hz, 1H, H-6b), 3.61 (ddd, *J*=2.4 Hz, *J*=5.1 Hz, *J*=9.8 Hz, 1H, H-5), 3.40 (dd, *J*=9.4 Hz, *J*=11.6 Hz, 1H, H-5′b), 3.28 (s, 1H, H-2), 2.47–2.43 (m, 1H, H-3a), 2.42 (s, 3H, Ph–C*H₃*), 2.17, 2.05, 2.04, 2.03, 2.02 (5×s, 15H, 5×*Ac*–C*H₃*), 2.00–1.98 (m, 1H, H-3b) ppm; ¹³C NMR (125 MHz, CDCl₃) δ 170.7, 169.9, 169.7, 169.6 (5C, 5×*C*OCH₃), 143.6, 138.8 (2C, 2×C$_q$ arom), 129.5, 127.2 (4C, arom), 82.8 (1C, C-1′), 82.5 (1C, C-1), 76.9 (1C, C-5), 72.3 (1C, C-3′), 69.4 (1C, C-2′), 68.3 (1C, C-4′), 66.0 (1C, C-5′), 64.2 (1C, C-4), 62.7 (1C, C-6), 45.2 (1C, C-2), 36.9 (1C, C-3), 21.6 (1C, Ph–C*H₃*), 21.0, 20.8, 20.7 (5C, 5×*Ac*–C*H₃*) ppm; ESI-HRMS: m/z calcd for $C_{28}H_{37}NNaO_{14}S_2$ [M+Na]$^+$ 698.1553, found 698.1526.

Acknowledgements

Conflict of Interest

The authors declare no conflict of interest.

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