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Synthesis and characterization of 3-*O*-esters of *N*-acetyl-D-glucosamine derivatives as organogelators†

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Carbohydrate derived low molecular weight organogelators are interesting compounds with many potential applications. Selective functionalization of the different hydroxyl substituents on D-glucose and D-glucosamine resulted in small molecular gelators. Previously we have found that the C-2 acylated derivatives including esters and carbamates of 4,6-*O*-benzylidene protected glucose and glucosamine derivatives have shown remarkable applications as molecular gelators. In this research, in order to probe the structural influence of sugar derivatives on molecular self-assembly, we introduced acylation functional groups to the 3-hydroxyl group of 4,6-*O*-benzylidene acetal protected *N*-acetyl glucosamine derivatives. A library of fourteen ester derivatives was synthesized and characterized. The ester derivatives typically formed gels in pump oil and aqueous mixtures of dimethyl sulfoxide or ethanol. The resulting gels were characterized using optical microscopy, and rheology, *etc.* All alkyl ester derivatives were gelators for pump oil. A short chain ester derivative was able to form gels in a few different oils and the corresponding oil water mixtures phase selectively. The compound was also used to trap naproxen sodium and formed a stable co-gel. The controlled release of the drug from the gel to the aqueous phase was analyzed using UV-vis spectroscopy. These results show that the functionalization at the 3-OH position of the *N*-acetyl glucosamine derivative is a feasible strategy in designing new classes of organogelators.

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Introduction

Low molecular weight gelators (LMWGs) are an interesting class of compounds that have influenced many research fields.[1–3] LMWGs form gels in organic solvents or aqueous solutions through non-covalent intermolecular forces such as hydrogen bonding, π–π stacking, van der Waals forces, *etc.*[2,4,5] The resulting gels are often termed supramolecular gels and the gel to solution transitions are reversible. There are many studies on the preparation of organogels and hydrogels from various components including amino acids and carbohydrates. Many carbohydrate derivatives have been found to be suitable LMWGs in different solvents, and they have already been studied for a wide variety of applications in biomedical research, environmental science, and other research fields.[6–14] Those organogelators that are able to form gels in various oils have intriguing applications for environmental science. These compounds have been explored for oil spill clean-ups and phase selective oil gelation for other applications.[15–24] Several organogelators for oils were found to be useful for drug delivery studies[25–28] and they were also studied for food processing since an organogel matrix can help reduce oxidative damage for entrapped agents.[29–31] Since carbohydrates are readily available and biocompatible, several sugar based organogelators have also been studied for oil spill recovery.[10,32–35] In addition to environmental applications, sugar based organogelators for oils have found applications as optical devices and microreactors as well.[11,35]

We have designed and synthesized effective carbohydrate based low molecular weight organogelators and hydrogelators using D-glucose and D-glucosamine as starting materials.[36] Selective functionalization of the hydroxyl group or amino group at C-2 positions led to several series of compounds that

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† Electronic supplementary information (ESI) available: Preparation of acid chloride intermediates if not commercially available. Copies of ^{1}H and ^{13}C NMR spectra for compounds **5–18**, measurement of melting point ranges of gels, rheological data and amplitude experiments, ^{1}H NMR spectra at varied temperatures for compounds **6** and **15**, and FTIR spectra for compounds **6** and **15**. Gelation test for a water and DMSO mixture for compounds **6** and **8**, and the gel photos for naproxen co-gels and release profile at pH 10, and photos for gel degradation at pH 14. See DOI: 10.1039/c9nj00630c

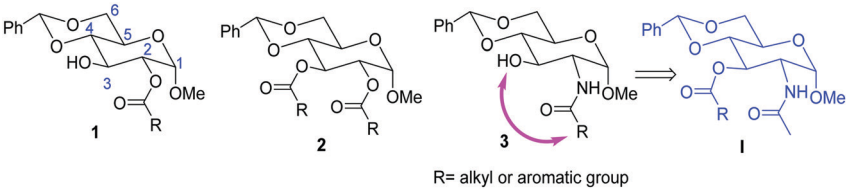


Fig. 1 Structures of several classes of sugar derivatives.

are effective organogelators for a wide range of solvents.[37–42] As shown in Fig. 1, certain 4,6-*O*-benzylidene α-*O*-methyl-D-glucopyranoside derivatives with the general structures **1** and **2** are able to form gels. The di-esters **2** were not as effective gelators in aqueous solutions in comparison to the C-2 mono-esters **1**, in which the 3-hydroxyl group is not protected. The 3-hydroxyl group participates in hydrogen bonding with other sugar derivatives and with solvents, which was important in the organogelation process. However, when longer hydrocarbon chains were used for the esters, they were able to form gels in a few organic solvents, especially when there is a diacetylene functional group present in the compounds.[38] C-2 mono alkyl esters with the general structure of **1** require the presence of a terminal alkyne group in order for them to form hydrogels. The glucosamine derivatives **3** are a class of effective LMWGs, forming gels in a series of polar solvents and aqueous mixtures. The amide derivatives **3** are more effective gelators than the corresponding esters **1**, this is attributed to the hydrogen bonding capacity of the amido group in **3** in comparison to ester **1**.

Previously we have mostly focused on the synthesis and study of C-2 derivatives from 4,6-*O*-benzylidene α-*O*-methyl-D-glucopyranoside or glucosamine derivatives (**1** and **3**).[41,43] The crystal structure of a C-2 ester derivative exhibited intermolecular hydrogen bonding between the 3-hydroxyl group and ring oxygen.[39] The 3-hydroxyl group in the amides **3** also participates in hydrogen bonding in gelation as shown in an analog through NMR analysis.[44] Switching the acyl functional group from the C-2 position to the C-3 position in amide **3** will lead to compounds **I**. These resulting compounds could be effective organic gelators. The intermolecular interactions in the structures are shown in Fig. 2; with the 3-hydroxy group esterified, only the 2-NHAc can provide a hydrogen bond donor. Ester derivatives **I** contain suitable functional groups that can contribute to molecular self-assembly and gelation in organic solvents.

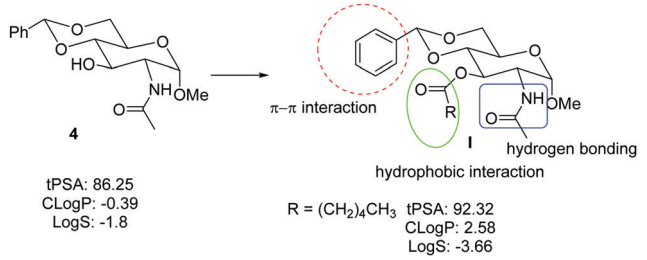


Fig. 2 Rationalization of LMWG design by esterification at the 3-OH group.

These compounds contain several types of intermolecular forces that may result in supramolecular gelation. These include van der Waals interactions and hydrophobic forces from the additional ester functions. Compound **4** was synthesized from *N*-acetyl glucosamine in two steps conveniently in high yield.[37,43] It contains an acetamide functional group at the C-2 position, which can contribute to hydrogen bonding. Using this compound as the head group, through further functionalization at the 3-hydroxyl position, a series of compounds **I** can be obtained. As shown in Fig. 2, after introducing an acyl functional group, the *C* log *P* value changed from −0.39 for compound **4** to 2.58 for hexanoate derivative **I**, which indicates that the molecule will be more soluble in organic solvents. The functionalization of the C-3 hydroxyl group of compound **4** can be done *via* straightforward methods in one step. In addition, the ester derivatives can be hydrolyzed selectively over amides under alkaline conditions to afford chemical triggered gelators. The acyl derivative can also be cleaved using certain lipases to afford enzyme-triggered gelators.

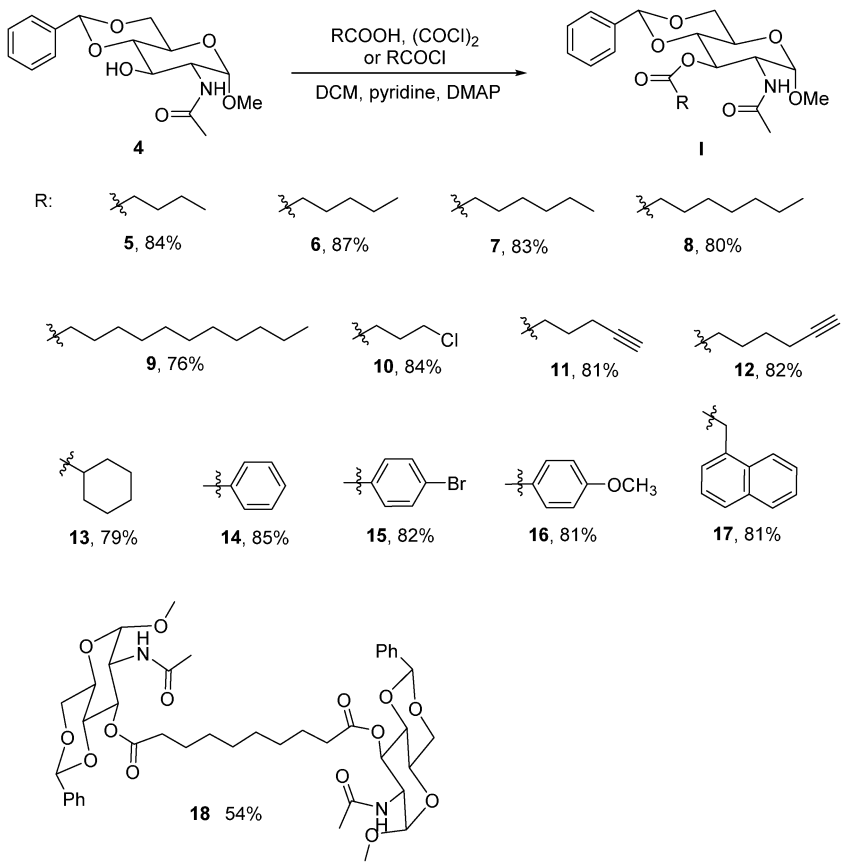
Results and discussion

Synthesis of the 3-*O*-esters

In order to understand the structural influence on the gelation properties and produce sustainable functional organogelators, we synthesized and characterized a series of compounds **I**. The synthesis of these 3-acyl derivatives is shown in Scheme 1.[43] Using a combinatorial approach, a small library of ester compounds was synthesized; these include short chain linear alkyl esters with 4, 5, 6, 7, and 11 carbons, terminal chloro or acetylene substituted alkyl derivatives, cyclohexyl ester, and a few aromatic derivatives. The esterification using an unhindered fatty acid or the corresponding acid chloride was typically carried out at room temperature, and for certain aromatic derivatives such as 4-bromobenzoate the reaction requires heating and longer reaction times. The 3-position of compound **4** is sterically hindered, therefore two equivalents of acid chlorides were necessary to obtain good yields. After these compounds were synthesized, we tested their gelation properties in a panel of organic solvents; the results are shown in Table 1. Hexane and water were included in the screen, and all compounds were insoluble in water and hexane at 20 mg mL^{-1}.

Gelation properties of the synthesized esters

As shown in Table 1, interestingly all eleven aliphatic ester derivatives prepared in this study were able to form gels in pump oil (VWR® vacuum pump oil #19), and only one aromatic



Scheme 1 Synthesis of 3-ester derivatives **5–18**.

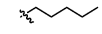
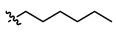
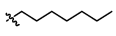
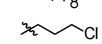
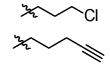
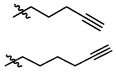
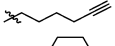
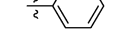
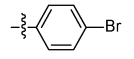
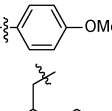
containing derivative was effective for the oil. A majority of the alkyl esters showed gelation properties for a mixture of water and DMSO or water and ethanol. Short chain linear aliphatic esters containing 6 to 8 carbon chains were the most versatile gelators, forming gels in at least six different solvents. These include compounds **6–8** with six to eight straight carbon chains, and compounds **11** and **12** containing six and seven carbon chains with terminal acetylene. Compound **9** contains a longer alkyl chain; it formed gels in pump oil with the lowest MGC of the entire series, 4.0 mg mL^{-1}. A dimeric ester, compound **18**, was also synthesized and studied; it showed effective gelation in seven of the tested solvents, which indicates that formation of dimeric derivatives containing two sugar units is a feasible method for achieving molecular self-assembly. The hexanoate compound **6** was an effective gelator for seven solvents too and at lower concentrations than compound **18**. Compound **6** was selected and tested for several other oils and it formed stable gels in mineral oil (4.0 mg mL^{-1}) and engine oil (6.7 mg mL^{-1}) too, besides pump oil. The gels were mostly opaque for aqueous mixtures with polar solvents, and transparent for pump oil. Some photos of the gels are shown in Fig. 3.

Compound **6** was then tested for phase selective gelation of oil and water mixtures. As shown in Fig. 4, the gelator was effective in selective gelation for the oil phase in the presence of an aqueous phase, which contained copper sulfate to give a blue color for easy visualization of the layers. The oil gels were strong enough to hold the weight of the aqueous phases for all three samples.

Gel morphology characterization

The optical micrographs of several representative dried gels are shown in Fig. 5. The morphologies of the most versatile gelator, compound **6**, in different solvents are shown in Fig. 5A and B. The gel in DMSO/H_2O (v/v 1 : 2) formed uniform long and curved fibrous assemblies (Fig. 5A) with an estimated diameter of 0.5 μm and several hundred microns in length; the fibers or tubules were curved and birefringent. The gel in EtOH/H_2O (v/v 1 : 1) formed long and uniform fibers (Fig. 5B) and on increasing the water content to EtOH : H_2O (v/v 1 : 2), the morphologies were very similar to those of compound **6** in EtOH/H_2O (v/v 1 : 1). The octanoate derivative **8** showed similar gelation properties; it formed gels in six tested solvents. The morphologies of some of these dried gels are shown in Fig. 5C–E. The gel of compound **8** in DMSO/H_2O (v 1 : 2) at 5.0 mg mL^{-1} showed similar fibrous morphologies (Fig. 5C) to compound **6** (Fig. 5A), and similar diameters. The DMSO/H_2O (v/v 1 : 1) gel however also formed uniform fibrous assemblies, but with much thinner widths of the fibers or tubules (Fig. 5D) in comparison with Fig. 5B. The EtOH/H_2O (v/v 1 : 2) gel also showed uniform fibrous features with thin diameters (Fig. 5E). The gel of compound **9** in EtOH/H_2O (v/v 1 : 1) at 2.8 mg mL^{-1} showed uniform

Table 1 Gelation properties of the synthesized compounds

No.	R:	Pump oil	Tol	i-PrOH	EtOH	EtOH : H_2O (1 : 1)	EtOH : H_2O (1 : 2)	DMSO : H_2O (1 : 1)	DMSO : H_2O (1 : 2)	EG	Glycerol
5		G 6.7 C	S	S	S	S	G 6.7 O	G 5.0 O	G 5.0 O	P	S
6		G 4.0 C	S	S	S	G 10.0 O	G 3.3 O	G 5.0 O	G 5.0 O	G 10.0 O	G 20.0 O
7		G 20.0 C	S	S	S	G 20.0 O	G 20.0 O	G 10.0 O	G 20.0 O	G 10.0 O	P
8		G 20.0 C	S	S	S	G 6.7 O	G 6.7 O	G 5.0 O	G 5.0 O	G 20.0 O	P
9		G 4.0 C	S	S	S	G 2.8 O	P	P	P	G 20.0 O	P
10		G 10.0 C	S	P	S	S	P	P	P	S	S
11		G 10.0 C	S	P	S	G 20.0 O	G 20.0 O	G 20.0 O	G 20.0 O	S	G 20.0 O
12		G 10.0 O	S	P	P	G 20.0 O	G 20.0 O	G 20.0 O	G 20.0 O	S	G 20.0 O
13		G 10.0 C	S	S	S	P	P	G 10.0 O	G 10.0 O	S	P
14		G 6.7 O	P	P	S	P	P	P	P	G 20.0 O	P
15		I	G 20.0 O	P	G 20.0 O	I	I	P	I	P	P
16		S	S	P	S	P	I	P	G 20.0 O	P	P
17		I	P	P	P	I	I	I	I	I	I
18		G 10.0 C	G 20.0 C	G 20.0 O	G 20.0 O	G 6.7 O	I	G 10.0 O	G 10.0 O	P	P

G, gel at room temperature, the numbers are the corresponding minimum gelation concentrations (MGCs) in mg mL^{-1}; C for clear or transparent; T, translucent; O, opaque; UG, unstable gel; I, insoluble; P, crystallize or precipitate; S, soluble at ~20.0 mg mL^{-1}; pump oil, VWR® vacuum pump oil #19; Tol, toluene; EG, ethylene glycol.

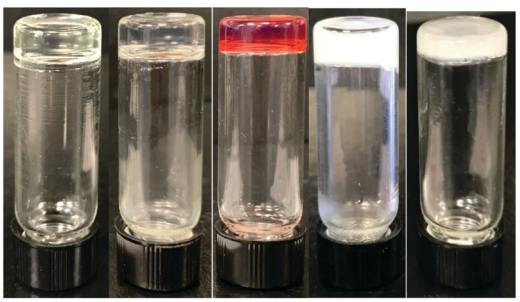


Fig. 3 A transparent gel formed by **6** at (a) 4.0 mg mL^{-1} in pump oil; (b) 4.0 mg mL^{-1} in mineral oil and (c) 6.7 mg mL^{-1} in engine oil; (d) an opaque gel formed by **8** in DMSO/H_2O (v/v 1 : 1) at 5.0 mg mL^{-1}; (e) an opaque gel formed by **15** in toluene at 20.0 mg mL^{-1}.

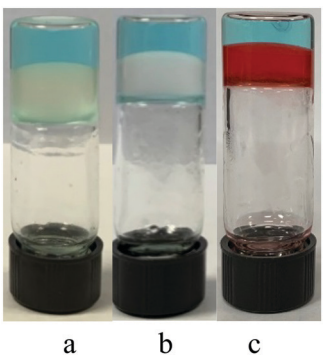


Fig. 4 The phase selective gelation by compound **6** in an oil and water ($CuSO_4$ solution) mixture: (a) compound **6** (4.0 mg) in pump oil (1 mL) and water (1 mL). (b) Compound **6** (3.0 mg) in mineral oil (0.75 mL) and water (0.75 mL). (c) Compound **6** (4.0 mg) in engine oil (0.6 mL) and water (0.6 mL).

birefringent fibrous or tubular assemblies (Fig. 5F). One interesting observation is that if the gelators are more efficient, *e.g.* forming gels at lower concentrations, the morphologies are typically long and narrow fibers. But when they are not very efficient, such as forming gels at higher MGCs such as 20 mg mL^{-1}, they usually form wider or larger tubules and sometimes planar sheets. For example the gel formed by compound **12** in EtOH/H_2O (v/v 1 : 1) at 20.0 mg mL^{-1} showed planar sheet like features; these also showed liquid crystal like optical images (Fig. 5G). The toluene gel of compound **15** formed bundles of fibers rather than individual fibers; the morphology was not as uniform as the others (Fig. 5H). And the ethanol gel of compound **15** exhibited more rigid rod like structures; the dried gels contained both fibers and crystalline planar sheets (Fig. 5I).

Rheological properties of the gels

The rheological properties of the gels formed by compounds **6**, **7** and **8** in mixed solvents of water with DMSO or water with ethanol are shown in Fig. 6a and the rheological properties for the oil gels are shown in Fig. 6b. For all the tested gels, their storage moduli G' are greater than the loss moduli G'', indicating that the gels have viscoelastic

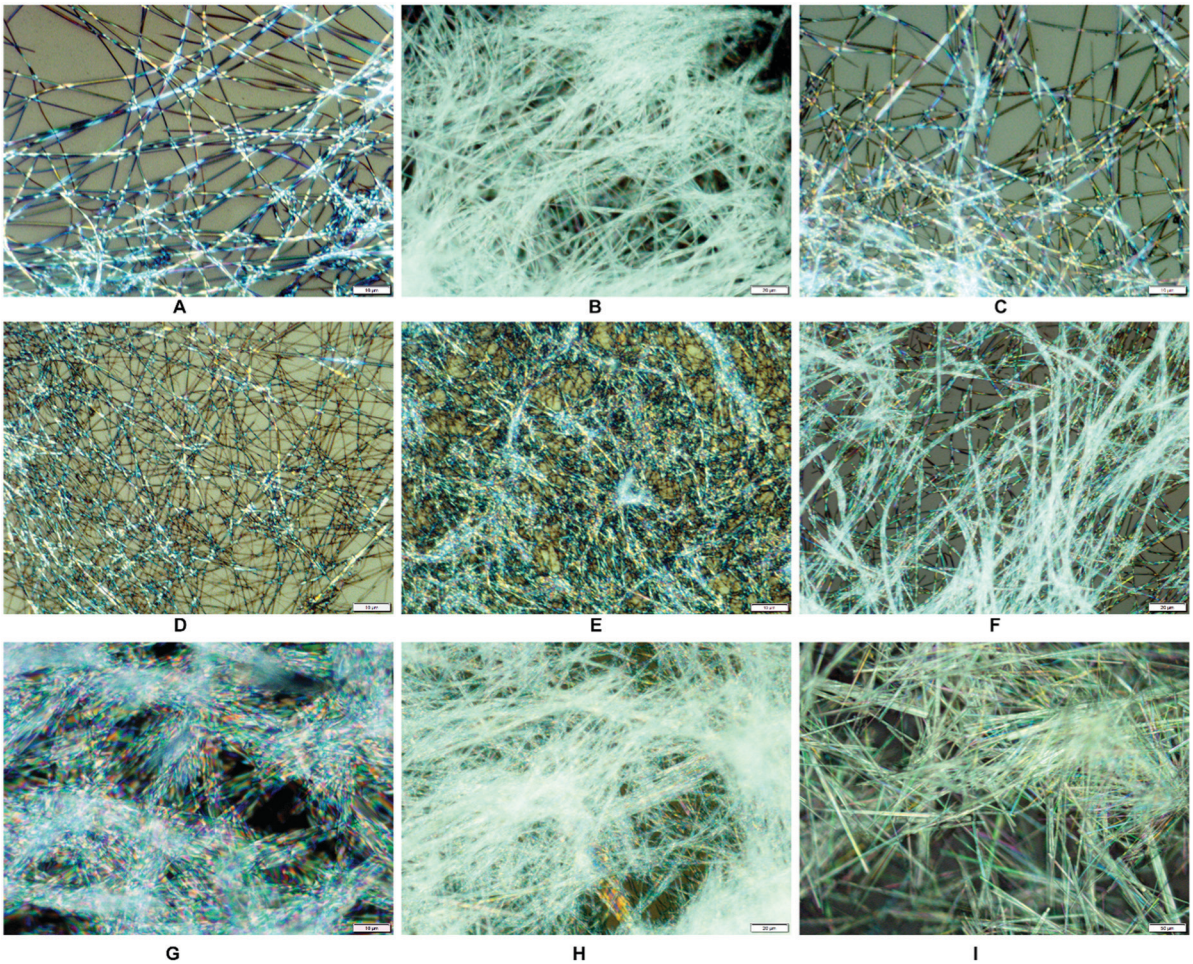


Fig. 5 Optical micrographs of the gels formed by several compounds in different solvents. (A) Compound **6** in DMSO/H_2O (v 1 : 2) at 5.0 mg mL^{-1}; (B) compound **6** in EtOH/H_2O (v/v 1 : 1) at 10.0 mg mL^{-1}; (C) compound **8** in DMSO/H_2O (v 1 : 2) at 5.0 mg mL^{-1}; (D) compound **8** in DMSO/H_2O (v 1 : 1) at 5.0 mg mL^{-1}; (E) compound **8** in EtOH/H_2O (v/v 1 : 2) at 6.7 mg mL^{-1}; (F) compound **9** in EtOH/H_2O (v/v 1 : 1) at 2.8 mg mL^{-1}; (G) compound **12** in EtOH/H_2O (v/v 1 : 1) at 20.0 mg mL^{-1}; (H) compound **15** in toluene at 20.0 mg mL^{-1}; (I) compound **15** in ethanol at 20.0 mg mL^{-1}.

properties and are stable gels. For the gels in aqueous mixtures, compound **8** in DMSO/H_2O (v 1 : 1) at a 5.0 mg mL^{-1} concentration had the highest values of G' and G'' and it was the strongest gel among all the tested samples. And the gel formed by compound **6** in DMSO/H_2O (v 1 : 2) had the largest G'/G'' values. We also carried out amplitude sweep experiments for these gels, and the results are shown in the ESI,† Fig. S1–S8.

Thermal stability

To further test the relative thermal stability, the melting points for a few DMSO : H_2O (v/v 1 : 1) gels formed by compounds **5–8** with different alkyl chain lengths were measured. As shown in Table 2, the melting points of gels with the same concentration range increased with an increase of the chain length. At 10.0 mg mL^{-1} concentrations for the four gelators, compound **8** with the longest chain had the highest melting points, and compound **5** with the shortest chain had the lowest middle-melting points among the four gelators. This trend is understandable by the fact that when increasing the hydrophobic chain length, the intermolecular interactions increase and enhance the gelation. The gels formed by compound **7** in different concentrations were also tested, and the melting points increased when the concentration of the gels was increased. At higher concentrations the gels were more stable, though the change in temperature was not huge. This indicates that concentration only plays a limited role in the gel stability, but the structures of the gelator make much bigger differences towards the stability.

Characterization of gelator structures using NMR spectroscopy

To elucidate the structural influences on molecular self-assembly, we carried out the study of ^1H NMR spectroscopy at different temperatures for compounds **6** and **15**. The ^1H NMR spectra of compound **15** showed shifts in some of the signals when the temperature was increased (ESI,† Fig. S12 and S13). From 30 to 55 °C, the acetyl NH signal of compound **15** shifted from 5.84 to 5.80 ppm and the anomeric signal shifted from 4.77 to 4.78 ppm. There were also small

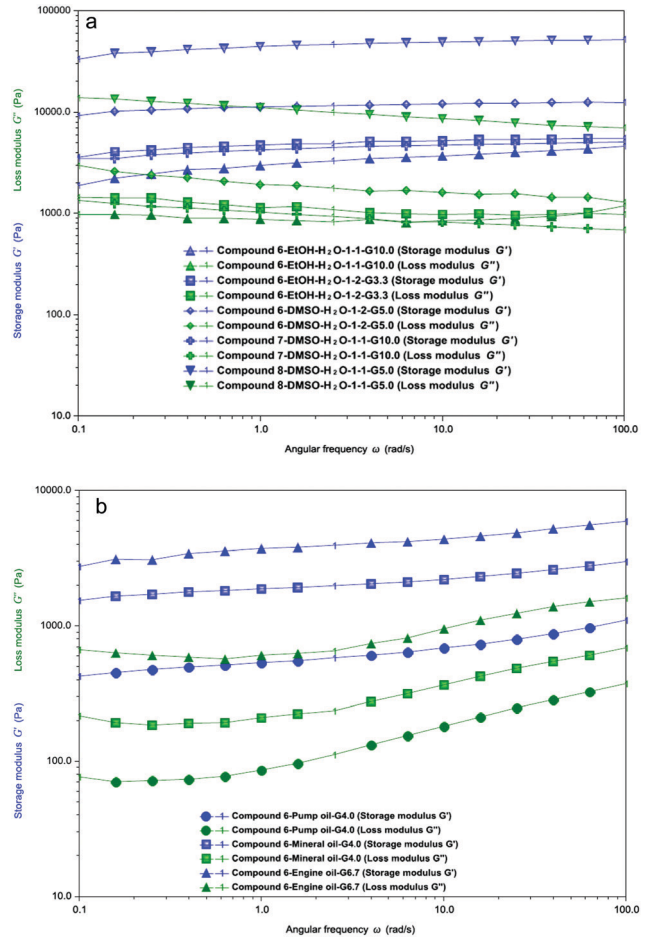


Fig. 6 (a) Rheological properties of the gels formed by compound **6** (EtOH/H_2O, v 1 : 1, 10.0 mg mL^{-1}), compound **6** (EtOH/H_2O, v 1 : 2, 3.3 mg mL^{-1}), compound **6** (DMSO/H_2O, v 1 : 2, 5.0 mg mL^{-1}), compound **7** (DMSO/H_2O, v 1 : 1, 10.0 mg mL^{-1}) and compound **8** (DMSO/H_2O, v 1 : 1, 5.0 mg mL^{-1}). The applied strain was 1% for all the samples. (b) Rheological properties of the gels formed by compound **6** in pump oil (4.0 mg mL^{-1}), mineral oil (4.0 mg mL^{-1}), and engine oil (6.7 mg mL^{-1}). The applied strain was 1% for all the samples.

shifts observed in the acetal (5.57 to 5.55 ppm) and OCH_3 (3.44 to 3.45 ppm) signals. These results suggest that the NH protons participate in hydrogen bonding interactions, which contribute to the molecular packing necessary for gelation.

The ^1H NMR spectra of compound **6** are shown in Fig. 7. The amide N–H signal showed the most obvious shift among all signals, from 5.81 ppm shifted upfield to 5.77 ppm upon heating from 30 to 55 °C, which indicates that the amide hydrogen bonding is important for gelation. Other signals didn't show significant changes; the anomeric proton and the OCH_3 both slightly shifted downfield by 0.01 ppm at higher temperature, which indicates that the intramolecular hydrogen bonding between the NH and OCH_3 slightly enhances while intermolecular hydrogen bonding decreases. In oil and other non-polar solvents, the intermolecular hydrogen bonding among the gelator molecules plays an important role in the gel stability and strength.

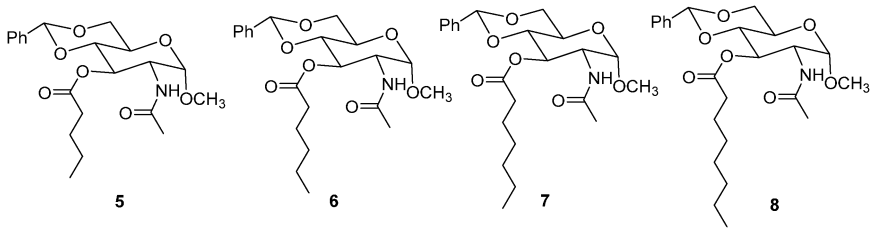
Drug encapsulation and release

Compound **6** was also tested in a series of DMSO and water mixtures by sequentially adding water to DMSO. It formed stable gels in DMSO : H_2O (v/v 1 : 3) at a 5.0 mg mL^{-1} concentration (ESI,† Fig. S6 and Table S6). This gel was used for entrapping a model drug naproxen and the release of naproxen from the co-gels at different time was monitored by UV-vis spectroscopy. The UV-vis absorbance and release% over time are shown in Fig. 8. About 50% of naproxen was released to the water phase during the first 10 h, and more slowly after that. About 75% was released to the aqueous phase at 48 h. The naproxen co-gels were also subjected to a pH = 10 solution and the gel was stable during the period of 48 hours, when naproxen release was monitored by UV-vis spectroscopy. This is shown in Fig. S19 (ESI†); the naproxen release speed was almost the same as using pH 7 water as shown in Fig. 8. We tested the stability of the gel formed by compound **6** in DMSO : H_2O (v/v 1 : 3) at 5.0 mg mL^{-1} and treated the gels with a stronger base solution (pH = 14); the gel was stable for several hours but showed slow degradation over 10 hours (Fig. S20, ESI†). The results indicated that the gels were stable under mild alkaline conditions and should be suitable to use in the presence of a wide pH range.

Conclusions

In summary, a series of fourteen 3-*O*-ester derivatives of 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside were synthesized and characterized. All the ten synthesized alkyl ester derivatives were effective gelators for pump oil and many of them were gelators for aqueous mixtures of ethanol and DMSO. In contrast, the aromatic ester derivatives did not perform well; only the benzoate derivative formed gels in oil and the *p*-bromobenzoate formed two organogels. The dimeric ester derivative **18** can be considered as covalently linking two monomers (compound **5**); the dimerization resulted in a greater gelation tendency in organic solvents. Optical microscopy studies showed that the gelators formed typically uniform fibrous networks and some derivatives formed crystalline sheets. The rheological studies showed that the storage moduli G' for the gels were higher than the loss moduli G'' indicating the viscoelastic properties of the gels. The hexanote derivative **6** was able to encapsulate naproxen and form a co-gel, and the gelator showed sustained release of the trapped naproxen from the gel to the aqueous phase. In addition, the hexanoate compound **6** was also effective in phase selective gelation for several different oils in the presence of an aqueous phase. The ^1H NMR spectra of compound **6** at different temperatures showed that the amide function played an important role in the intermolecular hydrogen bonding during molecular assembly. Since this new class of carbohydrate derived esters can be synthesized *via* straightforward methods from readily available starting materials, they could have many practical applications including oil spill cleanup. The systematic derivatization at the C-3 position of *N*-acetyl glucosamine derivatives led to a new class

Table 2 The melting point range for some of the gels in DMSO : H_2O (v/v 1 : 1)



Compound number	G–C (mg mL^{-1})	G–C (mM)	T_1 (°C)	T_2 (°C)	T_3 (°C)
5	10.0	24.6	48.7	55.4	60.7
6	10.0	23.7	53.6	67.2	77.6
7	10.0	23.0	56.2	83.5	99.4
7	15.0	34.5	62.4	89.0	103.4
7	20.0	46.0	65.7	94.3	108.4
8	10.0	22.3	58.7	87.6	102.3

G–C: gelation concentration. T_1: initial melting temperature. T_2: temperature when the gel is half melted. T_3: the temperature when the entire gel melts and the ball reaches the bottom of the tube.

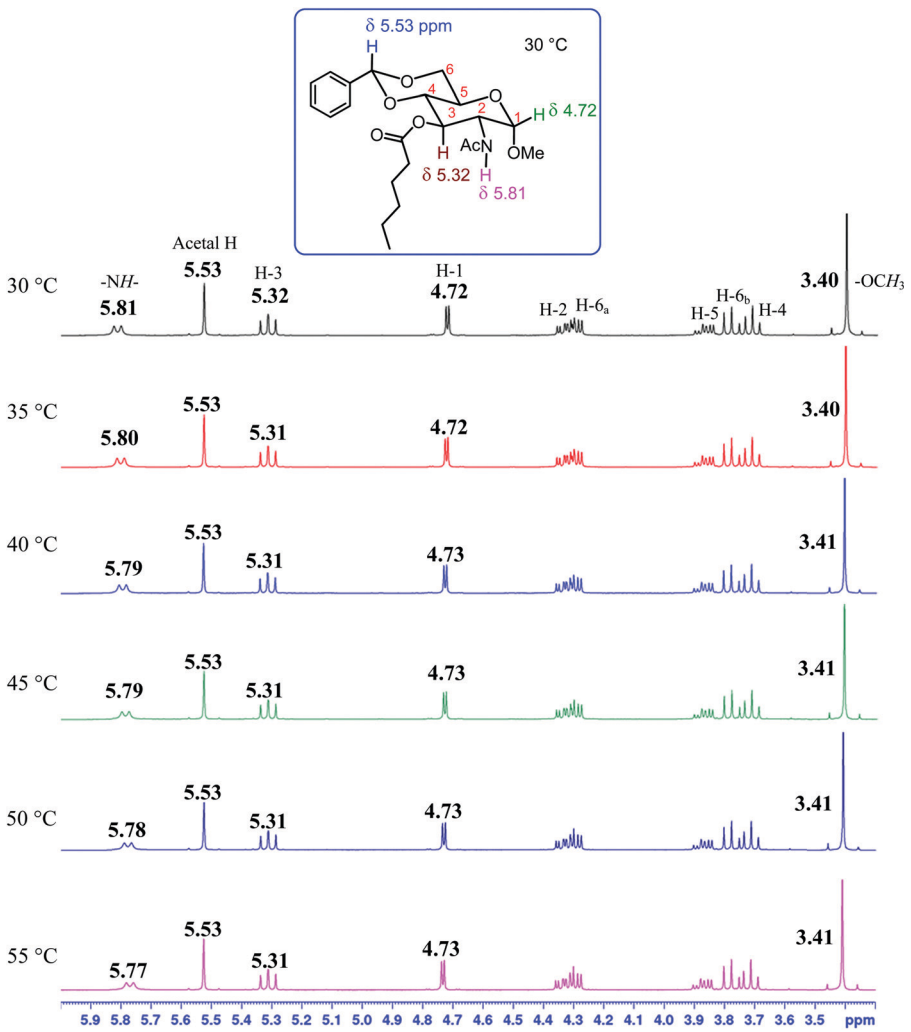


Fig. 7 The ^1H NMR spectra (3.3 to 6.0 ppm) of compound **6** from 30 °C to 55 °C in $CDCl_3$ (10.0 mg mL^{-1}).

of low molecular weight organogelators. The general structural features obtained from this series of compounds can be applied to other sugar derivatives and afford functional and versatile organogelators.

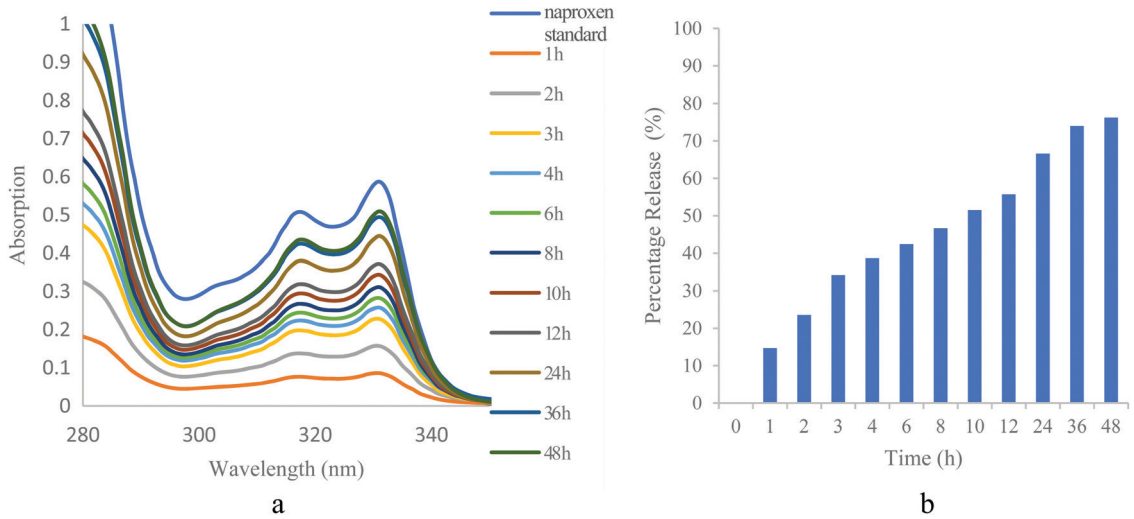


Fig. 8 Release of naproxen from the gel to the aqueous phase. (a) UV spectra of naproxen timed release; the gel was formed by 7.5 mg of compound **6** in 1.5 mL DMSO : H_2O (v/v 1 : 3) with 0.3 mg of naproxen, then 1.5 mL of water (pH 7) was added to the top of the gel. The naproxen control was prepared by dissolving 0.3 mg of naproxen in 3 mL of water (pH 7). (b) The % release at different time based on the UV absorbance at 331 nm.

Experimental section

General method and materials

Reagents and solvents were used as they were received from the suppliers. All purification was conducted by flash chromatography using 230–400 mesh silica gel with a gradient of solvent systems. ^{1}H NMR and proton-decoupled ^{13}C NMR spectra were obtained with Bruker 400 MHz spectrometers in $CDCl_3$. The chemical shifts were reported using $CDCl_3$/d_6-DMSO calibrated at 7.26/2.50 ppm and 77.00/39.50 ppm respectively. Melting point measurements were carried out using a Fisher Jones melting point apparatus. Rheology experiments were done using a HR-2 Discovery hybrid rheometer from TA instruments and a 25 mm Peltier plate. FTIR experiments were conducted using liquid or solid samples directly. The molecular mass was measured using LCMS on an Agilent 6120B Single Quad mass spectrometer coupled with a LC1260 system and a Shimadzu LC 2030C system with a LCMS 2030 mass spectrometer.

Optical microscopy

A small amount of the gels was placed on a clean glass slide and this was observed under an Olympus BX60M optical microscope and an Olympus DP73-1-51 high performance 17MP digital camera with pixel shifting and Peltier cooling. The imaging software for image capturing was CellSens 1.11. For aqueous DMSO mixtures, the gel was left to air dry for a day or so; for other solvents the slides were observed directly.

Gelation test

About 2 mg of dried compound was placed in a 1 dram glass vial and the corresponding solvent was added to obtain a concentration of 20 mg mL^{-1}. The mixture was then heated until the solid was fully dissolved, sometimes sonication was needed to dissolve the sample, and then the solution was allowed to cool to room temperature and left standing for 30 minutes. If a stable gel formed (observed by inverting the vial), it was then serially diluted till the minimum gelation concentration (MGC), the concentration prior to unstable gelation, was obtained.

Phase selective gelation tests for oil and water mixtures. The test results of compound **6** in several oil and water mixtures are shown in Fig. 4. Compound **6** (4.0 mg) was added to a mixture of 1 mL pump oil and 1 mL of copper sulfate solution. Then the sample vial was heated till all was dissolved and then was left cooling to rt; 10 minutes later, the pump oil gel was formed and was strong enough to hold the aqueous phase. The other oils were tested similarly, so only the quantities of samples are given here: 3 mg of compound **6**, 0.75 mL of mineral oil and 0.75 mL of copper sulfate solution. For engine oil the time waiting for gelation was 1 hour; the gel was prepared using 4 mg of compound **6**, 0.6 mL of engine oil and 0.6 mL of copper sulfate solution.

Rheological analyses

The rheological behavior of the gel was investigated with an HR-2 Discovery hybrid rheometer from TA Instruments with TRIOS software. A sample (approximately 1 mL of the gel) was placed on the steel plate of the rheometer. The cone geometry was a 25 mm Peltier plate with a gap of 100 μm. The experimental temperature was 25 °C, and the sample was subjected to an amplitude sweep for oscillation strains from 0.125 to 100%. A frequency sweep was then performed for the sample in the range of 0.1 to 100 rad s^{-1} for the angular frequency. The results were expressed as the storage modulus (G') and loss modulus (G'') as a function of angular frequency.

Measurement of the melting point ranges of gels

The gelator was dissolved in a small vial at a certain gelation concentration and heated to form a solution. The hot solution was transferred to an NMR tube or a narrow glass tube, where it was allowed to cool down to form the gel. A metal ball was

placed on top of the gel. The NMR tube was immersed in an oil bath which was heated gradually. T_1 is the temperature of the initial melting at which a liquid is first seen, T_2 is the temperature at which the gel is estimated to be half melted and T_3 is the temperature at which the entire gel turns into a colorless liquid and the ball reaches the bottom of the tube.

Naproxen release study

The gels were formed by adding 7.5 mg compound **6**, followed by 1.5 mL of DMSO : H_2O (v/v 1 : 3) containing 0.3 mg naproxen. The mixture was heated and cooled to form a stable gel in a vial. Water (1.5 mL, pH = 7 or 10) was pipetted on top of the gel carefully. The aqueous phase was periodically transferred to a quartz cuvette and the UV-vis spectrum was measured. The naproxen standard was prepared by dissolving 0.3 mg naproxen sodium in 3 mL of water (pH = 7). All measurements were carried out using a Thermo Scientific™ Evolution™ 201 UV-visible spectrophotometer.

Liquid chromatography-mass spectrometer (LC-MS) conditions

The molecular mass acquisition was performed using an Agilent 1260 Infinity LC system coupled to a G6120B single quadrupole mass spectrometer with an atmospheric pressure ionization electrospray (API-ES). The analytical column was an Agilent poroshell 120 EC-C18 4.6 mm × 50 mm column with a 2.7 μm particle size. The mobile phase was 0.1% formic acid in acetonitrile/water (70/30, v/v) with an ejection volume of 5 μL and 8 minutes total run time typically. The flow rate was 0.40 mL min^{-1} and the column temperature set at 25 °C. The diode-array detector (DAD) operated at 254 nm. Agilent OpenLAB CDS ChemStation (Version C.01.05) was used for data processing. The ESI spray voltage was set to 4000 V, the source temperature was 350 °C and the nebulizer gas setting was 35 psi.

General procedure for the synthesis of compounds 5–18

Compound **4** (100 mg, 0.313 mmol, 1 equiv.) was dissolved in CH_2Cl_2 (4 mL, anhydrous) at 0 °C in a round bottom flask under nitrogen atmosphere and the flask was protected from moisture using a drying tube. Then pyridine (5 equiv. typically) and DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.) were added. The resulting mixture was stirred at 0 °C for about 30 minutes. Two equivalents of acyl chloride (commercially available or prepared *in situ* by treating the corresponding acid with oxalyl chloride) was then added drop-wise to the reaction mixture followed by stirring at room temperature for 6 hours unless otherwise stated. TLC (5% MeOH/CH_2Cl_2) and ^{1}H NMR spectrum of the reaction mixture indicated the complete consumption of the starting material to the desired product. The reaction was then quenched with satd. $NaHCO_3$ (aq. 5 mL) and the phases were then separated and the aqueous phase was further extracted with CH_2Cl_2 (15 mL × 2). The combined organic phases were dried with anhydrous Na_2SO_4, filtered and concentrated to afford the crude product, which was purified by column chromatography to obtain the desired product. Detailed syntheses for compound **5** and di-ester compound **18** are included only; and for all other compounds the amount of the reagents, yield, R_f value and characterization data of the products are listed respectively.

Synthesis of 3-*O*-pentanoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 5. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.) was added followed by DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.) to a mixture of compound **4** (100 mg, 0.313 mmol, 1 equiv.) in CH_2Cl_2 and the resulting mixture was stirred at 0 °C for about 30 minutes. Pentanoyl chloride (0.626 mmol, 2 equiv.) in 1 mL of CH_2Cl_2 was then added dropwise and the reaction mixture was stirred for about 6 hours at room temperature. The product was obtained as a white solid (107 mg, 84%). R_f = 0.45 in 60% EtOAc/hexanes, m.p. 133.0–135.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.48–7.45 (m, 2H), 7.38–7.36 (m, 3H), 5.83 (d, J = 9.5 Hz, 1H), 5.55 (s, 1H), 5.34 (t, J = 10.0 Hz, 1H), 4.75 (d, J = 3.6 Hz, 1H), 4.38–4.30 (m, 2H), 3.93–3.87 (m, 1H), 3.81 (t, J = 10.1 Hz, 1H), 3.74 (t, J = 9.5 Hz, 1H), 3.43 (s, 3H), 2.34 (dt, J = 7.4, 2.9 Hz, 2H), 1.97 (s, 3H), 1.61–1.55 (m, 2H), 1.35–1.28 (m, 2H), 0.87 (t, J = 7.3 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 174.3, 169.9, 137.0, 129.0, 128.2, 126.1, 101.5, 99.1, 79.1, 69.9, 68.9, 62.8, 55.3, 52.6, 34.0, 27.1, 23.2, 22.1, 13.6. LC-MS (ESI+) calcd $C_{21}H_{30}NO_7$ $[M + H]^+$ 408.2 found 408.2.

Synthesis of 3-*O*-hexanoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 6. Pyridine (0.12 mL, 1.55 mmol), DMAP (6.0 mg, 0.047 mmol), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and hexanoyl chloride (0.086 mL, 0.618 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (114 mg, 87%). R_f = 0.55 in 60% EtOAc/hexanes, m.p. 142.0–144.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.38–7.36 (m, 2H), 7.29–7.26 (m, 3H), 5.73 (d, J = 9.4 Hz, 1H), 5.46 (s, 1H), 5.24 (t, J = 10.0 Hz, 1H), 4.65 (d, J = 3.6 Hz, 1H), 4.29–4.21 (m, 2H), 3.83–3.77 (m, 1H), 3.71 (t, J = 10.1 Hz, 1H), 3.64 (t, J = 9.4 Hz, 1H), 3.33 (s, 3H), 2.30–2.17 (m, 2H), 1.88 (s, 3H), 1.55–1.47 (m, 2H), 1.21–1.16 (m, 4H), 0.76 (t, J = 6.9 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 174.3, 169.9, 137.1, 129.0, 128.2, 126.1, 101.5, 99.1, 79.1, 68.9, 62.8, 55.3, 52.6, 34.3, 31.1, 24.7, 23.2, 22.2, 13.8. LC-MS (ESI+) calcd $C_{22}H_{32}NO_7$ $[M + H]^+$ 422 found 422.

Synthesis of 3-*O*-hepanoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 7. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and heptanoyl chloride (0.096 mL, 0.618 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (112 mg, 83%). R_f = 0.6 in 60% EtOAc/hexanes, m.p. 137.0–139.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.47–7.41 (m, 2H), 7.37–7.32 (m, 3H), 5.82 (d, J = 9.4 Hz, 1H), 5.52 (s, 1H), 5.30 (t, J = 10.1 Hz, 1H), 4.72 (d, J = 3.6 Hz, 1H), 4.36–4.27 (m, 2H), 3.91–3.82 (m, 1H), 3.78 (t, J = 10.1 Hz, 1H), 3.71 (t, J = 9.5 Hz, 1H), 3.40 (s, 3H), 2.30 (dt, J = 7.4, 3.6 Hz, 2H), 1.95 (s, 3H), 1.58–1.53 (m, 2H), 1.31–1.18 (m, 6H), 0.84 (t, J = 6.7 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 174.3, 169.9, 137.0, 129.0, 128.2, 126.1, 101.5, 99.1, 79.1, 69.9, 68.9, 62.8, 55.3, 52.6, 34.3, 31.4, 28.6, 25.0, 23.2, 22.4, 14.0. LC-MS (ESI+) calcd $C_{23}H_{34}NO_7$ $[M + H]^+$ 436 found 436.

Synthesis of 3-*O*-octanoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 8. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and octanoyl chloride

(0.11 mL, 0.618 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (111 mg, 80%). R_f = 0.6 in 60% EtOAc/hexanes, m.p. 128.0–130.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.48–7.45 (m, 2H), 7.38–7.35 (m, 3H), 5.82 (d, J = 9.6 Hz, 1H), 5.55 (s, 1H), 5.34 (t, J = 10.1 Hz, 1H), 4.75 (d, J = 3.6 Hz, 1H), 4.38–4.30 (m, 2H), 3.93–3.87 (m, 1H), 3.81 (t, J = 10.2 Hz, 1H), 3.74 (t, J = 9.4 Hz, 1H), 3.43 (s, 3H), 2.39–2.27 (m, 2H), 1.98 (s, 3H), 1.63–1.56 (m, 2H), 1.29–1.23 (m, 8H), 0.87 (t, J = 7.0 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 174.3, 169.9, 137.1, 129.0, 128.2, 126.1, 101.5, 99.1, 79.1, 69.9, 68.9, 62.8, 55.3, 52.6, 34.3, 31.6, 28.93, 28.87, 25.0, 23.2, 22.6, 14.0. LC-MS (ESI+) calcd $C_{24}H_{36}NO_7$ $[M + H]^+$ 450 found 450.

Synthesis of 3-*O*-dodecanoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 9. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and lauroyl chloride (0.626 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (120 mg, 76%). R_f = 0.6 in 60% EtOAc/hexanes, m.p. 96.0–98.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.47–7.40 (m, 2H), 7.37–7.30 (m, 3H), 5.81 (d, J = 9.5 Hz, 1H), 5.53 (s, 1H), 5.31 (t, J = 10.0 Hz, 1H), 4.72 (d, J = 3.7 Hz, 1H), 4.37–4.27 (m, 2H), 3.91–3.83 (m, 1H), 3.80 (t, J = 10.1 Hz, 1H), 3.71 (t, J = 9.4 Hz, 1H), 3.40 (s, 3H), 2.34–2.25 (m, 2H), 1.95 (s, 3H), 1.61–1.52 (m, 2H), 1.34–1.14 (m, 16H), 0.88 (t, J = 6.9 Hz, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 174.3, 169.9, 137.1, 129.0, 128.2, 126.1, 101.5, 99.1, 79.1, 69.9, 68.9, 62.8, 55.3, 52.6, 34.3, 31.9, 29.59, 29.57, 29.4, 29.3, 29.2, 29.0, 25.0, 23.2, 22.7, 14.1. LC-MS (ESI+) calcd $C_{28}H_{44}NO_7$ $[M + H]^+$ 506 found 506.

Synthesis of 3-*O*-4′-chlorobutanoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 10. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and 4-chlorobutyryl chloride (0.07 mL, 0.626 mmol, 2 equiv.) were added similarly to above. The product was obtained as an off-white solid (111 mg, 84%). R_f = 0.5 in 60% EtOAc/hexanes, m.p. 129.0–131.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.47–7.41 (m, 2H), 7.38–7.32 (m, 3H), 5.79 (d, J = 9.6 Hz, 1H), 5.53 (s, 1H), 5.31 (t, J = 10.0 Hz, 1H), 4.71 (d, J = 3.7 Hz, 1H), 4.39–4.28 (m, 2H), 3.91–3.84 (m, 1H), 3.79 (t, J = 10.1 Hz, 1H), 3.72 (t, J = 9.5 Hz, 1H), 3.52 (t, J = 6.2 Hz, 2H), 3.41 (s, 3H), 2.54–2.47 (m, 2H), 2.08–2.00 (m, 2H), 1.96 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 173.0, 170.0, 136.9, 129.1, 128.2, 126.1, 101.6, 99.0, 79.0, 70.5, 68.9, 62.8, 55.3, 52.4, 43.7, 31.3, 27.7, 23.2. LC-MS (ESI+) calcd $C_{20}H_{27}ClNO_7$ $[M + H]^+$ 428 found 428.

Synthesis of 3-*O*-5′-hexynoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 11. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and 5-hexynoyl chloride (0.626 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (105 mg, 81%). R_f = 0.3 in 60% EtOAc/hexanes, m.p. 162.0–164.0 °C, ^{1}H NMR (d_6-DMSO, 400 MHz) δ 7.95 (d, J = 9.4 Hz, 1H), 7.41–7.32 (m, 5H), 5.65 (s, 1H), 5.18 (t, J = 10.2 Hz, 1H), 4.67 (d, J = 3.5 Hz, 1H), 4.27–4.16 (m, 2H), 3.85–3.76 (m, 2H), 3.75–3.67 (m, 1H), 3.36 (s, 3H), 2.76 (t, J = 2.6 Hz, 1H), 2.40–2.27 (m, 2H), 2.14 (dt, J = 7.1, 2.6 Hz, 2H), 1.82 (s, 3H), 1.71–1.58 (m, 2H); ^{13}C NMR (d_6-DMSO, 100 MHz) δ 171.7, 169.6, 137.3, 128.8, 128.0, 126.0, 100.3, 98.8, 83.5, 78.8, 71.6, 69.4, 67.8, 62.6, 54.9, 51.2, 32.3, 23.7, 22.2, 16.8. LC-MS (ESI+) calcd $C_{22}H_{28}NO_7$ $[M + H]^+$ 418, found 418.

Synthesis of 3-*O*-6′-heptynoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 12. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and 6-heptynoyl chloride (0.626 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (111 mg, 82%). R_f = 0.45 in 60% EtOAc/hexanes, m.p. 159.0–161.0 °C, ^{1}H NMR (d_6-DMSO, 400 MHz) δ 7.94 (d, J = 9.4 Hz, 1H), 7.39–7.34 (m, 5H), 5.64 (s, 1H), 5.17 (t, J = 9.6 Hz, 1H), 4.67 (d, J = 3.5 Hz, 1H), 4.27–4.16 (m, 2H), 3.84–3.76 (m, 2H), 3.75–3.67 (m, 1H), 3.36 (s, 3H), 2.72 (t, J = 2.6 Hz, 1H), 2.34–2.18 (m, 2H), 2.08 (dt, J = 7.0, 2.6 Hz, 2H), 1.82 (s, 3H), 1.60–1.50 (m, 2H), 1.44–1.34 (m, 2H); ^{13}C NMR (d_6-DMSO, 100 MHz) δ 172.0, 169.6, 137.3, 128.8, 128.0, 126.0, 100.3, 98.9, 84.0, 78.8, 71.2, 69.3, 67.8, 62.6, 54.9, 51.2, 33.0, 27.0, 23.7, 22.3, 17.3. LC-MS (ESI+) calcd $C_{23}H_{30}NO_7$ $[M + H]^+$ 432.2 found 432.2.

Synthesis of 3-*O*-cyclohexanoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 13. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and cyclohexanecarbonyl chloride (0.2 mL, 1.24 mmol, 4 equiv.) were added similarly to above. Then the reaction mixture was stirred for about 90 minutes at 0 °C. The product was obtained as a white solid (106 mg, 79%). R_f = 0.22 in 50% EtOAc/hexanes. m.p. 175.0–177.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.47 (m, 2H), 7.39–7.35 (m, 3H), 5.80 (d, J = 9.6 Hz, 1H), 5.55 (s, 1H), 5.34 (t, J = 10.0 Hz, 1H), 4.74 (d, J = 3.6 Hz, 1H), 4.40–4.31 (m, 2H), 3.92–3.86 (m, 1H), 3.81 (t, J = 10.1 Hz, 1H), 3.74 (t, J = 9.6 Hz, 1H), 3.43 (s, 3H), 2.35 (tt, J = 11.1, 3.6 Hz, 1H), 1.97 (s, 3H), 1.86 (m, 2H), 1.76–1.72 (m, 2H), 1.65–1.61 (m, 1H), 1.50–1.37 (m, 2H), 1.33–1.20 (m, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 176.5, 169.9, 137.1, 129.0, 128.2, 126.1, 101.4, 99.1, 79.2, 69.6, 68.9, 62.9, 55.3, 52.6, 43.1, 28.93, 28.87, 25.7, 25.3, 25.2, 23.2. LC-MS (ESI+) calcd $C_{23}H_{32}NO_7$ $[M + H]^+$ 434.2 found 434.2.

Synthesis of 3-*O*-benzoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 14. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and benzoyl chloride (0.070 mL, 0.618 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (112 mg, 85%). R_f = 0.45 in 60% EtOAc/hexanes, m.p. 194.0–196.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.05–8.03 (m, 2H), 7.59–7.54 (m, 1H), 7.47–7.42 (m, 4H), 7.34–7.31 (m, 3H), 5.89 (d, J = 9.6 Hz, 1H), 5.64–5.55 (m, 2H), 4.81 (d, J = 3.6 Hz, 1H), 4.54 (dt, J = 10.1, 3.6 Hz, 1H), 4.36 (dd, J = 10.2, 4.6 Hz, 1 H), 4.01–3.96 (m, 1H), 3.90 (t, J = 9.4 Hz, 1H), 3.86 (t, J = 10.2 Hz, 1H), 3.47 (s, 3 H), 1.89 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 170.0, 167.0, 137.0, 133.2, 129.9, 129.6, 129.0, 128.4, 128.2, 126.1, 101.5, 99.2, 79.4, 70.8, 69.0, 63.0, 55.4, 52.6, 23.2. LC-MS (ESI+) calcd $C_{23}H_{26}NO_7$ $[M + H]^+$ 428.2 found 428.2.

Synthesis of 3-*O*-4′-bromobenzoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 15. Pyridine (3.0 mL), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and 4-bromobenzoyl chloride (140 mg, 0.62 mmol, 2 equiv.) were added similarly to above. Then the reaction mixture was stirred at 60 °C for about 9 hours.

The product was obtained as a white solid (128 mg, 82%). R_f = 0.5 in 60% EtOAc/hexanes, m.p. 262.0–264.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.89 (d, J = 8.6 Hz, 2H), 7.58 (d, J = 8.6 Hz, 2H), 7.44–7.41 (m, 2H), 7.33–7.32 (m, 3H), 5.92 (d, J = 9.6 Hz, 1H), 5.57 (t, J = 9.6 Hz, 1H), 5.57 (s, 1H), 4.79 (d, J = 6.6 Hz, 1H), 4.55 (d, J = 3.6, 10.1 Hz, 1H), 4.35 (dd, J = 4.6, 10.1 Hz, 1H), 4.00–3.95 (m, 1H), 3.91–3.82 (m, 2H), 3.46 (s, 3H), 1.88 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 170.0, 166.2, 136.9, 131.8, 131.4, 129.1, 128.5, 128.4, 128.2, 126.1, 101.6, 99.2, 79.3, 71.2, 68.9, 63.0, 55.4, 52.5, 23.1. LC-MS (ESI+) calcd $C_{23}H_{25}NO_7Br$ $[M + H]^+$ 506.1 found 506.1.

Synthesis of 3-*O*-4′-methoxybenzoyl 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 16. Pyridine (2.0 mL), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and 4-methoxy benzoyl chloride (0.08 mL, 0.626 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (115 mg, 81%). R_f = 0.4 in 60% EtOAc/hexanes, m.p. 196.0–198.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 8.01–7.98 (m, 2H), 7.45–7.42 (m, 2H), 7.34–7.31 (m, 3H), 6.93–6.90 (m, 2H), 5.91 (d, J = 9.5 Hz, 1H), 5.58 (s, 1H), 5.57 (t, J = 9.96 Hz, 1H), 4.81 (d, J = 3.6 Hz, 1H), 4.54–4.48 (m, 1H), 4.35 (dd, J = 10.1, 4.6 Hz, 1H), 4.00–4.95 (m, 1H), 3.91–3.83 (overlapping m and s, 5H), 3.46 (s, 3H), 1.88 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 170.0, 166.7, 163.6, 137.0, 132.0, 129.0, 128.2, 126.1, 121.9, 113.7, 101.5, 99.2, 79.4, 70.4, 69.0, 63.0, 55.42, 55.36, 52.8, 23.2. LC-MS (ESI+) calcd $C_{24}H_{28}NO_8$ $[M + H]^+$ 458.2 found 458.2.

Synthesis of 3-*O*-[2-(1-naphthalenyl) acetyl] 2-acetamido-2-deoxy-4,6-*O*-benzylidene methyl-α-D-glucopyranoside 17. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.), DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.), compound **4** (100 mg, 0.313 mmol, 1 equiv.) and 1-naphthalene acetyl chloride (0.626 mmol, 2 equiv.) were added similarly to above. The product was obtained as a white solid (121 mg, 81%). R_f = 0.4 in 60% EtOAc/hexanes, m.p. 231.0–233.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.95 (d, J = 8.5 Hz, 1H), 7.83 (d, J = 8.1 Hz, 1H), 7.77 (d, J = 8.0 Hz, 1H), 7.46–7.34 (m, 9H), 5.73 (d, J = 9.5 Hz, 1H), 5.50 (s, 1H), 5.36 (t, J = 10.0 Hz, 1H), 4.72 (d, J = 3.6 Hz, 1H), 4.40–4.35 (m, 1H), 4.34–4.28 (m, 1H), 4.17–4.04 (m, 2H), 3.91–3.85 (m, 1H), 3.80 (t, J = 9.3 Hz, 1H), 3.75 (t, J = 8.6 Hz, 1H), 3.39 (s, 3H), 1.70 (s, 3H); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 172.0, 170.0, 137.0, 133.8, 132.0, 130.1, 129.0, 128.6, 128.2, 128.1, 128.0, 126.4, 126.2, 125.7, 125.5, 123.7, 101.6, 99.0, 79.1, 70.5, 68.9, 62.8, 55.3, 52.5, 38.9, 23.0. LC-MS (ESI+) calcd $C_{28}H_{30}NO_7$ $[M + H]^+$ 492.2 found 492.2.

Synthesis of di-ester compound 18. Pyridine (0.12 mL, 1.55 mmol, 5 equiv.) was added followed by DMAP (6.0 mg, 0.047 mmol, 0.15 equiv.) to a mixture of compound **4** (100 mg, 0.313 mmol, 1 equiv.) in CH_2Cl_2 and the resulting mixture was stirred at 0 °C for about 30 minutes. Decanedioyl dichloride (0.141 mmol, 0.45 equiv.) in 1 mL of CH_2Cl_2 was then added dropwise and the reaction mixture was stirred for about 12 hours at room temperature. The di-ester product was obtained as a white solid (62 mg, 54%). R_f = 0.6 in 5% MeOH/DCM, m.p. 215.0–217.0 °C, ^{1}H NMR ($CDCl_3$, 400 MHz) δ 7.45–7.40 (m, 4H), 7.36–7.31 (m, 4H), 5.88 (d, J = 9.5 Hz, 2H), 5.51 (s, 2H), 5.32 (t, J = 9.8 Hz, 2H), 4.72 (d, J = 3.6 Hz, 2H), 4.37–4.26 (m, 4H), 3.91–3.84 (m, 2H), 3.78 (t, J = 10.1 Hz, 2H), 3.71 (t, J = 9.5 Hz, 2H), 3.40 (s, 6H), 2.31–2.25 (m, 4H), 1.95 (s, 6H), 1.58–1.48 (m, 4H), 1.27–1.14 (m, 8H), 0.88; ^{13}C NMR ($CDCl_3$, 100 MHz) δ 174.2, 170.0, 137.1, 129.0, 128.2, 126.1, 101.5, 99.1, 79.1, 69.9, 68.9, 62.8, 55.4, 52.6, 34.2, 28.8, 28.7, 24.9, 23.2. LC-MS (ESI+) calcd $C_{42}H_{57}N_2O_{14}$ $[M + H]^+$ 813.4 found 813.4.

Conflicts of interest

There are no conflicts to declare.

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