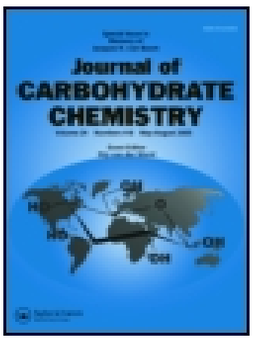

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Sulfonated graphene oxide as highly efficient catalyst for glycosylation

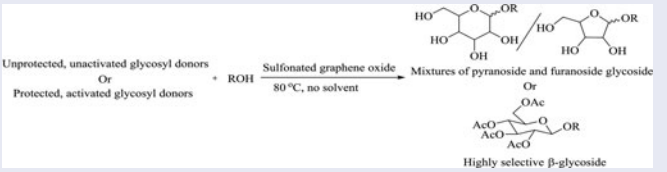
Raju S. Thombal and Vrushali H. Jadhav

Division of Organic Chemistry, National Chemical Laboratory (CSIR-NCL), Pune, India

ABSTRACT

Heterogeneous sulfonated graphene oxide for the first time has been used as a green and efficient catalyst for atom-economic glycosylation of unprotected, unactivated glycosyl donors or 2,3,4,6-tetra-*O*-acetylglycosyltrichloroacetimidate with various acceptors basically in the absence of solvent. The unprotected, unactivated glycosyl donors afforded mixtures of α- and β-glycosides, while the 2,3,4,6-tetra-*O*-acetylglycosyltrichloroacetimidate afforded β-glycosylated products with high yields and selectivity. The main advantages of this methodology are easy catalyst preparation, no need for dry reagents and reaction conditions, easy catalyst separation and recycling, and high product yields.

GRAPHICAL ABSTRACT



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KEYWORDS
Sulfonated graphene oxide; reusability; glycol donor; glycosyl acceptor; glycosylation

Introduction

Glycosylation is an important reaction to synthesize carbohydrate derivatives and an array of novel therapeutic agents and has thus gained significant attention and witnessed vast development over the last few decades.[1] Glycosidic bond formation is a crucial step in oligosaccharide synthesis, but despite many efforts, there is still a need to identify a general, mild, and convenient glycosylation promoter to achieve high yields. To date, a number of homogeneous systems like $BF_3{\cdot}Et_2O$,[2] $Sc(OTf)_3$,[3] TMSOTf,[4] TBSOTf,[5] AgOTf,[6] $Ti(OtBu)_4$,[7] and sulphamic acid[8] have been used as promoters for the glycosylation reaction. They are strong and moisture sensitive and hence suffer from drawbacks, such as corrosion and contamination, and need neutralization after the reaction. As a result, the workup is

CONTACT Vrushali H. Jadhav vh.jadhav@ncl.res.in Division of Organic Chemistry, National Chemical Laboratory (CSIR-NCL), Pune-411008, India.

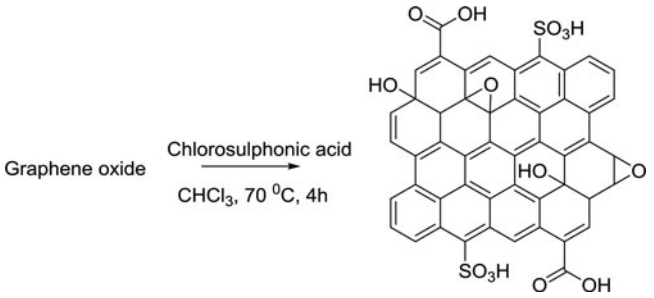


Figure 1. Schematic representation of sulfonated graphene oxide.

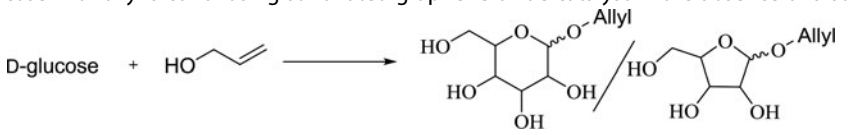
tedious. Very low temperatures and absolutely dry conditions are required for glycosylation reactions too. These catalysts are difficult to separate from the reaction mixture and cannot be reused. Such methods do not promote green synthesis and atom efficiency. Hence, there is still a need to develop an efficient process for glycosylation from both academic and industrial points of view. Recently, Liu et al.[9] synthesized a biomass-derived carbonaceous heterogeneous catalyst and used it for glycosylation reactions of various sugars. They compared this catalyst with other homogeneous catalyst systems for glycosylation reaction and found that the heterogeneous catalyst works well, giving good yields of glycosylation products. Heterogeneous catalytic processes have advantages over homogeneous catalytic systems such as straightforward catalyst separation, catalyst regeneration, and relatively low cost, which makes them more applicable. To overcome the above said difficulties in glycosylation and develop new glycosylation protocols, we herewith report the glycosylation of unprotected, unactivated glycosyl donors and glycosylation of glycosyl trichloroacetimidates with various acceptors using sulfonated graphene oxide as an inexpensive, efficient, reusable, and environmentally benign catalyst, which gave high yields of the glycosides.

Results and discussion

Graphene oxide was obtained from graphene by the Hummers method[10] and contained a high density of hydrophilic functional groups such as hydroxyl, carboxyl, and epoxy groups. Sulfonation of graphene oxide using chlorosulfonic acid afforded sulfonated graphene oxide by known procedure.[11] The FT-IR and P-XRD data was found to be consistent with that reported. A schematic representation of sulfonated graphene oxide is shown in Figure 1. Sulfonated graphene oxide was reported to be a highly efficient, recyclable solid acid catalyst for a number of reactions due to its low cost, metal-free composition, and expected high stability and high reusability.[12] Intrigued by these previous studies and our work in this field,[13] we were interested in examining whether sulfonated graphene oxide could be used as an efficient carbon catalyst for the glycosylation reaction.

Glycosylation of unprotected sugars is important and practical as it avoids protection-deprotection steps required for synthesis of glycosyl donors and hence

Table 1. Optimization of reaction time, temperature, and catalyst loading in glycosylation of D-glucose with allyl alcohol using sulfonated graphene oxide catalyst in the absence of a solvent.



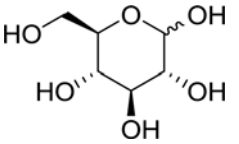
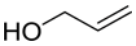
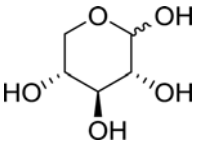
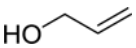
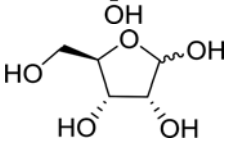
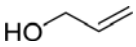
Entry	Allyl alcohol (mmol)	Catalyst loading (wt %)	Time (h)	Temp (°C)	Yield[a] (%)
1	2.5	5	12	rt	0
2	2.5	5	12	40	6
3	2.5	5	12	60	15
4	2.5	5	12	80	22
5	5	5	12	rt	0
6	5	5	12	40	11
7	5	5	12	60	62
8	5	5	4	80	94
9	5	10	12	rt	0
10	5	10	12	40	15
11	5	10	12	60	65
12	5	10	4	80	95

[a]Isolated yields.

is economical. Thus, initially, we studied glycosylation reactions of the unprotected sugars like D-glucose with allyl alcohol as an acceptor using the sulfonated graphene oxide catalyst without using any solvent. To confirm the effect of sulfonation on graphene oxide, we initially tried glycosylation of D-glucose with allyl alcohol using 5 wt% graphene oxide as catalyst with respect to glycosyl donor in the absence of solvent. No glycosylation was found to occur even at higher temperatures, indicating that sulfonating groups on graphene oxide play an important role in the glycosylation reaction.

We optimized the glycosylation reaction conditions using sulfonated graphene oxide catalyst. D-Glucose and allyl alcohol were used as the substrates. As the reaction was carried out without using solvent, it was necessary to fix the amount of acceptor required to gain maximum yield of the glycosylated product. When 2.5 mmol of allyl alcohol was used, the alcohol was not sufficient to dissolve the glycosyl donor. To this undissolved solution, 5 wt% of the catalyst was added and then stirred at different temperatures, but probably due to incomplete solubility of the sugar, low yields of the glycosides were obtained (Table 1, entries 1–4). When 5.0 mmol of allyl alcohol and 5 wt% of the catalyst were used, good yields of glycosylated products at different temperatures were obtained. At room temperature, a reaction did not occur (Table 1, entry 5), and it was sluggish at 40°C (Table 1, entry 6). A 62% yield of the glycoside was obtained at 60°C, while a 94% yield was obtained at 80°C (Table 1, entries 7 and 8). The catalyst concentration was also studied using 1 wt%, 5 wt%, and 10 wt% of the catalyst. Traces of glycosylated product were observed using 1 wt% of the catalyst, while 5 wt% of catalyst gave maximum yield of the product at 80°C. Increasing the catalyst concentration further to 10 wt% did not have any significant impact on yields of the product (Table 1, entries 9–12).

Table 2. Glycosylation of unprotected and unactivated glycosyl donors with various acceptors using sulfonated graphene oxide catalyst in the absence of a solvent[a].

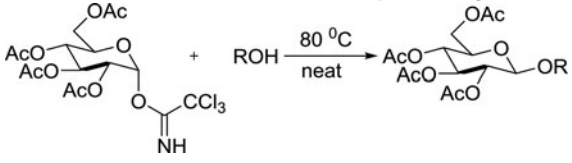
Entry	Glycosyl donor	Acceptor	Time(h)	Yield[b] (%)
1			4	94
2			4	96
3			4	97

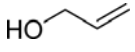
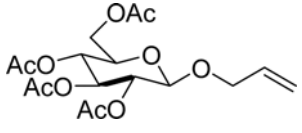
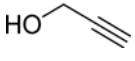
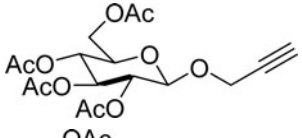
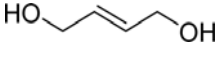
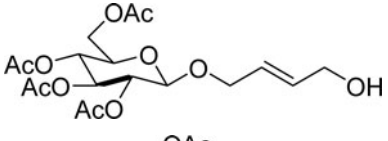
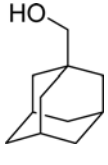
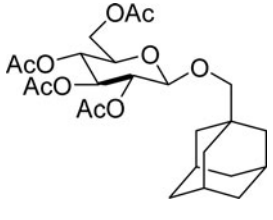
[a]Reaction of 1 mmol of glycosyl donor and 5 mmol of glycosyl acceptor.
[b]Isolated yields.

Inspired by these results, we began to demonstrate the catalytic activity of this catalyst on various unprotected and unactivated sugars. As seen from Table 2, the neat glycosylation of glucose afforded a mixture of pyranoside and furanoside allyl glycosides (94%), but the ratio was difficult to judge from ^{1}H NMR due to overlapping of peaks. Xylose gave a 3:1 α,β-mixture of pyranoside allyl glycoside, whereas ribose gave a 5:1 α:β-mixture of furanoside allyl glycosides in 96% and 97% yields, respectively (Table 2, entries 1–3). In the case of unprotected sugars, the glycosylation reaction probably leads to the thermodynamically stable anomers, produced directly or via anomerization of a kinetic product. Different temperatures, different activators, and different solvents may also give rise to different amounts of anomeric glycosides formed.[14] In our case, use of a high-temperature and solvent-free condition may have favored the formation of mixtures of anomeric glycosides.

With the success of glycosylation of unprotected and unactivated sugars, we then studied the catalytic activity of sulfonated graphene oxide on the glycosylation reactions of 2,3,4,6-tetra-*O*-acetylglycosyl trichloroacetimidate using various primary, secondary, and hindered acceptors. 2,3,4,6-Tetra-*O*-acetylglycosyl trichloroacetimidate was prepared from D-glucose by a known procedure.[15] Initially, we tried the glycosylation of 2,3,4,6-tetra-*O*-acetylglycosyl trichloroacetimidate with 5 mmol of allyl alcohol at 80°C (Table 3, entry 1). The reaction proceeded smoothly in 4 h forming selectively β-glycoside as seen from the ^{1}H and ^{13}C NMR in a 97% yield. We then tried the glycosylation using various acceptors including propagyl alcohol, 2-butene diol, 1-adamantanemethanol, undecanol, and oleyl alcohol, which afforded the glycosylated products in excellent yields (Table 3, entries 2–6). Secondary alcohols like cyclohexanol, (−) menthol, and cholesterol also gave excellent yields of the glycosylated products (Table 3, entries 7–9). Glycosylation with *t*-butanol did not give any glycosylated product due to the less reactivity of tertiary alcohol (Table 3, entry

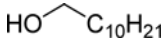
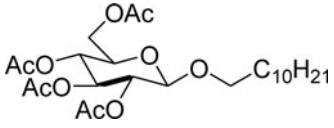
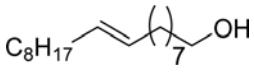
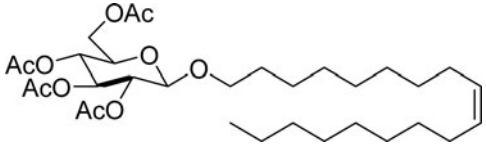
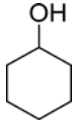
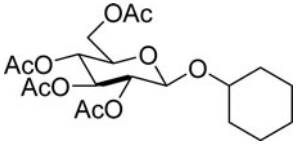
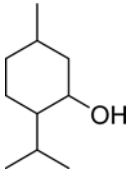
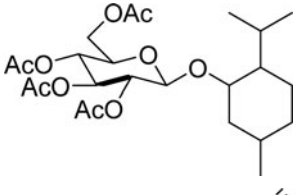
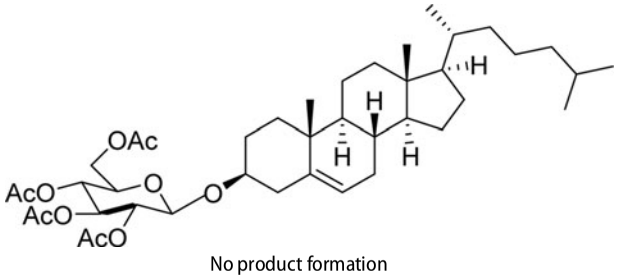
Table 3. Glycosylation of 2,3,4,6-tetra-*O*-acetylglycosyl trichloroacetimidate with various acceptors using sulfonated graphene oxide catalyst in the absence of solvent.



Entry	Acceptor	Product	Time (h)	Yield[a] (%)
1			4	97
2			4	97
3			4	94
4[b]			4	97

(Continued)

Table 3. Continued

Entry	Acceptor	Product	Time(h)	Yield[a] (%)
5			4	98
6			4	92
7			6	93
8			6	94
9[b]	Cholesterol		6	78
10	*t*-BuOH	No product formation	–	–

[a]Isolated yields.
[b]Reaction carried out in toluene as acceptors were solid compounds.

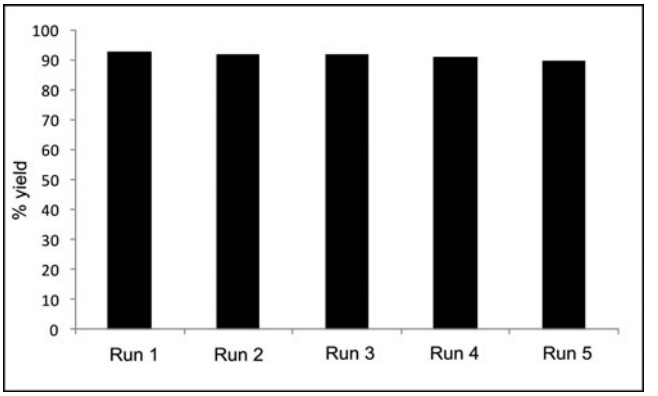


Figure 2. Reusability of sulfonated graphene oxide catalyst.

10). Generally, the high reactivity of glycosyl trichloroacetimidate often leads to side reactions or decomposition of the donor before reacting with the acceptor, thus significantly decreasing the yield of the reaction. However, this was not observed in our case, and fortunately, the trichloroacetimidate was found to be sufficiently stable during the reaction at high temperatures. Thus, all the glycosylation reactions proceeded smoothly, giving high yields and selectivity of the desired products. To our knowledge, this is the first report of glycosylation of glycosyl trichloroacetimidate without use of any solvent (expect entries 4 and 9). This process can thus be considered highly efficient and economic.

As it is very convenient to recover the catalyst by simple filtration at the end of the reaction, the solid catalyst could be readily reused for the next run of reaction without any further activation. Therefore, the recycled sulfonated graphene oxide catalyst without any regeneration step could be readily used in the glycosylation of D-glucose with allyl alcohol at 80°C. As shown in Figure 2, it can be conveniently recycled for five subsequent runs, having no impact on reaction time or the yields of glycosylated products.

Conclusion

In summary, we have demonstrated an efficient way for the glycosylation of unprotected and unactivated glycosyl donors using sulfonated graphene oxide as a catalyst in the absence of solvent. Glycosyl trichloroacetimidate was also employed for glycosylation of various alcohols, giving high yields and stereoselectivity of the glycosides. This catalyst was also air and moisture stable, was easily recovered, and showed high reusability, making the glycosylation reactions simple, economical, and efficient. Some advantages of using this catalyst system were no need for dry and moisture-sensitive reagents or low temperature and no need for molecular sieves.

Experimental

General methods

All reagents were purchased from Aldrich, Fluka, MERCK, and TCI and were used without further purification. Water was deionized with a Millipore system as a Milli-Q grade. NMR spectra were recorded in $CDCl_3$ or DMSO-d6at 25°C on either a Bruker 400 (400 MHz) or Bruker 200 (200 MHz) spectrometer. For ^1H NMR spectra, proton chemical shifts (δ) are given in ppm relative to tetramethylsilane (0.00 ppm) in $CDCl_3$ or DMSO-d6. Multiplicities are indicated by s (singlet), d (doublet), t (triplet), m (multiplet), and br (broad). For ^{13}C NMR spectra, carbon chemical shifts were internally referenced to the deuterated solvent signal of $CDCl_3$ (77.16 ppm) or DMSO-d6 (39.5). HRMS was recorded on Thermo Scientific Q Exactive. FT-IR was recorded on the Spectrum 400 instrument. PXRD was recorded on Panalytical X'Pert Pro.

General procedure for glycosylation of unprotected sugars

A mixture of unactivated, unprotected sugars (1 mmol), alcohol (5 mmol), and 5 wt% sulfonated graphene oxide was taken at rt and then stirred at 80°C for the required time. A small amount of reaction mixture was taken out at regular intervals using a micropipette and diluted with methanol, and the reaction progress was monitored by TLC. After consumption of all of the glycosyl donor, the reaction mixture was cooled to rt and diluted with methanol, and the catalyst was separated by filtration. The filtrate was concentrated at reduced pressure and crude products were purified by column chromatography to remove the excess alcohol to obtain the desired glycoside.

General procedure for glycosylation of protected sugars (Table 3, entries 1–3, 5, 6–8)

A mixture of protected sugars (1 mmol), alcohol (5 mmol), and 5 wt% sulfonated graphene oxide was taken at rt and then stirred at 80°C for the required time. A small amount of reaction mixture was taken out at regular intervals using a micropipette and diluted with ethyl acetate, and the reaction progress was monitored by TLC. After consumption of all of the glycosyl donor, the reaction mixture was cooled to rt and diluted with ethyl acetate, and the catalyst was separated by filtration. The filtrate was concentrated at reduced pressure, and crude products were purified by column chromatography to remove the excess alcohol to obtain the desired glycoside.

General procedure for glycosylation of protected sugars (Table 3, entries 4, 9)

The protected sugar (1 mmol) and alcohol (1.2 mmol) were dissolved in toluene at rt and then 5 wt% sulfonated graphene oxide was added at rt by itself, and then the

reaction mixture was stirred at 80°C for the required time. The reaction progress was monitored directly by TLC. After consumption of all of the glycosyl donor, the reaction mixture was cooled to rt, and the catalyst was separated by filtration and washed with ethyl acetate. The filtrate was then concentrated at reduced pressure, and crude products were purified by column chromatography to obtain the desired glycoside.

Allyl 2,3,4,6-tetra-O-acetyl-β-(D)-glucopyranoside (Table 3, entry 1)

White crystals; Yield 97%; $R_f = 0.2$ (EtOAc-Pet ether = 1:2); mp = 73–75°C, $[\alpha]_D^{25}$ = –13.4 (c = 1.03, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.01 (s, 3H), 2.02 (s, 3H), 2.05 (s, 3H), 2.09 (s, 3H), 3.65–3.73 (m, 1H), 4.04–4.12 (m, 1H), 4.14–4.17 (m, 1H), 4.24 (d, J = 4.5 Hz, 1H), 4.29–4.40 (m, 1H), 4.56 (d, J = 7.8 Hz, 1H), 4.98–5.07 (m, 1H), 5.12 (d, J = 9.4 Hz, 1H), 5.17–5.23 (m, 2H), 5.23–5.33 (m, 1H), 5.76–5.95 (m, 1H)); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 20.6, 20.66, 20.7, 61.8, 68.3, 70.0, 71.2, 71.7, 72.8, 99.4, 117.6, 133.2, 169.3, 169.4, 170.3, 170.6; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{17}H_{24}O_{10}Na$ 411.1267, found 411.1262.

Propargyl 2,3,4,6-tetra-O-acetyl-β-(D)-glucopyranoside (Table 3, entry 2)

White crystalline solid; Yield 97%; $R_f = 0.3$ (EtOAc-Pet ether = 1:2); mp 113–114°C; $[\alpha]_D^{25}$ –22.93 (c = 1.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.01 (s, 3H), 2.03 (s, 3H), 2.06 (s, 3H), 2.09 (s, 3H), 2.48 (t, J = 2.2 Hz, 1H), 3.71–3.75 (m, 1H), 4.11–4.17 (m, 1H), 4.26–4.30 (m, 1H), 4.37 (d, J = 2.7 Hz, 2H), 4.78 (d, J = 7.8 Hz, 1H), 5.0–5.04 (m, 1H), 5.11 (t, J = 10.0 Hz, 1H), 5.25 (t, J = 9.6 Hz, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 20.5, 20.6, 29.6, 55.8, 60.3, 61.6, 68.1, 70.8, 71.8, 72.6, 75.4, 78.0, 98.0, 169.3, 169.4, 170.2, 170.6; HRMS (ESI) m/z [M + Na]+ calcd for C17H22O10Na 409.1111, found 409.1105.

4-Hydroxybut-2-enyl tetra-O-acetyl-β-(D)-glucopyranoside (Table 3, entry 3)

White solid; Yield 94%; $R_f = 0.3$ (EtOAc-Pet ether = 1:1); mp 95–97°C; $[\alpha]_D^{25}$ –2.44 (c = 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 2.01 (s, 3H), 2.03 (s, 3H), 2.06 (s, 3H), 2.10 (s, 3H), 3.69–3.70 (m, 1H), 4.15–4.21 (m, 3H), 4.24 (d, J = 4.5 Hz, 1H), 4.28 (t, J = 5.9 Hz, 1H), 4.32 (bs, 1H), 4.35–4.39 (m, 1H), 4.58 (d, J = 7.7 Hz, 1H), 4.98–5.03 (m, 1H), 5.09 (t, J = 9.6 Hz, 1H), 5.21 (t, J = 9.6 Hz, 1H), 5.6–5.67 (m, 1H), 5.83–5.89 (m, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 20.6, 20.7, 20.73, 58.5, 61.9, 64.3, 68.4, 71.2, 71.7, 72.7, 99.2, 126.7, 133.3, 169.4, 169.4, 170.3, 170.8; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{18}H_{26}O_{11}Na$ 441.1373, found 441.1367.

1-Adamantylmethyl 2,3,4,6-tetra-O-acetyl-β-(D)-glucopyranoside (Table 3, entry 4)

White solid; Yield 97%; $R_f = 0.6$ (EtOAc-Pet ether = 1:1); mp 132°C; $[\alpha]_D^{26}$ 0.95 (c = 1.06, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.48–1.52 (m, 3H), 1.58–1.74 (m,

12H), 2.02 (s, 3H), 2.03 (s, 3H), 2.06 (s, 3H), 2.10 (s, 3H), 2.97 (d, $J = 9.4$ Hz, 1H), 3.51 (d, $J = 9.4$ Hz, 1H), 3.63–3.71 (m, 1H), 4.16 (dd, $J = 9.4$ Hz, 1H), 4.28 (dd, $J = 7.7$ and 4.5 Hz, 1H), 4.43 (d, $J = 7.7$ Hz, 1H), 5.01 (dd, $J = 9.4$ and 4.8 Hz, 1H), 5.09 (t, $J = 9.47$ Hz, 1H), 5.21 (t, $J = 9.3$ Hz, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 20.6, 20.68, 20.7, 28.0, 33.8, 37.0, 39.2, 61.9, 68.4, 71.2, 71.6, 72.7, 80.9, 101.7, 169.2, 169.4, 170.3, 170.7; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{25}H_{36}O_{10}Na$ 519.2206, found 519.2201.

Undecyl 2,3,4,6-tetra-O-acetyl-β-(D)-glucopyranoside, (Table 3, entry 5)

White semisolid; Yield 98%; $R_f = 0.6$ (EtOAc-Pet ether = 1:2); $[\alpha]_D^{26}$ –1.41 (c = 1.0, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.87 (t, J = 7.1 Hz, 3H), 1.24 (bs, 18H), 1.5–1.59 (m, 2H), 2.0 (s, 3H), 2.2 (s, 3H), 2.4 (s, 3H), 2.8 (s, 3H), 3.43–3.49 (m, 1H), 3.67–3.71 (m, 1H), 3.84–3.89 (m, 1H), 4.11–4.14 (m, 1H), 4.26 (dd, $J = 7.8$ and 4.6 Hz, 1H), 4.49 (d, $J = 7.8$, 1H), 4.97 (dd, $J = 8$, 1.4 Hz, 1H), 5.08 (t, $J = 9.7$, 9.5 Hz), 5.2 (t, $J = 9.5$, 9.2 Hz, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 14.2, 20.5, 22.5, 25.7, 29.2, 29.5, 31.7, 61.8, 68.3, 70.2, 71.2, 71.5, 72.7, 100.7, 169.3, 169.4, 170.3, 170.7; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{25}H_{42}O_{10}Na$ 525.2676, found 525.2670.

(9Z)-9-octadecenyl tetra-O-acetyl-β-(D)-glucopyranoside (Table 3, entry 6)

White foam; Yield 92%; $R_f = 0.3$ (EtOAc-Pet ether = 1:2); $[\alpha]_D^{26}$ –6.62 (c = 0.5, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.89 (t, $J = 8.0$ Hz, 1H), 1.26 (bs, 24H), 1.5–1.67 (m, 4H), 2.01 (s, 3H), 2.03 (s, 3H), 2.05 (s, 3H), 2.09 (s, 3H), 3.44–3.5 (m, 1H), 3.67–3.72 (m, 1H), 3.85–3.90 (m, 1H), 4.14 (dd, $J = 9.7$ and 2.4 Hz, 1H), 4.5 (d, $J = 8$ Hz, 1H), 4.99 (dd, $J = 7.8$ and 1.4 Hz, 1H), 5.1 (t, $J = 9.7$ Hz, 1H), 5.21 (t, $J = 9.5$ Hz, 1H), 5.34–5.37 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 14.1, 20.6, 20.7, 20.8, 22.7, 25.8, 25.9, 27.2, 29.3, 29.4, 29.5, 29.6, 29.7, 29.8, 31.9, 62.0, 68.5, 70.3, 71.3, 71.7, 72.9, 100.8, 129.8, 130.0, 169.3, 169.4, 170.3, 170.7; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{32}H_{54}O_{10}Na$ 621.3615, found 621.3609.

Cyclohexyl 2,3,4,6-tetra-O-acetyl-β-(D)-glucopyranoside (Table 3, Entry 7)

White solid; Yield 93%; $R_f = 0.2$ (EtOAc-Pet ether = 1:2); mp 107–109°C; $[\alpha]_D^{26}$ –10.57 (c = 1.02, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 1.24–1.26 (m, 4H), 1.38–1.48 (m, 2H), 1.64–1.77 (m, 3H), 1.83–1.86 (m, 1H), 1.99 (s, 3H), 2.01 (s, 3H), 2.02 (s, 3H), 2.07 (s, 3H), 3.58–3.63 (m, 1H), 3.64–3.69 (m, 1H), 4.10 (dd, $J = 11.9$ and 2.3 Hz, 1H), 4.25 (dd, $J = 11.9$ and 4.5 Hz, 1H), 4.57 (d, $J = 7.8$ Hz, 1H), 4.95 (dd, $J = 9.6$ and 8.2 Hz, 1H), 5.07 (t, $J = 9.6$ Hz, 1H), 5.19 (t, $J = 9.6$ Hz, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 20.6, 20.65, 20.68, 20.7, 23.5, 23.6, 25.4, 31.5, 33.1, 62.0, 68.5, 71.4, 71.5, 72.8, 78.0, 99.3, 169.2, 169.4, 170.3, 170.7; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{20}H_{30}O_{10}Na$ 453.1737, found 453.1731.

(−) Menthyl 2,3,4,6-tetra-O-acetyl-β-(D)-glucopyranoside (Table 3, entry 8)

White solid; Yield 94%; $R_f = 0.5$ (EtOAc-Pet ether = 1:2); mp 135°C; $[\alpha]_D^{25}$ −3.05 (c = 1.25, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 200 MHz) δ 0.73 (d, J = 4.6 Hz, 3H), 0.85 (s, 3H), 0.89 (d, J = 1.7Hz, 3H), 0.91–0.93 (m, 2H), 1.14–1.41 (m, 4H), 1.55–1.72 (m, 5H), 2.01 (s, 3H), 2.03 (s, 3H), 2.06 (s, 3H), 2.08 (s, 3H), 3.25–3.45 (m, 1H), 3.63–3.76 (m, 1H), 4.07–4.28 (m, 2H), 4.56 (d, J = 7.9 Hz, 1H), 4.97 (dd, J = 9.7 and 3.6 Hz, 1H), 5.07 (dd, J = 8.9 and 2.2 Hz, 1H), 5.21 (t, J = 9.4 Hz, 1H); ^{13}C NMR ($CDCl_3$, 50 MHz) δ 15.4, 15.9, 20.5, 20.6, 20.7, 20.9, 21.0, 22.3, 22.8, 25.0, 31.4, 31.6, 34.0, 34.1, 40.8, 42.8, 47.4, 48.0, 62.4, 68.7, 68.9, 71.5, 71.6, 73.0, 79.1, 83.1, 98.7, 101.9, 169.3, 169.5, 170.2, 170.4; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{24}H_{38}O_{10}Na$ 509.2363, found 509.2357.

Cholesteryl 2,3,4,6-tetra-O-acetyl-β-D-glucopyranoside (Table 3, entry 9)

White solid; Yield 78%; $R_f = 0.2$ (EtOAc-Pet ether = 1:2); mp 105°C; $[\alpha]_D^{25}$ −9.68 (c = 0.52, $CHCl_3$); ^{1}H NMR ($CDCl_3$, 400 MHz) δ 0.68 (s, 3H), 0.86 (d, J = 1.7 Hz, 3H), 0.88 (d, J = 1.7 Hz, 3H), 0.92 (d, J = 6.6 Hz, 3H), 0.99 (s, 3H), 1.04–1.20 (m, 8H), 1.22–1.39 (m, 10H), 1.42–1.54 (m, 6H), 1.79–1.93 (m, 3H), 2.01 (s, 3H), 2.03 (s, 3H), 2.06 (s, 3H), 2.09 (s, 3H), 2.13–2.29 (m, 2H), 3.45–3.53 (m, 1H), 3.66–3.70 (m, 1H), 4.12 (dd, J = 10.0 and 2.2 Hz, 1H), 4.26 (dd, J = 7.5 and 4.6 Hz, 1H), 4.6 (d, J = 8 Hz, 1H), 4.97 (dd, J = 8.7 and 7.8 Hz, 1H), 5.08 (t, J = 9.7 Hz, 1H), 5.21 (t, J = 9.5 Hz, 1H), 5.36–5.37 (m, 1H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 11.8, 18.7, 19.3, 20.6, 20.6, 20.7, 20.8, 21.0, 22.5, 22.8, 23.8, 24.3, 28.0, 28.2, 29.4, 29.7, 31.8, 31.9, 35.7, 36.1, 36.7, 31.1, 38.9, 39.5, 39.7, 42.3, 50.15, 56.1, 56.7, 62.1, 68.5, 71.4, 71.6, 72.9, 80.1, 99.6, 122.2, 140.3, 169.3, 169.4, 170.4, 170.7; HRMS (ESI) m/z $[M + Na]^+$ calcd for $C_{41}H_{64}O_{10}Na$ 739.4397, found 739.4391.

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References

1. Dube, D.H.; Bertozzi, C.R. Glycans in cancer and inflammation-potential for therapeutics and diagnostics. *Nat. Rev. Drug Discovery.* **2005**, *4*, 477–488.
2. Schmidt, R.R.; Michel, J. Facile synthesis of α- and β-*O*-glycosyl imidates; preparation of glycosides and disaccharides. *Angew. Chem. Int. Ed. Engl.* **1980**, *19*, 731–732.
3. Auge, J.; Sizun, G. Ionic liquid promoted atom economic glycosylation under Lewis acid catalysis. *Green Chem.* **2009**, 11, 1179–1183.

4. Kulkarni, S.S.; Hung, S.C. Metal trifluoromethanesulfonates as versatile catalysts in carbohydrate synthesis. *Lett. Org. Chem.* **2005**, *2*, 670–677.
5. Haase, W.C.; Seeberger, P.H. Recent progress in polymer supported synthesis of oligosaccharides and carbohydrate libraries. *Curr. Org. Chem.* **2000**, *4*, 481–511.
6. Douglas, S.P.; Whitfield, D.M.; Krepinsky, J.J. Silver trifluoromethanesulfonate(triflate) activation of trichloroacetimidates in glycosylation reactions. *J. Carbohydr.Chem.* **1993**, *12*, 131–136.
7. Pfaffe, M.; Mahrwald, R. Direct glycosylation of unprotected and unactivated carbohydrates under mild conditions. *Org. Lett.* **2012**, 14, 792–795.
8. Guchhait, G.; Misra, A.K. Efficient glycosylation of unprotected sugars using sulfamic acid: a mild eco-friendly catalyst. *Catal Comm***. 2011**, *14*, 52–57.
9. Gorityala, B.K.; Ma, J.; Pasunooti, K.K.; Cai, S.; Liu, X.W. Green glycosylation promoted by reusable biomass carbonaceous solid acid: an easy access to β-stereoselective terpene galactosides. *Green Chem*. **2011**, 13, 573–577.
10. Lerf, A.; He, H.Y.; Forster, M.; Klinowski, J. Structure of graphite oxide revisited. *J. Phys. Chem. B.* **1998**, *102*, 4477–4482.
11. Upare, P.P.; Yoon, J.W.; Kim, M.Y.; Kang, H.Y.; Hwang, D.W.; Hwang, Y.K.; Kung, H.H.; Chang, J.S. Chemical conversion of biomass-derived hexose sugars to levulinic acid over sulfonic acid-functionalized graphene oxide catalysts. G*reen Chem*. **2013**, *15*, 2935–2943.
12. Antunes, M.M.; Russo, P.A.; Wiper, P.V.; Veiga, J.M.; Pillinger, M.; Mafra, L.; Evtuguin, D.V.; Pinna, N.; Valente, A.A. Sulfonated graphene oxide as effective catalyst for conversion of 5-(hydroxymethyl)-2-furfural into biofuels. *ChemSusChem*. **2014**, *7*, 804–812.
13. Jadhav, V.H.; Pedersen, C.M.; Bols, M. A study of ahydrocellulose-is a cellulose structure with residues in a $^1C_4$ conformation more prone to hydrolysis? *Org. Biomol. Chem*. **2011**, *9*, 7525–7534.
14. Hanessian, S. Stereocontrolled glycosyl transfer reactions with unprotected glycosyl donors. *Chem. Rev.* **2000**, *100*, 4443–4463.
15. Wegner, J.; Ley, S.V.; Kirschning, A.; Hansen, A.; Garcia, J.M.; Baxendale, I.R. A total synthesis of millingtonine A. *Org. Lett.* **2012**, *14*, 696–699.