

PAPER

View Article Online
View Journal | View Issue



Cite this: *Org. Biomol. Chem.*, 2025, **23**, 5847

Received 5th May 2025,
Accepted 21st May 2025
DOI: 10.1039/d5ob00730e
rsc.li/obc

Total synthesis of the D-acofriose-containing trisaccharide repeating unit of the O-antigen from *Azospirillum brasilense* JM6B2†

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The unique D-acofriose (6-deoxy-3-O-methyl-D-mannose) unit present in the target oligosaccharide was synthesized from commercially available D-mannose in six steps with ~50% overall yield. The synthesis was found to be equally successful at the multigram scale (100 mmol). 2-Bromoethyl α-L-fucopyranoside, required at the reducing end, was prepared exclusively via H₂SO₄–silica promoted Fischer glycosylation. The influence of the protecting group at the 3-position of the fucosyl moiety on glycosylation at the 4-position was studied and ether protection was found to be essential over ester protection. Further global deprotection gave the target conjugation-ready trisaccharide in 34% overall yield.

Introduction

Selective enrichment of the rhizosphere with adapted microorganisms results in increased plant growth activity and productivity.^{1,2} Such plant–microbe associations have been extensively studied with *Azospirillum* bacteria.³ The surface-located glycopolymers produced by the *Azospirillum* species are key to their rhizosphere adaptation, with lipopolysaccharides (LPSS) playing an important role. The success of the initial stages of bacteria–root association^{4,5} is governed by bacterial surface polysaccharides that are involved in the adhesion and adsorption of microorganisms to the roots of plants. Furthermore, the O-specific polysaccharide (OPS) portion of the LPS interacts with the environment and possesses antigenic determinants as part of its structure. Owing to the significant influence of *Azospirillum* species on plant growth activities and productivity, their OPS structures have been the subject of detailed studies. In this context, Fedonenko *et al.*⁶ reported the OPS structure of *Azospirillum brasilense* (*A. brasilense*) Jm6B2, which has a unique 3-O-methyl-D-rhamnose (D-acofriose) that is not found in other *Azospirillum* species. In continuation of our effort towards the chemical synthesis of biologically relevant bacterial oligosaccharides,^{7–9} we herein report the total synthesis of the trisaccharide repeating unit of the OPS from *A. brasilense* Jm6B2 in the form of its 2-aminoethyl glycoside (Fig. 1). Literature studies on D-acofriose reveal

that it is also abundant in some *Pseudomonas aeruginosa* species.^{10,11} This information prompted us to develop a convenient route for the gram-scale synthesis of D-acofriose from commercially available D-mannose.

Results and discussion

Retrosynthetic analysis for the synthesis of the target trisaccharide **1** revealed that sequential glycosylation of the suitably functionalized fucosyl acceptor **18** with the fully protected D-xylose donor **15** and D-acofriose donor **7** would successfully afford the protected trisaccharide. Since no other amino functionalities are present in the structure, an azidoethyl glycoside at the reducing end was considered ideal; this can be subsequently converted to the corresponding 2-aminoethyl glycoside to facilitate further conjugation. Literature reports indicate that insertion of a sugar at the 3-O-position of a fucose moiety significantly reduces the nucleophilicity of the 4-O-position, thereby hindering the introduction of another sugar at that position.¹¹ To address this, we planned to protect the 3-O-

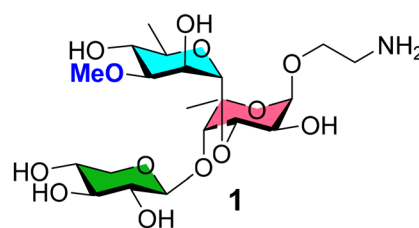


Fig. 1 Structure of the target trisaccharide repeating unit of the OPS from *A. brasilense* Jm6B2 in the form of its 2-aminoethyl glycoside.

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†Electronic supplementary information (ESI) available: Copies of the NMR spectra of all new compounds. See DOI: <https://doi.org/10.1039/d5ob00730e>



position of the fucosyl moiety with a temporary protecting group and introduce a protected *D*-xylose moiety at the 4-*O*-position. Furthermore, the removal of the 3-*O*-protection and introduction of the *D*-acofriose unit would lead to the protected trisaccharide. Finally, the removal of the protecting groups and reduction of the terminal azide to the corresponding amine would furnish the target molecule (Fig. 2).

For the synthesis of *D*-acofriose, commercially available *D*-mannose was converted to methyl *D*-mannoside (2) using H_2SO_4 -silica in dry MeOH at 65 °C.¹² Our previously developed Fischer glycosylation strategy worked perfectly to give compound 2 in 95% yield. Further reaction with iodine in the presence of PPh_3 using dry DMF¹³ as solvent gave the 6-iodo derivative, which was filtered through a silica gel column to remove triphenylphosphine oxide, and the iodo-derivative was hydrogenolyzed using H_2 in the presence of 10% Pd-C¹⁴ to give methyl *D*-rhamnoside (3)¹⁵ in 87% overall yield. Methylation at the 3-*O*-position was successfully achieved *via* stannylene chemistry. The formation of the tin ketal using Bu_2SnO in refluxing toluene followed by reaction with MeI in the presence of Bu_4NI ¹⁶ gave methyl 3-*O*-methyl *D*-acofrioside (4) in 73% yield. It is worth noting that the methylation reac-

tion proceeded rather slowly as the low boiling point of MeI limits its availability as an electrophile and excess MeI is required to drive the reaction to completion with 73% yield. Acetolysis of compound 4 afforded the per-*O*-acetylated acofriose derivative 5 in 86% yield. Finally, Zemplen de-*O*-acetylation gave *D*-acofriose (6) in 96% yield (Scheme 1). Following this route, *D*-acofriose was obtained in 50% overall yield *via* six steps from commercially available *D*-mannose. All reactions were performed at the gram scale without any alteration in yields. It is worth noting that the current method for the preparation of *D*-acofriose is significantly superior to the methods reported by Sauvageau *et al.*^{17,18} and Brimacombe *et al.*¹⁹ (for the *L*-isomer). Moreover, it is observed that the process is equally efficient at the 100 mmol scale and therefore may be used for large-scale preparation of *D*-acofriose. To fulfil the requirement of our *D*-acofriose donor for total synthesis, the per-*O*-acetylated derivative 5 was reacted with *p*-thiocresol in the presence of $\text{BF}_3 \cdot \text{Et}_2\text{O}$ at -5 °C to give the corresponding thioglycoside donor 7 in 89% yield (Scheme 1).

The initial challenge with the synthesis of the fucosyl acceptor was to install the reducing end α -glycoside. Therefore, the known thioglycoside donor 8²⁰ was activated by NIS and TMSOTf in the presence of 2-bromoethanol. Different solvents at varying temperatures were tested to achieve α -selectivity, but with limited success. Glycosylations in pure CH_2Cl_2 showed no selectivity at 0 °C or -20 °C and only marginal selectivity (3 : 2) at -40 °C (entries 1, 2 and 3, Table 1). Switching to a CH_2Cl_2 - Et_2O mixture²¹ in varying ratios could achieve only up to a ratio of 2 : 1 of the desired α -glycoside (entries 4–6). Pre-activation of the donor with DMF²² in CH_2Cl_2 followed by glycosylation with 2-bromoethanol was also tested, but glycoside 9 was obtained only in a 5 : 1 (α/β) ratio (entry 7, Table 1). In addition, we were unable to separate the mixture and use the desired isomer further.

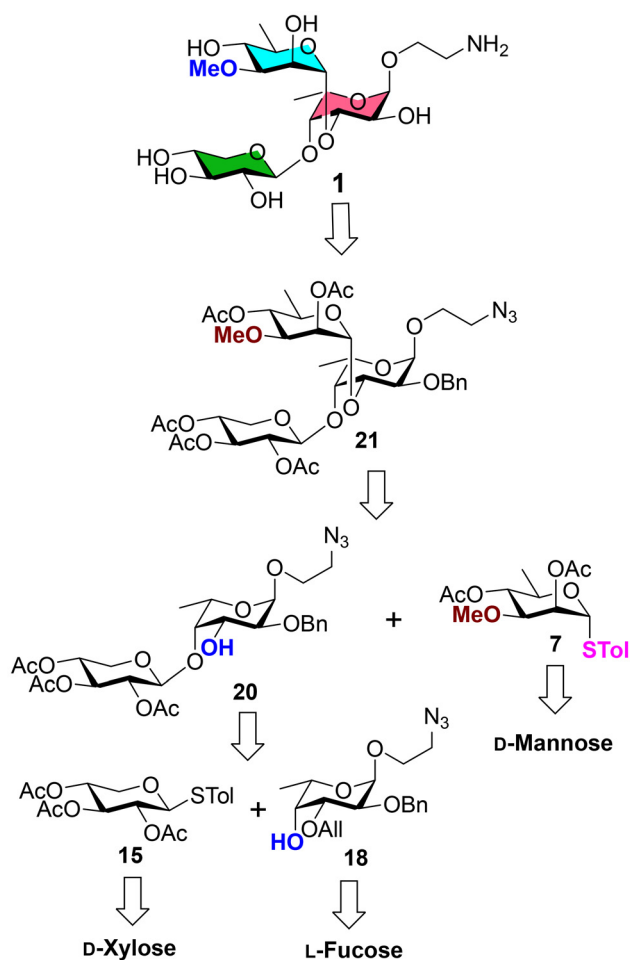
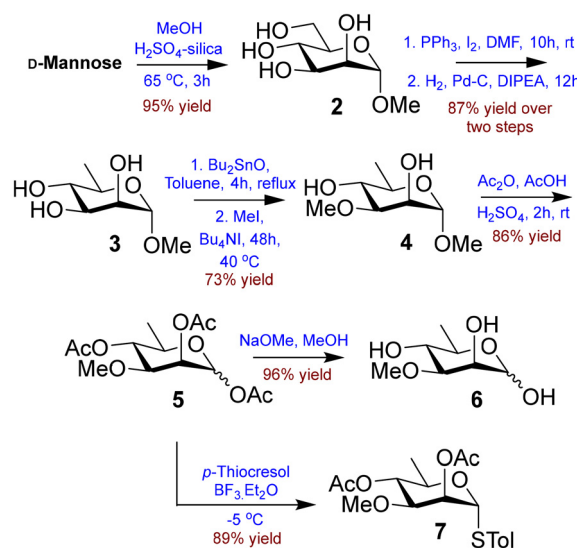
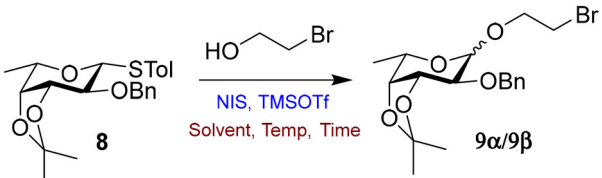


Fig. 2 Retrosynthetic analysis for the synthesis of the target trisaccharide 1.



Scheme 1 Synthesis of *D*-acofriose (6) and the thioglycoside donor 7 from commercially available *D*-mannose.



Table 1 Optimization of the α -glycosylation for the synthesis of the reducing end fucosyl moiety **9**


Entry	Solvent	Temp.	Time	9 α :9 β ^a	Yield
1	Dry CH ₂ Cl ₂	0 °C	1 h	1 : 1	81%
2		-20 °C	3 h	1 : 1	72%
3		-40 °C	3 h	3 : 2	74%
4	CH ₂ Cl ₂ -Et ₂ O (3 : 2)	-40 °C	3 h	3 : 2	76%
5	CH ₂ Cl ₂ -Et ₂ O (1 : 1)	-40 °C	3 h	3 : 2	75%
6	CH ₂ Cl ₂ -Et ₂ O (1 : 3)	-40 °C	3 h	2 : 1	76%
7	Dry CH ₂ Cl ₂ pre-activation with DMF	-20 °C	3 h	5 : 1	78%

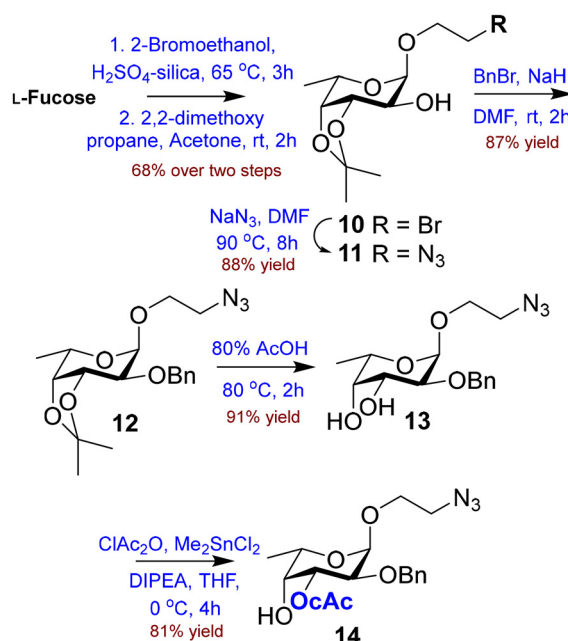
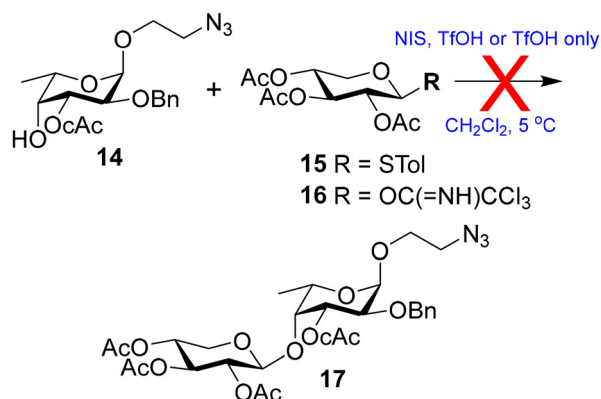
^a As obtained from the ¹H NMR of the mixture.

Finally, we resorted to H₂SO₄-silica promoted Fischer glycosylation¹² of free L-fucose with 2-bromoethanol and successfully achieved the desired glycoside. After removal of excess 2-bromoethanol using diethyl ether, the residue was treated with 2,2-dimethoxypropane in acetone to afford the isopropylidene derivative **10** in 68% yield over two steps.

No further acid catalyst was required as H₂SO₄-silica was present in the mixture and only α -glycoside was isolated in pure form. Furthermore, the terminal bromide was replaced with azide using NaN₃ in DMF²³ at 90 °C to give the azido derivative **11** in 88% yield. The transformation was confirmed by the IR peak at 2104 cm⁻¹. The free 2-O-position was benzylation using BnBr and NaH²⁴ to afford the fully protected derivative **12** in 87% yield. Next, the hydrolysis of the isopropylidene group using 80% aq. AcOH at 80 °C²⁵ gave diol **13** in 91% yield. Selective chloroacetylation of diol **13** using chloroacetic anhydride in the presence of Me₂SnCl₂^{26,27} gave the 3-O-chloroacetate derivative **14** in 81% yield (Scheme 2).

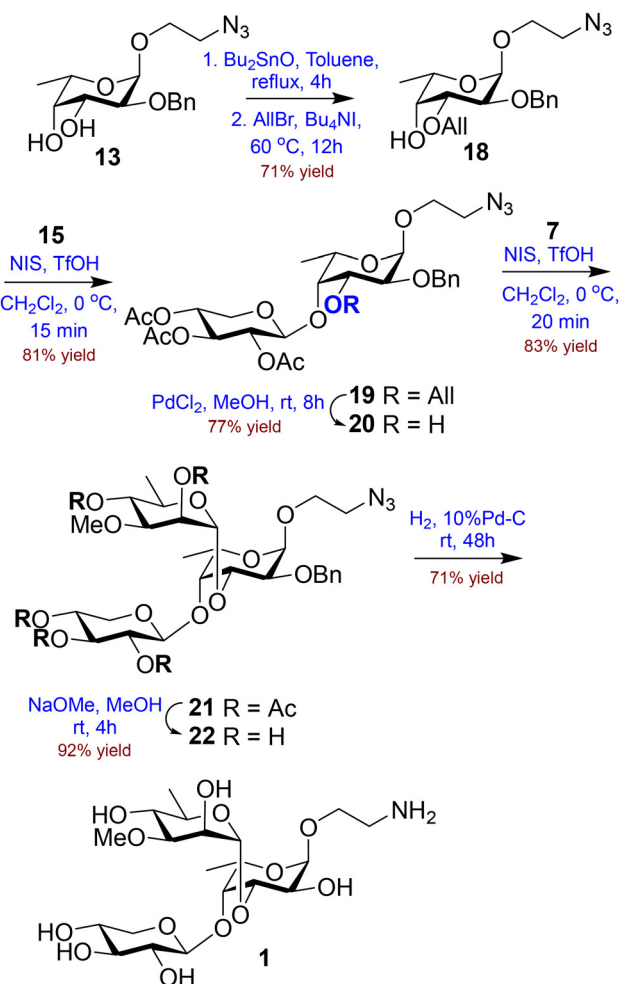
Next, the glycosylation of the fucosyl acceptor **14** with the known xylose donor **15**²⁸ was tested through the activation of thioglycoside using NIS in the presence of TfOH.²⁹ However, the desired disaccharide **17** was not formed; instead, the donor was converted to the corresponding hemiacetal. Changing the donor to the known xylose trichloroacetimidate (**16**)³⁰ led to the same hemiacetal of the donor instead of the desired disaccharide (Scheme 3). It was assumed that the electron-withdrawing chloroacetate group at the neighbouring 3-O-position significantly reduced the nucleophilicity of the 4-O-position of acceptor **14**.

Therefore, the diol **13** was converted to the 3-O-allyl derivative **18** in 71% yield *via* stannylene chemistry, using Bu₂SnO in refluxing toluene followed by reaction with AllBr in the presence of Bu₄NI.³¹ Finally, glycosylation of the fucosyl acceptor **18** and the xylosyl thioglycoside **15** using NIS in the presence of TfOH²⁸ at 0 °C gave disaccharide **19** in 81% yield with com-

**Scheme 2** Synthesis of the fucose acceptors **14**.**Scheme 3** Failed synthesis of disaccharide **17** with fucosyl acceptor **14**.

plete β -selectivity, as confirmed by the peaks at δ 4.74 (d, 1H, $J_{1,2}$ 2.0 Hz, H-1) and 4.68 (d, 1H, $J_{1',2'}$ 6.8 Hz, H-1') in the ¹H NMR spectra and at δ 98.2 (C-1) and 100.5 (C-1') in the ¹³C NMR spectra. The HRMS peak at 644.2433 [M + Na]⁺ further confirmed the successful formation of disaccharide **19**. In contrast to the chloroacetyl group at the 3-O-position, the allyl ether did not hamper the nucleophilicity of the 4-O-position. Furthermore, the allyl protection was removed using PdCl₂ in MeOH³² to afford the disaccharide acceptor **20** in 77% yield. Final glycosylation of the disaccharide acceptor **20** with the acofriose donor **7** using NIS in the presence of TfOH at 0 °C was uneventful and furnished the protected trisaccharide **21** in 83% yield. The successful formation of the trisaccharide was evident from the peaks at δ 97.5 (C-1), 101.4 (C-1') and 98.9 (C-1'') in the ¹³C NMR spectra. The HRMS peak at 848.3061 [M + Na]⁺ further affirmed the formation of trisaccharide **21**.





Scheme 4 Synthesis of the target trisaccharide 1.

Furthermore, Zemplen de-O-acetylation³³ using NaOMe in MeOH gave the de-O-acetylated trisaccharide 22 in 92% yield. Finally, catalytic hydrogenation using 10% Pd-C³⁴ in the presence of H₂ gave the target trisaccharide 1 in 71% yield (Scheme 4).

Conclusions

In conclusion, we have successfully accomplished the synthesis of the target trisaccharide repeating unit of the O-antigen from *A. brasilense* JM6B2 in the form of its 2-aminoethyl glycoside. In the process, we have developed a concise route for the preparation of D-acofriose from commercially available D-mannose *via* six steps with ~50% yield. The route has been tested and found to be effective up to the 100 mmol scale and therefore has the potential to be used for large scale preparation. The 1,2-*cis* 2-bromoethyl fucoside was obtained exclusively using H₂SO₄-silica promoted Fischer glycosylation. The target trisaccharide retains the 2-aminoethyl group, allowing for future glycoconjugate formation without affecting the

anomeric stereochemistry at the reducing end. The availability of this synthetic variant in its purest possible form will facilitate detailed investigations into the biological roles of this oligosaccharide repeat.

Experimental section

General methods

All solvents and reagents were dried before use according to standard methods.³⁵ The commercially purchased reagents were used without any further purification unless mentioned otherwise. Dichloromethane was dried and distilled over P₂O₅ to make it anhydrous and moisture-free. All reactions were monitored by thin layer chromatography (TLC) on silica-gel 60-F254 with detection by fluorescence, followed by charring after immersion in a 10% ethanolic solution of H₂SO₄. Flash chromatography was performed with silica gel (100–200 mesh). Optical rotations were measured on the sodium D-line at ambient temperature. IR data were collected on a Bruker Alpha FTIR spectrometer. ¹H and ¹³C NMR spectra were recorded at 400 MHz and 100 MHz or 500 MHz and 125 MHz, respectively, on a JEOL JNM ECZL 400S or Bruker Avance Neo 400 or Bruker Avance Neo 500 spectrometer. The ¹H and ¹³C peaks were assigned based on ¹H-¹H COSY and ¹H-¹³C HSQC spectra. In the target trisaccharide 1, proton signals were denoted as H for the reducing-end L-fucose unit, H' for D-xylose, and H'' for D-acofriose. Similarly, the carbon signals are denoted as C for the reducing-end L-fucose unit, C' for the D-xylose, and C'' for the D-acofriose unit. HRMS analysis was performed using a XeVO G2-XS Q-TOF (Waters Corporation) instrument in the +ve electrospray ionization mode.

Synthesis of methyl 6-deoxy-3-O-methyl-α-D-mannopyranoside (4). A mixture of compound 3 (2.4 g, 13.5 mmol) and Bu₂SnO (3.40 g, 13.7 mmol) in toluene (20 mL) was refluxed at 110 °C for 4 hours until the solution became clear. The solution was then cooled to room temperature and TBAI (5.0 g, 13.7 mmol) was added followed by MeI (4.2 mL, 67.4 mmol) and the solution was stirred at 40 °C for 24 hours. After 24 hours, the same amount (4.2 mL) of MeI was added again and the solution was stirred under the same conditions for another 24 hours. When TLC (CH₂Cl₂-MeOH; 7 : 1) showed complete conversion of the starting material to a faster-moving spot, the solvent was evaporated under reduced pressure. The crude product thus obtained was charged on a column of silica gel and eluted with CH₂Cl₂-MeOH (10 : 1) to afford the pure compound 4 (1.9 g, 73%) as a yellowish syrup.

$[\alpha]_D^{25}$: + 118 (c 0.8, CHCl₃).

IR (cm⁻¹, CHCl₃) ν: 3362, 2847, 1248, 1086, 1038, 791.

¹H NMR (400 MHz, CDCl₃) δ: 4.60 (d, 1H, *J*_{1,2} 1.6 Hz, H-1), 3.95 (dd, 1H, *J*_{1,2} 1.6 Hz, *J*_{2,3} 3.2 Hz, H-2), 3.55–3.51 (m, 1H, H-5), 3.41 (t, 1H, *J*_{3,4}, *J*_{4,5} 9.4 Hz, H-4), 3.37 (s, 3H, OCH₃), 3.27 (dd, 1H, *J*_{2,3} 3.2 Hz, *J*_{3,4} 9.4 Hz, H-3), 3.26 (s, 3H, OCH₃), 1.22 (d, 3H, *J*_{5,6} 6.0 Hz, C-CH₃).

¹³C NMR (100 MHz, CDCl₃) δ: 100.6 (C-1), 81.3 (C-3), 71.2 (C-4), 67.8 (C-5), 66.8 (C-2), 56.9 (OCH₃), 54.7 (OCH₃), 17.5 (C-CH₃).



HRMS calcd for $C_8H_{16}O_5Na$ $[M + Na]^+$: 215.0895; found: 215.0891.

Synthesis of acetyl 2,4-di-O-acetyl-6-deoxy-3-O-methyl- α/β -D-mannopyranoside (5). To a solution of compound 4 (1.9 g, 9.9 mmol) dissolved in CH_2Cl_2 (7.8 mL), Ac_2O (3.6 mL) was added followed by $AcOH$ (1.3 mL) and conc. H_2SO_4 (120 μ L). The solution was stirred at room temperature for 2 hours until TLC (*n*-hexane–EtOAc; 5 : 2) showed complete conversion of the starting material to a faster-moving spot. The solution was poured carefully into a solution of Na_2CO_3 (2.5 g) in 30 mL ice-cold water and stirred well with a glass rod. CH_2Cl_2 (20 mL) was added and the mixture was extracted twice. The organic layer was further washed with $NaHCO_3$ (30 mL) and brine solution (30 mL), separated, dried over anhydrous Na_2SO_4 , filtered and the solvent was evaporated *in vacuo*. The crude residue thus obtained was purified by column chromatography using *n*-hexane–EtOAc (3 : 1) to give an anomeric mixture (α/β ; 5 : 2) of compound 5 (2.6 g, 86%) as a colourless gel.

α -Product

$[\alpha]_D^{25}$: +29 (*c* 0.8, $CHCl_3$).

IR (cm^{-1} , $CHCl_3$) ν : 2853, 1745, 1252, 1083, 1041, 786.

1H NMR (400 MHz, $CDCl_3$) δ : 6.02 (d, 1H, $J_{1,2}$ 2.0 Hz, H-1), 5.31 (dd, 1H, $J_{1,2}$ 2.0 Hz, $J_{2,3}$ 2.8 Hz, H-2), 5.01 (t, 1H, $J_{3,4}$, $J_{4,5}$ 10.0 Hz, H-4), 3.90–3.80 (m, 1H, H-5), 3.60 (dd, 1H, $J_{2,3}$ 2.8 Hz, $J_{3,4}$ 10 Hz, H-3), 3.35 (s, 3H, OCH_3), 2.14, 2.13, 2.09 (3s, $3 \times 3H$, $3 \times COCH_3$), 1.20 (d, 3H, $J_{5,6}$ 6.4 Hz, C-CH₃).

^{13}C NMR (100 MHz, $CDCl_3$) δ : 170.1 ($COCH_3$), 169.9 ($COCH_3$), 168.4 ($COCH_3$), 91.0 (C-1), 76.8 (C-3), 71.9 (C-4), 68.8 (C-5), 66.9 (C-2), 57.8 (OCH_3), 20.9 (2) ($COCH_3$), 20.8 ($COCH_3$), 17.5 (C-CH₃).

HRMS calcd for $C_{13}H_{20}O_8Na$ $[M + Na]^+$: 327.1056; found: 327.1052.

Synthesis of 6-deoxy-3-O-methyl-D-mannopyranose (D-acofriose) (6). To a solution of compound 5 (2 g, 6.3 mmol) in MeOH (20 mL), NaOMe in MeOH (0.5M, 2 mL) was added and the solution was stirred at room temperature for 3 hours. Excess NaOMe was neutralized using DOWEX® 50 W H^+ resin. The mixture was filtered and the filtrate was evaporated *in vacuo* to afford compound 6 (1.2 g, 96%) as an anomeric mixture. Analytical data showed a satisfactory match with the data reported in the literature.¹⁸

Large scale (100 mmol) preparation of D-acofriose (6) from D-mannose. Commercially available D-mannose (18 g, 0.1 mol) was suspended in dry MeOH (200 mL) and stirred at 65 °C for 30 minutes. H_2SO_4 –silica (5 g) was added and the stirring was continued at 65 °C for 4 hours. The mixture was neutralized with Et_3N (5 mL) and filtered. The filtrate was evaporated *in vacuo* and the residue was used for the next reaction without any further purification. The residue was dissolved in dry DMF (70 mL) and PPh_3 (31.5 g, 0.12 mol) was added followed by dropwise addition of I_2 (15 g, 0.12 mol in 50 mL DMF). The brown coloured solution was allowed to stir at room temperature for 12 hours and the reaction was monitored by TLC (CH_2Cl_2 –MeOH; 9 : 1). Solvents were evaporated and the residue was triturated with EtOAc on an ice-bath. It was filtered

through a layered pad of Celite® and silica gel (100–200 mesh). The filtrate was evaporated and the residue was dissolved in MeOH (75 mL). 10% Pd–C (5 g) was added followed by DIPEA (20 mL, 0.11 mol) and the mixture was shaken in a Paar hydrogenation assembly at 3 atm H_2 for 12 hours. The mixture was filtered through a pad of Celite® and the filtrate was evaporated *in vacuo*. The residue was suspended in dry toluene (100 mL), Bu_2SnO (25 g, 0.1 mmol) was added and the mixture was stirred under reflux for 5 hours. The solution was cooled to room temperature and TBAI (37 g, 0.1 mmol) was added followed by MeI (37 mL, 0.6 mol). The mixture was stirred at 40 °C for 24 hours. Another portion of MeI (18.5 mL, 0.3 mol) was added and the stirring continued for 24 hours. The reaction progress was monitored by TLC (CH_2Cl_2 –MeOH; 7 : 1). The solvents were evaporated and the residue was dissolved in CH_2Cl_2 (80 mL), Ac_2O (36 mL) was added followed by $AcOH$ (13 mL) and conc. H_2SO_4 (1.2 mL) and the solution was stirred at room temperature for 3 hours. Then the solution was carefully poured into a solution of Na_2CO_3 (25 g) in 250 mL ice water and stirred well with a glass rod. CH_2Cl_2 (70 mL) was added and the organic layer was extracted. The process was repeated one more time with CH_2Cl_2 (30 mL). The combined organic layer was further washed with aq. $NaHCO_3$ (100 mL) and brine solution (100 mL), separated, dried over anhydrous Na_2SO_4 (25 g), and filtered and the solvent was evaporated *in vacuo*. The syrupy residue was purified by column chromatography to remove the tin salts. The light-yellow syrup obtained was redissolved in MeOH (100 mL). Freshly prepared NaOMe in MeOH (0.5 M, 10 mL) was added and the solution was stirred at room temperature for 3 hours. Excess NaOMe was neutralized with DOWEX® 50 W H^+ and filtered and the filtrate was evaporated *in vacuo* to give D-acofriose (8.4 g, 47%) as an off-white sticky mass. It was dissolved in H_2O (40 mL) and lyophilized to obtain a white amorphous powder.

Synthesis of tolyl 2,4-di-O-acetyl-6-deoxy-3-O-methyl-1-thio- α -D-mannopyranoside (7). To a solution of compound 5 (2.6 g, 8.5 mmol) in dry CH_2Cl_2 (20 mL), *p*-thiocresol (1.4 g, 11.1 mmol) was added and the mixture was stirred at –5 °C for 15 min. To the cooled solution, $BF_3 \cdot Et_2O$ (2.1 mL, 17.1 mmol) was added and the solution was stirred at the same temperature for 4 hours until TLC (*n*-hexane–EtOAc; 2 : 1) indicated complete conversion of the starting material to a faster-moving spot. The solution was then diluted with CH_2Cl_2 (10 mL) and washed successively with water (30 mL), saturated $NaHCO_3$ solution (2×30 mL) and brine (30 mL). The organic layer was separated, dried over anhydrous Na_2SO_4 and filtered. The solvent was evaporated *in vacuo* and the crude product thus obtained was purified by column chromatography using *n*-hexane–EtOAc (3 : 1) to afford the pure compound 7 (2.8 g, 89%) as a white amorphous powder.

$[\alpha]_D^{25}$: +62 (*c* 0.9, $CHCl_3$).

IR (cm^{-1} , $CHCl_3$) ν : 2973, 2860, 1740, 1374, 1211, 1040, 804.

1H NMR (400 MHz, $CDCl_3$) δ : 7.34 (d, 2H, ArH), 7.11 (d, 2H, ArH), 5.56 (dd, 1H, $J_{1,2}$ 1.6 Hz, $J_{2,3}$ 3.2 Hz, H-2), 5.35 (d, 1H, $J_{1,2}$ 1.6 Hz, H-1), 5.03 (t, 1H, $J_{3,4}$, $J_{4,5}$ 9.6 Hz, H-4), 4.33–4.23 (m, 1H, H-5), 3.57 (dd, 1H, $J_{2,3}$ 3.2 Hz, $J_{3,4}$ 9.6 Hz, H-3), 3.36 (s, 3H,



OCH₃), 2.32 (s, 3H, SC₆H₄CH₃), 2.12, 2.11 (2s, 2 × 3H, 2 × COCH₃), 1.21 (d, 3H, *J*_{5,6} 6.4 Hz, C-CH₃).

¹³C NMR (100 MHz, CDCl₃) δ: 170.3 (COCH₃), 170.1 (COCH₃), 138.1, 132.3, 130.0, 129.8, 86.4 (C-1), 77.5 (C-3), 72.6 (C-4), 69.6 (C-2), 67.7 (C-5), 57.7 (OCH₃), 21.1 (COCH₃), 21.0 (COCH₃), 20.9 (SC₆H₄CH₃), 17.3 (C-CH₃).

HRMS calcd for C₁₈H₂₄O₆Na [M + Na]⁺: 391.1191; found: 391.1185.

Synthesis of 2-bromoethyl 3,4-O-isopropylidene-α-L-fucopyranoside (10). A suspension of L-fucose (3.0 g, 18.3 mmol) in 2-bromoethanol was stirred at 65 °C for 15 minutes. H₂SO₄-silica (100 mg) was then added and the mixture was stirred at the same temperature for 3 hours. The resulting solution was cooled to room temperature and Et₂O (50 mL) was added and shaken well, causing the product to precipitate while excess 2-bromoethanol was dissolved in the ether layer. The ether layer was decanted and the process was repeated with Et₂O (20 mL). The residue was dried under vacuum for 30 minutes before being suspended in dry acetone (20 mL). 2,2-Dimethoxypropane (3.4 mL, 27.4 mmol) was added and the mixture was stirred at room temperature for 2 hours until TLC (*n*-hexane-EtOAc; 2 : 1) showed complete conversion to a faster running spot. The reaction mixture was quenched with Et₃N (1.5 mL), the solvent was evaporated and the residue was purified by column chromatography using *n*-hexane-EtOAc (3 : 1) to afford the pure compound **10** (3.9 g, 68%) as a colourless syrup.

[α]_D²⁵: -52 (c 0.8, CHCl₃).

¹H NMR (400 MHz, CDCl₃) δ: 4.78 (d, 1H, *J*_{1,2} 4.0 Hz, H-1), 4.17–4.12 (m, 2H, H-5, H-3), 3.99 (dd, 1H, *J*_{3,4} 6.0 Hz, *J*_{4,5} 2.4 Hz, H-4), 3.97–3.92 (m, 1H, OCH_{2a}), 3.81–3.75 (m, 1H, OCH_{2b}), 3.74–3.70 (m, 1H, H-2), 3.49–3.43 (m, 2H, CH₂Br), 2.76 (d, 1H, *J* 6.4 Hz, OH), 1.43 (s, 3H, isopropylidene-CH₃), 1.27 (s, 3H, isopropylidene-CH₃), 1.23 (d, 3H, *J*_{5,6} 6.8 Hz, C-CH₃).

¹³C NMR (100 MHz, CDCl₃) δ: 109.1 (isopropylidene-C), 97.8 (C-1), 75.9 (C-3), 75.5 (C-4), 69.2 (C-2), 67.9 (OCH₂), 64.2 (C-5), 30.6 (CH₂Br), 27.8 (isopropylidene-CH₃), 25.9 (isopropylidene-CH₃), 16.2 (C-CH₃).

HRMS calcd for C₁₁H₁₉BrO₅Na [M + Na]⁺: 333.0314; found: 333.0317.

Synthesis of 2-azidoethyl 3,4-O-isopropylidene-α-L-fucopyranoside (11). Compound **10** (3.9 g, 12.4 mmol) was dissolved in DMF (12 mL) and NaN₃ (4.0 g, 62 mmol) was added to it. The reaction mixture was stirred at 90 °C for 8 hours until TLC (*n*-hexane-EtOAc; 3 : 2) showed complete conversion of the starting material to a slower running spot. The solvent was evaporated and the residue was diluted with EtOAc (20 mL) and washed with brine solution (3 × 30 mL). The organic layer was separated, dried over anhydrous Na₂SO₄, and filtered; the solvent was evaporated under reduced pressure and the crude product thus obtained was purified by column chromatography using *n*-hexane-EtOAc (2 : 1) to afford the pure compound **11** (3.0 g, 88%) as a colourless syrup.

[α]_D²⁵: -39 (c 0.9, CHCl₃).

IR (cm⁻¹, CHCl₃) ν: 2991, 2933, 2104, 1381, 1211, 1059, 861.

¹H NMR (400 MHz, CDCl₃) δ: 4.86 (d, 1H, *J*_{1,2} 4.0 Hz, H-1), 4.23 (t, 1H, *J*_{2,3}, *J*_{3,4} 6.4 Hz, H-3), 4.21–4.16 (m, 1H, H-5), 4.08 (dd, 1H, *J*_{3,4} 6.4 Hz, *J*_{4,5} 2.0 Hz, H-4), 4.00–3.95 (m, 1H, OCH_{2a}), 3.82 (dd, 1H, *J*_{1,2} 4.0 Hz, *J*_{2,3} 6.4 Hz, H-2), 3.72–3.67 (m, 1H, OCH_{2b}), 3.52–3.46 (m, 1H, CH_{2a}N₃), 3.43–3.37 (m, 1H, CH_{2b}N₃), 2.43 (bs, 1H, OH), 1.51 (s, 3H, isopropylidene-CH₃), 1.36 (s, 3H, isopropylidene-CH₃), 1.33 (d, 3H, *J*_{5,6} 6.8 Hz, C-CH₃).

¹³C NMR (100 MHz, CDCl₃) δ: 109.2 (isopropylidene-C), 97.8 (C-1), 75.9 (C-3), 75.5 (C-4), 69.2 (C-2), 67.1 (OCH₂), 64.3 (C-5), 50.7 (CH₂N₃), 27.7 (isopropylidene-CH₃), 25.9 (isopropylidene-CH₃), 16.3 (C-CH₃).

HRMS calcd for C₁₁H₁₉N₃O₅Na [M + Na]⁺: 296.1222; found: 296.1225.

Synthesis of 2-azidoethyl 2-O-benzyl-3,4-O-isopropylidene-α-L-fucopyranoside (12). Compound **11** (3.0 g, 11.0 mmol) was dissolved in DMF (15 mL) and the solution was cooled to 0 °C. After 15 minutes, NaH (925 mg, 38.5 mmol, 50% dispersion in mineral oil) was added followed by the addition of BnBr (2.0 mL, 16.8 mmol), and the reaction mixture was stirred at room temperature for 2 hours until TLC (*n*-hexane-EtOAc; 4 : 1) showed complete conversion of the starting material to a faster-moving spot. Excess NaH was quenched with MeOH (5 mL) and the solvent was evaporated under reduced pressure. The residue was diluted with EtOAc and washed with brine solution (3 × 30 mL). The organic layer was collected, dried over anhydrous Na₂SO₄, and filtered and the solvent was evaporated *in vacuo*. The crude product thus obtained was purified by flash chromatography using *n*-hexane-EtOAc (4 : 1) to furnish the pure compound **12** (3.5 g, 87%) as a colourless syrup.

[α]_D²⁵: -57 (c 0.7, CHCl₃).

IR (cm⁻¹, CHCl₃) ν: 3068, 2927, 2108, 1513, 1151, 1073, 742.

¹H NMR (400 MHz, CDCl₃) δ: 7.40–7.27 (m, 5H, ArH), 4.84 (d, 1H, *J* 12.4 Hz, CH₂Ph), 4.77 (d, 1H, *J*_{1,2} 3.2 Hz, H-1), 4.73 (d, 1H, *J* 12.4 Hz, CH₂Ph), 4.37 (dd, 1H, *J*_{2,3} 7.6 Hz, *J*_{3,4} 5.6 Hz, H-3), 4.23–4.17 (m, 1H, H-5), 4.09 (dd, 1H, *J*_{3,4} 5.6 Hz, *J*_{4,5} 2.8 Hz, H-4), 3.89–3.83 (m, 1H, OCH_{2a}), 3.61–3.54 (m, 3H, OCH_{2b}, CH_{2a}N₃, H-2), 3.37–3.31 (m, 1H, CH_{2b}N₃), 1.44 (s, 3H, isopropylidene-CH₃), 1.37 (s, 3H, isopropylidene-CH₃), 1.35 (d, 3H, *J*_{5,6} 6.8 Hz, C-CH₃).

¹³C NMR (100 MHz, CDCl₃) δ: 138.4, 128.4, 127.9, 127.7, 108.8 (isopropylidene-C), 97.5 (C-1), 76.2 (C-2), 76.1 (C-4), 75.7 (C-3), 72.5 (CH₂Ph), 67.0 (OCH₂), 63.6 (C-5), 50.6 (CH₂N₃), 28.2 (isopropylidene-CH₃), 26.3 (isopropylidene-CH₃), 16.3 (C-CH₃).

HRMS calcd for C₁₈H₂₅N₃O₅Na [M + Na]⁺: 386.1692; found: 386.1688.

Synthesis of 2-azidoethyl 2-O-benzyl-α-L-fucopyranoside (13). A suspension of compound **12** (3.5 g, 9.6 mmol) in 80% AcOH (30 mL) was stirred at 80 °C for 2 hours until TLC (*n*-hexane-EtOAc; 1 : 2) showed complete conversion of the starting material to a slower-moving spot. The solvents were evaporated *in vacuo* and co-evaporated with toluene to ensure complete removal of AcOH. The crude product thus obtained was purified by column chromatography using *n*-hexane-EtOAc (1 : 4) to afford the pure compound **13** (2.8 g, 91%) as a colourless syrup.

[α]_D²⁵: -18 (c 0.7, CHCl₃).

IR (cm⁻¹, CHCl₃) ν: 3430, 2918, 2104, 1090, 1040, 742.



^1H NMR (400 MHz, CDCl_3) δ : 7.39–7.31 (m, 5H, ArH), 4.81 (d, 1H, $J_{1,2}$ 3.6 Hz, H-1), 4.67 (s, 2H, CH_2Ph), 4.05–3.98 (m, 2H, H-5, H-3), 3.85 (m, 1H, H-4), 3.83–3.79 (m, 1H, OCH_{2a}), 3.73 (dd, 1H, $J_{1,2}$ 3.6 Hz, $J_{2,3}$ 9.6 Hz, H-2), 3.53–3.47 (m, 2H, OCH_{2b} , CH_{2a}N_3), 3.39–3.34 (m, 1H, CH_{2b}N_3), 2.55 (d, 1H, J 2.8 Hz, OH), 2.37 (bs, 1H, OH), 1.30 (d, 3H, $J_{5,6}$ 6.8 Hz, C- CH_3).

^{13}C NMR (100 MHz, CDCl_3) δ : 138.2, 128.7, 128.2, 97.1 (C-1), 76.5 (C-2), 72.9 (CH_2Ph), 71.6 (C-4), 69.3 (C-5), 66.9 (OCH_2), 65.9 (C-3), 50.8 (CH_2N_3), 16.2 (C- CH_3).

HRMS calcd for $\text{C}_{15}\text{H}_{21}\text{N}_3\text{O}_5\text{Na}$ [$\text{M} + \text{Na}$] $^+$: 346.1379; found: 346.1383.

Synthesis of 2-azidoethyl 2-O-benzyl-3-O-chloroacetyl- α -L-fucopyranoside (14). To a solution of compound **13** (500.0 mg, 1.5 mmol) in dry THF (7 mL), Me_2SnCl_2 (17.0 mg, 0.075 mmol) and DIPEA (0.5 mL, 3.0 mmol) were added and the solution was cooled to 0 °C and stirred for 15 minutes. Chloroacetic anhydride (325.0 mg, 1.9 mmol) was added and the solution was stirred at the same temperature for 4 hours until TLC (*n*-hexane–EtOAc; 1 : 1) showed complete conversion of the starting material to a faster running spot. The reaction mixture was then quenched with 3% aqueous HCl (5 mL) and extracted with ethyl acetate (2 \times 15 mL). The combined organic layers were dried over anhydrous Na_2SO_4 and filtered, and the solvents were evaporated *in vacuo* and purified by column chromatography using *n*-hexane–EtOAc (1 : 1) to furnish the pure compound **14** (486.0 mg, 81%) as a white amorphous mass.

$[\alpha]_{\text{D}}^{25}$: –72 (*c* 0.7, CHCl_3).

IR (cm^{-1} , CHCl_3) ν : 3476, 2918, 2102, 1752, 1158, 1040, 752.

^1H NMR (400 MHz, CDCl_3) δ : 7.35–7.25 (m, 5H, ArH), 5.25 (dd, 1H, $J_{2,3}$ 10.4 Hz, $J_{3,4}$ 2.8 Hz, H-3), 4.78 (d, 1H, $J_{1,2}$ 3.6 Hz, H-1), 4.65 (d, 1H, J 12.4 Hz, CH_2Ph), 4.60 (d, 1H, J 12.4 Hz, CH_2Ph), 4.10–4.03 (m, 2H, H-5, CH_{2a}Cl), 3.99 (d, 1H, J 14.8 Hz, CH_{2b}Cl), 3.94–3.89 (m, 2H, H-4, H-2), 3.81–3.75 (m, 1H, OCH_{2a}), 3.58–3.52 (m, 1H, OCH_{2b}), 3.51–3.44 (m, 1H, CH_{2a}N_3), 3.42–3.35 (m, 1H, CH_{2b}N_3), 2.81 (bs, 1H, OH), 1.22 (d, 3H, $J_{5,6}$ 6.8 Hz, C- CH_3).

^{13}C NMR (100 MHz, CDCl_3) δ : 166.8 (COCH_2Cl), 138.1, 128.5, 128.0, 127.9, 97.5 (C-1), 74.5 (C-3), 73.3 (C-4), 73.1 (CH_2Ph), 70.3 (C-2), 66.9 (OCH_2), 65.7 (C-5), 50.6 (CH_2N_3), 40.9 (CH_2Cl), 16.0 (C- CH_3).

HRMS calcd for $\text{C}_{17}\text{H}_{22}\text{ClN}_3\text{O}_6\text{Na}$ [$\text{M} + \text{Na}$] $^+$: 422.1095; found: 422.1092.

Synthesis of 2-azidoethyl 3-O-allyl-2-O-benzyl- α -L-fucopyranoside (18). A suspension of compound **13** (500.0 mg, 1.5 mmol) and Bu_2SnO (548.0 mg, 2.2 mmol) in dry toluene (15 mL) was stirred at 110 °C for 4 hours until the solution became clear. After completion of the reaction, the solvent was evaporated *in vacuo* and the crude product was kept under vacuum for 1 hour. The residue was dissolved in dry toluene (20 mL) and TBAI (812.0 mg, 2.2 mmol) was added followed by the addition of allyl bromide (0.2 mL, 2.3 mmol) and the reaction mixture was stirred at 60 °C for 12 hours. After completion of the reaction (monitored by TLC in *n*-hexane–EtOAc; 1 : 1), the reaction mixture was diluted with EtOAc and washed with brine solution (2 \times 30 mL). The organic layer was then separated and

dried over anhydrous Na_2SO_4 , and the solvent was evaporated *in vacuo* and the crude product was purified by column chromatography using *n*-hexane–EtOAc (3 : 2) to provide the pure compound **18** (387.0 mg, 71%) as a yellowish syrup.

$[\alpha]_{\text{D}}^{25}$: –81 (*c* 0.7, CHCl_3).

IR (cm^{-1} , CHCl_3) ν : 3323, 2915, 2101, 1691, 1540, 1270, 1058, 743.

^1H NMR (400 MHz, CDCl_3) δ : 7.39–7.26 (m, 5H, ArH), 6.00–5.90 (m, 1H, AllCH), 5.32 (dd, 1H, J_{gem} 1.6 Hz, J_{trans} 17.2 Hz, All CH_{2a}), 5.2 (dd, 1H, J_{gem} 1.6 Hz, J_{cis} 10.4 Hz, All CH_{2b}), 4.8 (d, 1H, J 12.0 Hz, CH_2Ph), 4.75 (d, 1H, $J_{1,2}$ 2.8 Hz, H-1), 4.64 (d, 1H, J 12.0 Hz, CH_2Ph), 4.28–4.18 (m, 2H, OCH_2All), 3.98 (q, 1H, $J_{5,6}$ 6.8 Hz, H-5), 3.86 (d, 1H, $J_{3,4}$ 2.4 Hz, H-4), 3.84–3.77 (m, 3H, OCH_{2a} , H-2, H-3), 3.60–3.51 (m, 2H, OCH_{2b} , CH_{2a}N_3), 3.37–3.30 (m, 1H, CH_{2b}N_3), 2.58 (bs, 1H, OH), 1.29 (d, 3H, $J_{5,6}$ 6.8 Hz, C- CH_3).

^{13}C NMR (100 MHz, CDCl_3) δ : 138.4, 134.6 (AllCH), 128.2, 127.7, 127.5, 117.1 (All CH_2), 97.7 (C-1), 77.1 (C-2), 75.1 (C-3), 73.2 (CH_2Ph), 71.3 (OCH_2All), 70.0 (C-4), 66.6 (OCH_2), 65.5 (C-5), 50.5 (CH_2N_3), 16.0 (C- CH_3).

HRMS calcd for $\text{C}_{18}\text{H}_{25}\text{N}_3\text{O}_5\text{Na}$ [$\text{M} + \text{Na}$] $^+$: 386.1692; found: 386.1688.

Synthesis of 2-azidoethyl 2,3,4-tri-O-acetyl- β -D-xylopyranosyl-(1 \rightarrow 4)-3-O-allyl-2-O-benzyl- α -L-fucopyranoside (19). A mixture of fucosyl acceptor **18** (350.0 mg, 0.96 mmol), xylosyl donor **15** (513.0 mg, 1.34 mmol) and activated MS 4 Å (1.0 g) in dry CH_2Cl_2 (10 mL) was stirred under a N_2 atmosphere for 20 minutes. NIS (389.0 mg, 1.73 mmol) was added and the reaction mixture was stirred again under a N_2 atmosphere at 0 °C for 15 minutes. After that, TfOH (27 μL , 0.30 mmol) was added and the mixture was stirred at 0 °C for 15 minutes until TLC (*n*-hexane–EtOAc; 3 : 2) showed complete consumption of the acceptor. The mixture was filtered through Celite® and the filtrate was successively washed with $\text{Na}_2\text{S}_2\text{O}_3$ solution (2 \times 15 mL), saturated NaHCO_3 solution (20 mL) and brine solution (20 mL). The organic layer was separated, dried over anhydrous Na_2SO_4 , filtered and evaporated *in vacuo*. The yellowish syrup thus obtained was purified by column chromatography using *n*-hexane–EtOAc (2 : 1) to furnish the pure disaccharide **19** (485.0 mg, 81%) as a colourless syrup.

$[\alpha]_{\text{D}}^{25}$: +121 (*c* 0.8, CHCl_3).

IR (cm^{-1} , CHCl_3) ν : 2936, 2103, 1740, 1638, 1369, 1218, 1086, 1037, 733.

^1H NMR (400 MHz, CDCl_3) δ : 7.39–7.25 (m, 5H, ArH), 6.0–5.90 (m, 1H, AllCH), 5.32 (dd, 1H, J_{gem} 1.2 Hz, J_{trans} 17.2 Hz, All CH_{2a}), 5.17 (dd, 1H, J_{gem} 1.2 Hz, J_{cis} 10.4 Hz, All CH_{2b}), 5.09 (t, 1H, $J_{2',3'}$, $J_{3',4'}$ 6.4 Hz, H-3'), 5.01 (dd, 1H, $J_{1',2'}$ 6.8 Hz, $J_{2',3'}$ 6.4 Hz, H-2'), 4.95–4.90 (m, 1H, H-4'), 4.87 (d, 1H, J 12.8 Hz, CH_2Ph), 4.74 (d, 1H, $J_{1,2}$ 2.0 Hz, H-1), 4.68 (d, 1H, $J_{1',2'}$ 6.8 Hz, H-1'), 4.66 (d, 1H, J 12.8 Hz, CH_2Ph), 4.40 (dd, 1H, J_{gem} 12.4 Hz, $J_{4',5'}$ 4.0 Hz, H-5'a), 4.23 (m, 1H, $\text{OCH}_{2a}\text{All}$), 4.12 (m, 1H, $\text{OCH}_{2b}\text{All}$), 3.96 (q, 1H, $J_{5,6}$ 6.8 Hz, H-5), 3.87 (s, 1H, H-4), 3.83–3.77 (m, 3H, H-3, H-2, OCH_{2a}), 3.64–3.53 (m, 2H, OCH_{2b} , CH_{2a}N_3), 3.43 (dd, 1H, J_{gem} 12.4 Hz, $J_{4',5'}$ 6.4 Hz, H-5'b), 3.35–3.30 (m, 1H, CH_{2b}N_3), 2.09 (s, 3H, COCH_3), 2.08 (s, 3H, COCH_3), 1.95 (s, 3H, COCH_3), 1.23 (d, 3H, $J_{5,6}$ 6.8 Hz, C- CH_3).



^{13}C NMR (100 MHz, CDCl_3) δ : 169.9 (COCH_3), 169.8 (COCH_3), 169.3 (COCH_3), 138.8, 134.9 (AllCH), 128.2, 127.6, 127.5, 116.7 (AllCH₂), 100.5 (C-1'), 98.2 (C-1), 78.2 (C-4), 76.9 (C-3), 75.0 (C-2), 73.5 (CH_2Ph), 71.1 (OCH_2All), 69.7 (C-3'), 69.6 (C-2'), 68.4 (C-4'), 66.8 (OCH_2), 66.2 (C-5), 61.0 (C-5'), 50.6 (CH_2N_3), 20.8 (COCH_3), 20.7 (COCH_3), 20.6 (COCH_3), 16.3 (C-CH₃).

HRMS calcd for $\text{C}_{29}\text{H}_{39}\text{N}_3\text{O}_{12}\text{Na}$ $[\text{M} + \text{Na}]^+$: 644.2431; found: 644.2433.

Synthesis of 2-azidoethyl 2,3,4-tri-*O*-acetyl- β -D-xylopyranosyl-(1 \rightarrow 4)-2-*O*-benzyl- α -L-fucopyranoside (20). To a solution of compound **19** (450 mg, 0.73 mmol) in MeOH (10 mL), PdCl_2 (65.0 mg, 0.37 mmol) was added and the solution was stirred at room temperature for 8 hours until TLC (*n*-hexane-EtOAc; 3 : 2) showed complete conversion of the starting material to a slower running spot. The solvent was removed under reduced pressure and the crude product was immediately charged into a column of silica gel and eluted with *n*-hexane-EtOAc (2 : 3) to afford the pure compound **20** (325.0 mg, 77%) as a colourless syrup.

$[\alpha]_{\text{D}}^{25}$: +73 (*c* 0.8, CHCl_3).

IR (cm^{-1} , CHCl_3) ν : 3342, 2105, 1742, 1373, 1216, 1082, 1040, 753.

^1H NMR (400 MHz, CDCl_3) δ : 7.38–7.23 (m, 5H, ArH), 5.18 (t, 1H, $J_{2',3'}$, $J_{3',4'}$ 9.2 Hz, H-3'), 5.04–4.96 (m, 2H, H-2', H-4'), 4.83 (d, 1H, J 12.0 Hz, CH_2Ph), 4.68 (d, 1H, $J_{1,2}$ 3.6 Hz, H-1), 4.60 (d, 1H, J 12.0 Hz, CH_2Ph), 4.49 (d, 1H, $J_{1',2'}$ 7.6 Hz, H-1'), 4.15 (dd, 1H, J_{gem} 11.6 Hz, $J_{4',5'}$ 5.2 Hz, H-5'a), 4.03–3.96 (m, 2H, H-5, H-3), 3.76 (d, 1H, $J_{4,5}$ 2.8 Hz, H-4), 3.73–3.68 (m, 1H, OCH_{2a}), 3.57 (dd, 1H, $J_{1,2}$ 3.6 Hz, $J_{2,3}$ 10.0 Hz, H-2), 3.51–3.44 (m, 2H, OCH_{2b} , CH_{2a}N_3), 3.36–3.25 (m, 2H, CH_{2b}N_3 , H-5'b), 3.21 (d, J 8.8 Hz, OH), 2.02 (s, 6H, $2 \times \text{COCH}_3$), 2.01 (s, 3H, COCH_3), 1.17 (d, 3H, $J_{5,6}$ 6.8 Hz, C-CH₃).

^{13}C NMR (100 MHz, CDCl_3) δ : 170.1 (COCH_3), 169.6 (COCH_3), 169.1 (COCH_3), 138.6, 128.2, 127.8, 127.6, 102.2 (C-1'), 97.8 (C-1), 83.5 (C-4), 76.9 (C-2), 73.3 (CH_2Ph), 71.9 (C-3'), 71.4 (C-2'), 68.5 (C-4', C-3), 66.8 (OCH_2), 65.7 (C-5), 62.5 (C-5'), 50.6 (CH_2N_3), 20.6 (COCH_3), 20.5 ($2 \times \text{COCH}_3$), 16.0 (C-CH₃).

HRMS calcd for $\text{C}_{26}\text{H}_{35}\text{N}_3\text{O}_{12}\text{Na}$ $[\text{M} + \text{Na}]^+$: 604.2118; found: 604.2114.

Synthesis of 2-azidoethyl 2,4-di-*O*-acetyl-6-deoxy-3-*O*-methyl- α -D-mannopyranosyl-(1 \rightarrow 3)-2-*O*-benzyl-4-*O*-(2,3,4-tri-*O*-acetyl- β -D-xylopyranosyl)- α -L-fucopyranoside (21). A mixture of the disaccharide acceptor **20** (300.0 mg, 0.52 mmol), acofriosyl donor **7** (269.0 mg, 0.73 mmol) and activated MS 4 Å (1.0 g) in dry CH_2Cl_2 (10 mL) was stirred under a N_2 atmosphere for 30 minutes. NIS (211.5 mg, 0.94 mmol) was added and the reaction mixture was stirred again under a N_2 atmosphere at 0 °C for 30 minutes. Subsequently, TfOH (14 μL , 0.16 mmol) was added and the mixture was stirred at 0 °C for another 20 minutes until TLC (*n*-hexane-EtOAc; 2 : 3) confirmed complete consumption of the acceptor. The mixture was filtered through Celite® and the filtrate was successively washed with $\text{Na}_2\text{S}_2\text{O}_3$ solution (15 mL \times 2), saturated NaHCO_3 solution (30 mL) and brine solution (30 mL). The organic layer was separated, dried over anhydrous Na_2SO_4 , filtered and evaporated

in vacuo. The crude product thus obtained was purified by column chromatography using *n*-hexane-EtOAc (2 : 3) to afford the pure trisaccharide **21** (355.0 mg, 83%) as a yellowish syrup.

$[\alpha]_{\text{D}}^{25}$: +135 (*c* 0.9, CHCl_3).

IR (cm^{-1} , CHCl_3) ν : 2872, 2101, 1744, 1371, 1216, 1082, 1041, 746.

^1H NMR (400 MHz, CDCl_3) δ : 7.36–7.28 (m, 5H, ArH), 5.48 (s, 1H, H-2''), 5.24–5.17 (m, 2H, H-3', H-1''), 5.11 (t, 1H, $J_{1',2'}$, $J_{2',3'}$ 8.0 Hz, H-2'), 5.0–4.9 (m, 2H, H-4', H-4''), 4.78 (d, 1H, J 12.0 Hz, CH_2Ph), 4.66 (d, 1H, $J_{1,2}$ 2.8 Hz, H-1), 4.62–4.53 (m, 2H, CH_2Ph , H-1'), 4.34 (dd, 1H, J_{gem} 11.2 Hz, $J_{4',5'}$ 4.4 Hz, H-5'a), 4.08 (bd, 1H, $J_{2,3}$ 10.0 Hz, H-3), 4.04–3.92 (m, 2H, H-5, H-5''), 3.82 (d, 1H, $J_{1,2}$ 2.8 Hz, $J_{2,3}$ 10.0 Hz, H-2), 3.8–3.7 (m, 3H, H-4, OCH_{2a} , H-3''), 3.64–3.48 (m, 2H, OCH_{2b} , CH_{2a}N_3), 3.43 (s, 3H, OCH_3), 3.39–3.29 (m, 2H, CH_{2b}N_3 , H-5'b), 2.11 (s, 3H, COCH_3), 2.09 (s, 3H, COCH_3), 2.07 (s, 6H, $2 \times \text{COCH}_3$), 2.05 (s, 3H, COCH_3), 1.24 (d, 3H, $J_{5,6}$ 6.4 Hz, C-CH₃), 1.18 (d, 3H, $J_{5'',6''}$ 6.0 Hz, C-CH₃).

^{13}C NMR (100 MHz, CDCl_3) δ : 170.1 (COCH_3), 170.0 (COCH_3), 169.9 (COCH_3), 169.8 (COCH_3), 169.4 (COCH_3), 138.3, 128.4, 128.0, 127.8, 101.4 (C-1'), 98.9 (C-1''), 97.5 (C-1), 79.8 (C-4), 77.2 (C-3''), 76.5 (C-2), 73.2 (CH_2Ph), 73.0 (C-4'), 72.3 (C-3), 71.2 (C-3'), 71.1 (C-2'), 69.2 (C-4''), 68.1 (C-2''), 66.9 (OCH_2), 66.6 (C-5), 66.2 (C-5''), 61.6 (C-5'), 57.9 (OCH_3), 50.6 (CH_2N_3), 21.0 (COCH_3), 20.9 (COCH_3), 20.8 (COCH_3), 20.7 ($2 \times \text{COCH}_3$), 17.5 (C-CH₃), 16.2 (C-CH₃).

HRMS calcd for $\text{C}_{37}\text{H}_{51}\text{N}_3\text{O}_{18}\text{Na}$ $[\text{M} + \text{Na}]^+$: 848.3065; found: 848.3061.

Synthesis of 2-azidoethyl 6-deoxy-3-*O*-methyl- α -D-mannopyranosyl-(1 \rightarrow 3)-2-*O*-benzyl-4-*O*-(β -D-xylopyranosyl)- α -L-fucopyranoside (22). To a solution of compound **21** (300 mg, 0.36 mmol) in MeOH (5 mL), NaOMe in MeOH (0.5 mL, 0.5M) was added and the solution was stirred at room temperature for 4 hours. The solution was neutralized with DOWEX 50 W H⁺ resin and the resin was filtered off with a pad of cotton. The solvents were evaporated to obtain compound **22** (206.0 mg, 92%) as colourless foam.

$[\alpha]_{\text{D}}^{25}$: +98 (*c* 0.7, CHCl_3).

IR (cm^{-1} , CHCl_3) ν : 3432, 2921, 2105, 1092, 1037, 743.

^1H NMR (500 MHz, CD_3OD) δ : 7.42–7.28 (m, 5H, ArH), 5.13 (s, 1H, H-1''), 4.81 (d, 1H, $J_{1,2}$ 3.5 Hz, H-1), 4.70 (d, 1H, J 12.0 Hz, CH_2Ph), 4.64 (d, 1H, J 12.0 Hz, CH_2Ph), 4.31 (d, 1H, $J_{1',2'}$ 6.5 Hz, H-1'), 4.11–4.06 (m, 4H, H-3, H-2'', H-5'a, H-5), 3.95–3.88 (m, 3H, H-4'', H-2, H-5''), 3.82–3.78 (m, 1H, OCH_{2a}), 3.56–3.45 (m, 8H, H-4', H-4, H-3', OCH_{2b} , CH_{2a}N_3 , OCH_3), 3.42–3.37 (m, 1H, CH_{2b}N_3), 3.37–3.29 (m, 2H, H-2', H-3''), 3.15 (t, 1H, J_{gem} , $J_{4',5'}$ 11.0 Hz, H-5'b), 1.32 (d, 3H, $J_{5,6}$ 6.5 Hz, C-CH₃), 1.24 (d, 3H, $J_{5'',6''}$ 6.0 Hz, C-CH₃).

^{13}C NMR (125 MHz, CD_3OD) δ : 138.5, 128.1, 127.8, 127.5 (ArC), 104.8 (C-1'), 101.5 (C-1''), 97.4 (C-1), 80.3 (C-4), 79.4 (C-2), 76.5 (C-4''), 76.4 (C-3''), 74.1 (C-2'), 72.4 (C-3), 72.3 (CH_2Ph), 71.5 (C-4'), 69.9 (C-3'), 68.8 (C-5''), 67.1 (C-2''), 66.9 (OCH_2), 66.8 (C-5), 65.4 (C-5'), 56.1 (OCH_3), 50.4 (CH_2N_3), 16.6 (C-CH₃), 15.2 (C-CH₃).

HRMS calcd for $\text{C}_{27}\text{H}_{41}\text{N}_3\text{O}_{13}\text{Na}$ $[\text{M} + \text{Na}]^+$: 638.2537; found: 638.2532.



2-Aminoethyl 6-deoxy-3-O-methyl- α -D-mannopyranosyl-(1 \rightarrow 3)-4-O-(β -D-xylopyranosyl)- α -L-fucopyranoside (1). To a solution of compound 22 (50 mg, 0.08 mmol) in MeOH (5.0 mL), 10% Pd-C (25 mg) was added and the mixture was stirred at room temperature under a H₂ atmosphere for 48 hours. It was filtered through a pad of Celite® and the filtrate was evaporated *in vacuo*. The residue was dissolved in H₂O (2 mL) and lyophilized. The pure compound 1 (30.0 mg, 71%) was obtained as a white amorphous mass.

$[\alpha]_D^{25}$: +102 (c 0.4, CH₃OH).

¹H NMR (400 MHz, CD₃OD) δ : 5.08 (s, 1H, H-1''), 4.91 (s, 1H, H-1), 4.32 (d, 1H, $J_{1',2'}$ 7.2 Hz, H-1'), 4.20 (s, 1H, H-2''), 4.11–4.01 (m, 3H, H-3, H-5, H-5'a), 3.99–3.93 (m, 3H, H-5'', OCH_{2a}, H-4''), 3.89 (m, 1H, H-2), 3.80–3.74 (m, 1H, OCH_{2b}), 3.50–3.46 (m, 6H, H-4', H-4, H-3', OCH₃), 3.34–3.28 (m, 4H, H-3'', CH₂N, H-2'), 3.16 (t, 1H, J_{gem} , $J_{4',5'}$ 10.8 Hz, H-5'b), 1.36 (d, 3H, $J_{5,6}$ 6.4 Hz, C-CH₃), 1.26 (d, 3H, $J_{5'',6''}$ 6.0 Hz, C-CH₃).

¹³C NMR (100 MHz, CD₃OD) δ : 104.3 (C-1'), 101.6 (C-1''), 98.6 (C-1), 79.9 (C-4), 79.3 (C-2), 75.7 (C-3''), 73.6 (2C, C-2', C-4''), 70.8 (C-4'), 69.4 (C-3'), 69.0 (C-5''), 68.5 (C-3), 67.5 (C-5), 65.5 (C-2''), 64.9 (C-5'), 62.5 (OCH₂), 56.0 (2C, OCH₃, CH₂N), 16.6 (C-CH₃), 15.0 (C-CH₃).

HRMS calcd for C₂₀H₃₇NO₁₃Na [M + Na]⁺: 522.2163; found: 522.2157.

Author contributions

SM performed the experiments and collected analytical data. BM and SM contributed equally towards the analysis of the data and preparation of the manuscript and its associated content.

Data availability

Necessary data are available in the ESI† associated with the manuscript.

Conflicts of interest

There are no conflicts to declare.

Acknowledgements

SM is thankful to DST INSPIRE for a Senior Research fellowship (SRF). The analytical facility of IISER Kolkata is gratefully acknowledged. This work is supported by the research grant CRG/2022/005805 from the Science and Engineering Research Board (SERB), New Delhi to BM.

References

- G. Berg, Plant-microbe interactions promoting plant growth and health: perspectives for controlled use of micro-organisms in agriculture, *Appl. Microbiol. Biotechnol.*, 2009, **84**, 11–18.
- M. S. Zawoznik, M. Ameneiros, M. P. Benavides, S. Vazquez and M. D. Groppa, Response to saline stress and aquaporin expression in *Azospirillum*-inoculated barley seedlings, *Appl. Microbiol. Biotechnol.*, 2011, **90**, 1389–1397.
- S. Fibach-Paldi, S. Burdman and Y. Okon, Key physiological properties contributing to rhizosphere adaptation and plant growth promotion abilities of *Azospirillum brasilense*, *FEMS Microbiol. Lett.*, 2012, **326**, 99–108.
- O. Steenhoudt and J. Vanderleyden, *Azospirillum*, a free-living nitrogen-fixing bacterium closely associated with grasses: genetic, biochemical and ecological aspects, *FEMS Microbiol. Rev.*, 2000, **24**, 487–506.
- I. V. Egorenkova, S. A. Konnova, V. N. Sachuk and V. V. Ignatov, *Azospirillum brasilense* colonisation of wheat roots and the role of lectin–carbohydrate interactions in bacterial adsorption and root-hair deformation, *Plant Soil*, 2001, **231**, 275–282.
- A. S. Boyko, A. S. Dmitrenok, Y. P. Fedonenko, E. L. Zdorovenko, S. A. Konnova, Y. A. Knirel and V. V. Ignatov, Structural analysis of the O-polysaccharide of the lipopolysaccharide from *Azospirillum brasilense* Jm6B2 containing 3-O-methyl-D-rhamnose (D-acofriose), *Carbohydr. Res.*, 2012, **355**, 92–95.
- A. Adak, M. Bera and B. Mukhopadhyay, Synthesis of the Hexasaccharide Related to the Exopolysaccharide from *Lactobacillus mucosae* VG1 through Regioselective Glycosylation, *Org. Lett.*, 2023, **25**, 4711–4714.
- S. Maiti and B. Mukhopadhyay, Synthesis of the conjugation-ready β -mannosamine-containing O-antigen repeat from *Vibrio cholerae*, O14, *Org. Biomol. Chem.*, 2025, **23**, 1866–1873.
- S. Das, S. Maiti and B. Mukhopadhyay, Chemical synthesis of 6-deoxy-d-talose containing a tetrasaccharide repeating unit of the O-specific polysaccharide from *Enterobacter cloacae*, G3422 in the form of its 2-aminoethyl glycoside, *Org. Biomol. Chem.*, 2024, **22**, 2414–2422.
- C. M. Cairns, F. S. Michael, M. Jamshidi, H. van Faassen, Q. Yang, K. A. Henry, G. Hussack, J. Sauvageau, E. V. Vinogradov and A. D. Cox, Structural Characterization and Evaluation of an Epitope at the Tip of the A-Band Rhamnan Polysaccharide of *Pseudomonas aeruginosa*, *ACS Infect. Dis.*, 2022, **8**, 1336–1346.
- C. Qin, B. Schumann, X. Zou, C. L. Pereira, G. Tian, J. Hu, P. H. Seeberger and J. Yin, Total synthesis of a densely functionalized *Plesiomonas shigelloides* serotype 51 amino-glycoside trisaccharide antigen, *J. Am. Chem. Soc.*, 2018, **140**, 3120–3127.
- B. Roy and B. Mukhopadhyay, Sulfuric acid immobilized on silica: an excellent catalyst for Fischer type glycosylation, *Tetrahedron Lett.*, 2007, **48**, 3783–3787.
- P. Leon-Ruaud and D. Plusquellec, Synthesis of new surfactant glycosides via sugar halides. Methyl α -D-glucoside and methyl α -D-mannoside thioethers and sulfones, *Tetrahedron*, 1991, **47**, 5185–5192.



- 14 C. L. Stevens, R. P. Glinski, K. G. Taylor, P. Blumbergs and F. Sirokman, New rearrangements of hexose 4- and 5-O-sulfonates, *J. Am. Chem. Soc.*, 1966, **88**, 2073–2074.
- 15 E. Kaufmann, H. Hattori, H. Miyatake-Ondozabal and K. Gademann, Total Synthesis of the Glycosylated Macrolide Antibiotic Fidaxomicin, *Org. Lett.*, 2015, **17**, 3514–3517.
- 16 L. Xia, R. B. Zheng and T. L. Lowary, Revisiting the Specificity of an α -(1 \rightarrow 4)-Mannosyltransferase Involved in Mycobacterial Methylmannose Polysaccharide Biosynthesis, *ChemBioChem*, 2012, **13**, 1139–1151.
- 17 M. P. Jamshidi, C. Cairns, N. H. Khieu, K. Chan, F. St. Michael, A. Cox and J. Sauvageau, Optimization of the Synthesis and Conjugation of the Methyl Rhamnan Tip of *Pseudomonas aeruginosa* A-B and Polysaccharide and Immunogenicity Evaluation for the Continued Development of a Potential Glycoconjugate Vaccine, *ACS Infect. Dis.*, 2024, **10**, 1361–1369.
- 18 M. P. Jamshidi, C. Cairns, S. Chong, F. St. Michael, E. V. Vinogradov, A. D. Cox and J. Sauvageau, Synthesis and Immunogenicity of a Methyl Rhamnan Pentasaccharide Conjugate from *Pseudomonas aeruginosa* A-B and Polysaccharide, *ACS Infect. Dis.*, 2022, **8**, 1347–1355.
- 19 J. S. Brimacombe, N. Robinson and J. M. Webber, Syntheses of 6-Deoxy-3-O-methyl-D-gulose and 6-Deoxy-3-O-methyl-L-mannose (L-Acofriose), *J. Chem. Soc. C*, 1971, 613–618.
- 20 D. Budhadev and B. Mukhopadhyay, Chemical synthesis of a tetrasaccharide related to the exocellular polysaccharide from *Rhodococcus* sp. RHA1, *Carbohydr. Res.*, 2014, **394**, 26–31.
- 21 A. Kafle, J. Liu and L. Cui, Controlling the stereoselectivity of glycosylation via solvent effects, *Can. J. Chem.*, 2016, **94**, 894–901.
- 22 S.-R. Lu, Y.-H. Lai, J.-H. Chen, C.-Y. Liu and K.-K. T. Mong, Dimethyl formamide: an unusual glycosylation modulator, *Angew. Chem., Int. Ed.*, 2011, **50**, 7315–7320.
- 23 K. Boubbou, D. C. Zhu, C. Vasileiou, B. Borhan, D. Prosperi, W. Li and X. Huang, Magnetic Glyco-Nanoparticles: A tool to Detect, differentiate, and unlock the Glyco-Codes of cancer via magnetic resonance imaging, *J. Am. Chem. Soc.*, 2010, **132**, 4490–4499.
- 24 B. Thollas and C. Biosset, Total Synthesis of Floridoside, *Synlett*, 2007, 1736–1738.
- 25 P. A. Gent and R. Gigg, The allyl ether as a protecting group in chemistry. Part V. Preparation of benzyl ethers of carbohydrates for use in oligosaccharide synthesis, *J. Chem. Soc., Perkin Trans. 1*, 1974, 1446–1455.
- 26 Y. Demizu, Y. Kubo, H. Miyoshi, T. Maki, Y. Matsumura, N. Moriyama and O. Onomura, Regioselective protection of sugars catalyzed by Dimethyltin Dichloride, *Org. Lett.*, 2008, **10**, 5075–5077.
- 27 A. K. Mishra, B. K. Ghotekar, C. K. Puley and S. S. Kulkarni, Expanding the scope of a One-pot double displacement protocol to access the all-rare-sugar-containing trisaccharide unit of *Pseudomonas stutzeri* OX1, *Org. Lett.*, 2024, **26**, 9955–9960.
- 28 B. Mukhopadhyay, K. P. R. Kartha, D. A. Russell and R. A. Field, Streamlined synthesis of per-O-acetylated sugars, glycosyl iodides, or thioglycosides from unprotected reducing sugars, *J. Org. Chem.*, 2004, **69**, 7758–7760.
- 29 G. H. Veeneman, S. H. van Leeuwen and J. H. van Boom, Iodonium ion promoted reactions at the anomeric centre. II An efficient thioglycoside mediated approach toward the formation of 1,2-trans linked glycosides and glycosidic esters, *Tetrahedron Lett.*, 1990, **31**, 1331–1334.
- 30 G. Gu, Y. Du and R. J. Linhardt, Facile synthesis of saponins containing 2,3-branched oligosaccharides by using partially protected glycosyl donors, *J. Org. Chem.*, 2004, **69**, 5497–5500.
- 31 X. Zhang, G. Gu and Z. Guo, Synthesis of a trisaccharide repeating unit of the O-antigen from *Burkholderia multivorans* and Its oligomers, *Eur. J. Org. Chem.*, 2015, 7075–7085.
- 32 B. Mukhopadhyay and N. Roy, Synthesis of the pentasaccharide related to the repeating unit of the antigen from *Shigella dysenteriae*, type-4 In the form of Its methyl ester 2-(trimethylsilyl)ethyl glycoside, *Carbohydr. Res.*, 2003, **338**, 589–596.
- 33 G. Zemplén and A. Kunz, Studien über Amygdalin, IV: Synthese des natürlichen l-Amygdalins, *Ber. Deutsch. Chem. Ges.*, 1924, **57**, 1357–1359.
- 34 V. S. Rao and A. S. Perlin, Removal of O-benzyl protecting-groups of carbohydrate derivatives by catalytic, transfer hydrogenation, *Carbohydr. Res.*, 1980, **83**, 175–177.
- 35 D. D. Perrin, W. L. Amarego and D. R. Perrin, *Purification of Laboratory Chemicals*, Pergamon, London, 1996.

