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## C-Glycopyranosyl aldehydes: emerging chiral synthons in organic synthesis

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Herein, we have summarized the vast array of synthetic processes that have been developed for the synthesis of *C*-glycopyranosyl aldehydes and diverse *C*-glycoconjugates derived from them by covering the literature reported from 1979 to 2023. Notwithstanding its challenging chemistry, *C*-glycosides are considered stable pharmacophores and are used as important bioactive molecules. The discussed synthetic methodologies to access *C*-glycopyranosyl aldehydes take advantage of seven key intermediates, *viz.* allene, thiazole, dithiane, cyanide, alkene, and nitromethane. Furthermore, the integration of complex *C*-glycoconjugates derived from varied *C*-glycopyranosyl aldehydes involves nucleophilic addition/substitution, reduction, condensation, oxidation, cyclo condensation, coupling, and Wittig reactions. In this review, we have categorized the synthesis of *C*-glycopyranosyl aldehydes and *C*-glycoconjugates on the basis of the methodology used for their synthesis and on types of *C*-glycoconjugates, respectively.

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Dr Sandeep Kumar obtained his PhD from the Department of Chemistry, University of Delhi, India in February 2022 under the supervision of Prof. Ashok Kumar Prasad in the field of nucleosides and carbohydrate chemistry. His research interest lies in the synthesis of modified nucleosides and sugar based heterocyclic molecules for therapeutic applications. Dr Kumar secured All India Rank 14 in

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Dr Vinod Khatri studied Chemistry at Kurukshetra University, Kurukshetra Haryana and received his PhD from University of Delhi under the supervision of Professor Ashok K. Prasad. After PhD in 2017, he joined IISER Mohali as National Postdoctoral Fellow (DST-SERB) and worked on metal-catalyzed reactions on carbohydrates. In 2018, he joined as an Assistant Professor in the Department of Higher Education Haryana. He worked as postdoctoral fellow at Freie University Berlin Germany for one year with Dr Sumati Bhatia in 2021. His research interests are *C*-glycosides, sugar based copolymers and multivalent glycoconjugates.



## 1. Introduction

*C*-Glycosides constitute an important and useful class of organic molecules, in which anomeric carbon of a sugar is attached to an aglycon through C–C bonds. Molecules of this class are mimics of *O*-glycosides, where the sugar moiety is attached with aglycon through C-atom instead of O-atom at the anomeric position.<sup>1</sup>



Dr Priyanka received her PhD in Organic and Medicinal Chemistry in 2019 from University of Delhi (India), where she developed modified nucleosides using diastereoselective biocatalytic transformations of sugars and catalytic C–H functionalization of nucleobases. To continue her passion in the field of nucleic acid chemistry, she joined the Oligonucleotide Chemistry team at AstraZeneca, Sweden in 2021

as a post-doctoral research scientist. Her research focuses on the development of novel pH-sensitive endosomolytic agents to enhance the endosomal escape of oligonucleotides and improve gene-silencing.



Dr Chhatwal obtained her BSc and MSc degree from Kurukshetra University, Kurukshetra in 1993 and 1995, respectively. Then Dr Chhatwal did PhD from Guru Jambeshwar University in 2005. Her area of interest is “Spectral, Structural Elucidation and Co-ordination Abilities of Tin and Aluminium with Tri-phenyl Oxo Propoxide to Yield Starting Material Triphenyl Tin(IV) Aluminium(III) Oxo Propoxide Compound”. Currently, Dr Chhatwal is an Assistant Professor in Maitreyi College-University of Delhi.

Glycosides have made their presence felt in foodstuffs to the components of nucleic acids and cell surface glycoconjugates. The structural alteration resulting from the transformation of the anomeric centre from C–O acetal to a strong C–C bond in *C*-glycosides stimulates the resistance towards chemical/enzymatic hydrolysis and metabolic processes.<sup>2</sup> As a consequence, the dominance of *C*-glycosides to personate native *O*-glycosides as



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Gwyer Hall at Delhi university. Professor Parmar's research interests include: green/sustainable Chemistry, nanotechnology, organic synthesis, nucleic acid chemistry, advanced materials, medicinal chemistry, biocatalysis and the chemistry of natural products. He has mentored 85 PhD and postdoctoral scientists and has published over 500 research papers. He was awarded the Dean's Research Excellence Award of the School of Science, Health and Technology, MEC-CUNY, New York, USA for the years 2019 & 2020.



Late Professor Ashok K. Prasad (1961–2023): Professor Prasad obtained his PhD from the Department of Chemistry, University of Delhi, in 1990 in the area of synthesis of bioactive polyphenolic natural products. After spending about a decade as a post-doctoral fellow/visiting scientist at the University of Southern Denmark, the Max Planck-Institute for Molecular Physiology (Germany), Sapienza

University Rome (Italy), and the University of Massachusetts Lowell (USA), Professor Prasad joined the Department of Chemistry, University of Delhi, as Reader in 2001 and subsequently became Professor in 2009. He was the Head of the Chemistry Department and Dean of Science Faculty, University of Delhi. He had published more than 300 research papers in journals of international repute. His research interests were in the areas of nucleic acid chemistry, biotransformations, natural product chemistry, and synthesis of bioactive heterocyclic compounds. We dedicate this review to the fond memory of Late Professor Ashok K. Prasad.



potential therapeutic candidates has become undoubtedly apparent. Moreover, the occurrence of *C*-glycosidic linkage is common in natural products obtained from plants and microorganisms, such as saptomycin B,<sup>3</sup> mangiferin,<sup>4</sup> aspalathin,<sup>5</sup> tunicamycin V,<sup>6</sup> and aureonuclemycin,<sup>7</sup> which have shown significant biological activities<sup>8</sup> (Fig. 1).

Remarkable structural diversity in naturally occurring *C*-glycosides has drawn considerable attention to chemically synthesized complex *C*-glycosides. The successful examples of the chemical evolution of *C*-glycosides include pro-xylene as anti-aging cosmetic agent,<sup>9</sup> dapagliflozin, canagliflozin and empagliflozin as SGLT2 inhibitors for the treatment of type II diabetes,<sup>10–12</sup> metabolically stable *C*-analogue of KRN7000 as anticancer agent,<sup>13</sup> *C*-mannosyl-Trp for post-transitional modification affecting folding, stability and other functions of proteins,<sup>14</sup> etc. (Fig. 2).

A literature survey on *C*-glycosides illustrates that earlier reported review articles have mainly been on *exo*-glycals,<sup>15</sup> *C*-mannopyranosides,<sup>16</sup> *C*-nucleosides,<sup>17</sup> *C*-glycoconjugates,<sup>18</sup> *C*-

arylglycosides,<sup>19,20</sup> and on chemical synthesis of *C*-glycosides.<sup>21,22</sup> Although  $\alpha$ - and  $\beta$ -*C*-glycopyranosyl aldehydes constitute an important class of precursor molecules for the formation of complex *C*-glycosides, it has been overlooked to make their explicit presence in any review article. About two decades ago, Dondoni presented a review that mainly referred to sugar thiazole as a key synthetic intermediate for the synthesis of *C*-glycopyranosyl aldehyde and explained its role as a precursor for the formation of *C*-disaccharide and *C*-amino acids.<sup>23</sup> Consequently, these facts encouraged us to compile the literature on the synthesis of  $\alpha$ - and  $\beta$ -*C*-glycopyranosyl aldehydes and their applications in the synthesis of diverse biologically relevant *C*-glycoconjugates in this review article.

## 2. Synthesis of *C*-glycopyranosyl aldehydes

Generally, syntheses of *C*-glycosides involve the nucleophilic addition of aglycon part on sugar moiety followed by treatments

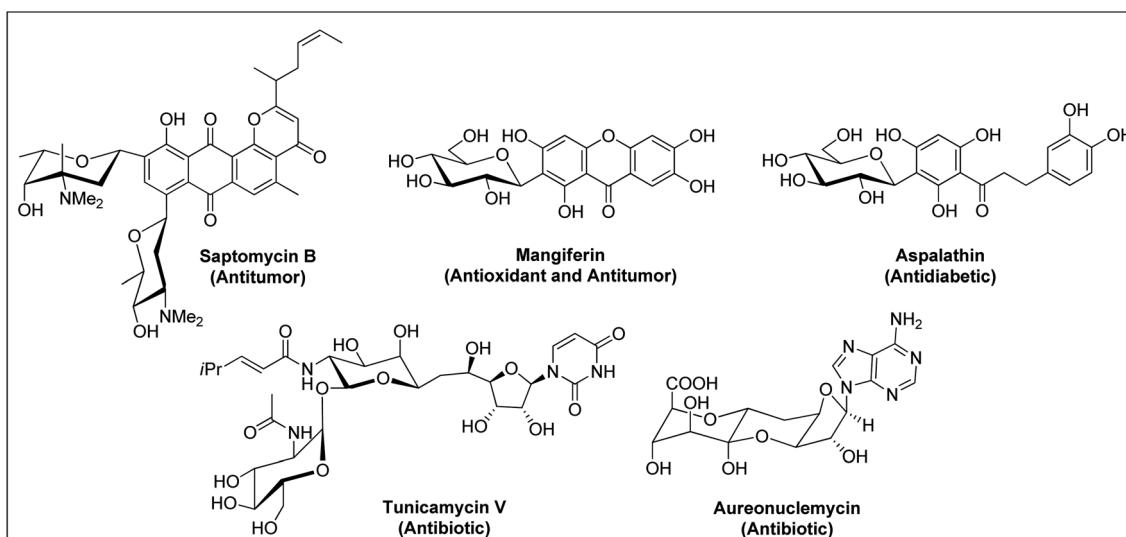


Fig. 1 Structures of some selected naturally occurring bioactive *C*-glycosides.

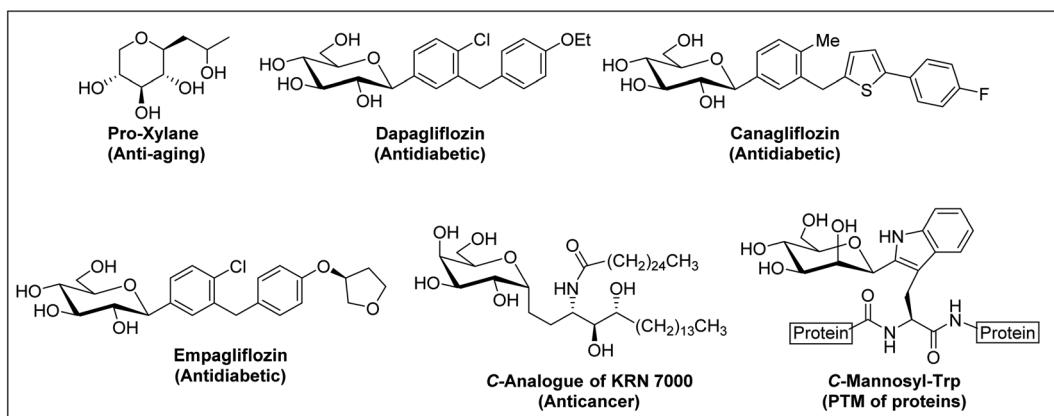


Fig. 2 Structures of some bioactive synthetic *C*-glycosides.



using dehydration, oxidation, reduction, and reductive hydrolysis reactions to obtain targeted  $\alpha$ -C-glycopyranosyl aldehydes. In comparison to the syntheses of  $\alpha$ -C-glycopyranosyl aldehydes, more methodologies have been reported on the synthesis of  $\beta$ -C-glycopyranosyl aldehydes. Further, it has been observed that  $\alpha$ -C-glycopyranosyl aldehydes can be easily converted into  $\beta$ -C-glycopyranosyl aldehydes in the presence of organic bases. Seven key intermediates have been used for the preparation of  $\alpha$ - and  $\beta$ -C-glycopyranosyl aldehydes, which have been described below (Fig. 3).

## 2.1 Allene approach

Kobertz *et al.*<sup>24</sup> reported the use of  $\alpha$ -C-glycopyranosyl allenes **2a–c** as key synthetic intermediates for the synthesis of C-glycopyranosyl aldehydes, which in turn can be synthesized from methyl tetra-O-benzyl- $\alpha$ -D-glycopyranosides **1a–c** with high

Table 1 Overall yields and equilibrium ratio of  $\beta/\alpha$  for the conversion of **2a–c** into **4a–c**

Reactant	$\beta$ -linked products	$\beta : \alpha$	Yield (%)
<b>2a</b>	<b>4a</b>	>20 : 1	41
<b>2b</b>	<b>4b</b>	8 : 1	42
<b>2c</b>	<b>4c</b>	10 : 1	49

diastereoselectivity (>20 : 1) *via* Lewis acid catalysed nucleophilic substitution reaction using propargyl trimethylsilane in the presence of trimethylsilyl triflate (TMSOTf) in acetonitrile. Furthermore, ozonolysis of allenes **2a–c** in dichloromethane at  $-78^{\circ}\text{C}$  provided  $\alpha$ -C-glycopyranosyl aldehydes **3a–c**, which on treatment with 10% triethylamine in isopropanol : DCM (1 : 1) at  $25^{\circ}\text{C}$  for 24 h yielded  $\beta$ -C-glycopyranosyl aldehydes **4a–c** (Scheme 1). The overall yields and equilibrium ratio of  $\beta/\alpha$  for the conversion of C-glycopyranosyl allenes **2a–c** into  $\beta$ -linked C-glycopyranosyl aldehydes **4a–c** are shown in Table 1.

In another synthetic approach reported by Kroger *et al.*<sup>25</sup> peracetylated D-galactose **5** was used as a starting material to access the sugar allene precursor (Scheme 2). 1,2,3,4,6-Penta-O-acetyl- $\beta$ -D-galactopyranose (**5**) was converted into the corresponding  $\alpha$ -C-glycosidic allene **6** using propargyl trimethylsilane in the presence of Lewis acid ( $\text{BF}_3 \cdot \text{Et}_2\text{O}$ ) in acetonitrile at  $0^{\circ}\text{C}$  in 48% yield. Further, compound **6** on ozonolysis afforded acetylated  $\alpha$ -C-galactopyranosyl aldehyde **7**, which was found to be very labile and further used without isolation for the synthesis of O-glycosyl amino acid mimetics. The details of synthetic methods for these O-glycosyl amino acid mimetics are described in Section 3.4 (Scheme 50).

Alternatively, Kolypadi *et al.*<sup>26</sup> synthesized both  $\alpha$ - and  $\beta$ -linked glycopyranosyl aldehydes using allene as the key precursor, which was obtained from peracetylated D-galactose **5** following the method of Kroger *et al.*<sup>25</sup> (Scheme 3). However, here combination of Lewis acids  $\text{BF}_3 \cdot \text{Et}_2\text{O}$ -TMSOTf produced allene **6** in 80% yield. Since Kroger observed that the acetyl-protected glycopyranosyl aldehyde **7** was very labile, here, acetylated allene **6** was converted into the perbenzylated  $\alpha$ -C-glycosyl allene **2c** by deprotection of acetyl group with sodium

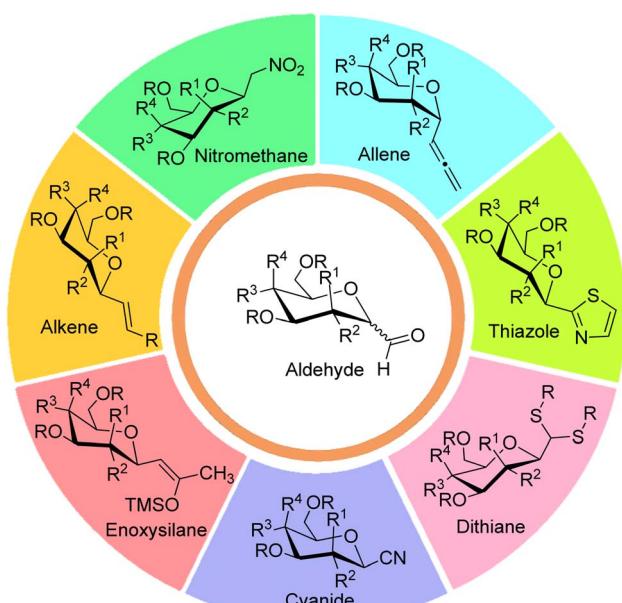
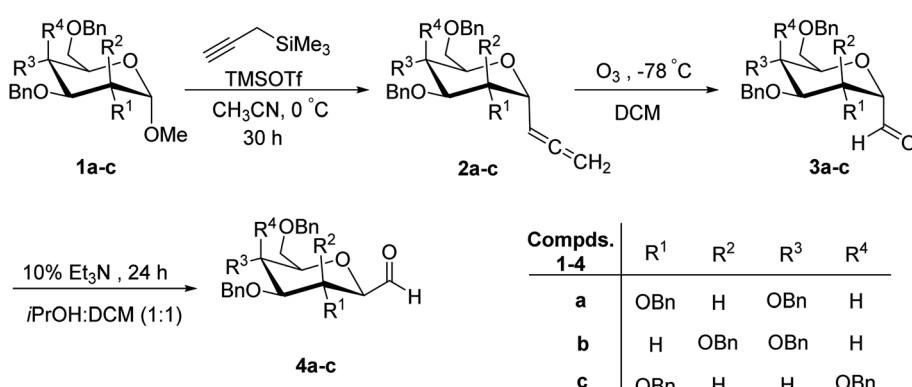
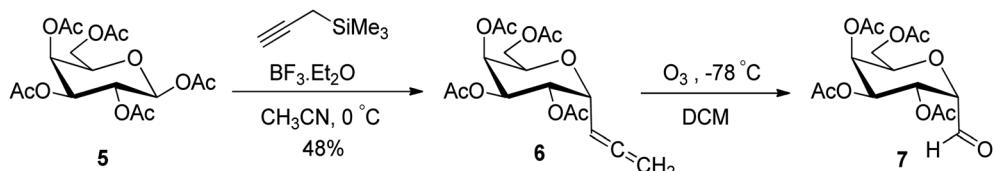
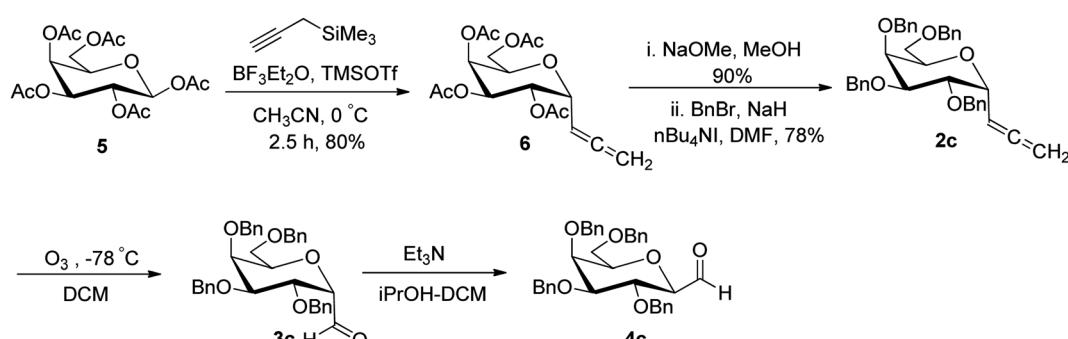


Fig. 3 Key intermediates for the synthesis of C-glycopyranosyl aldehydes.



Scheme 1 Synthesis of  $\beta$ -C-glycopyranosyl aldehydes **4a–c**.



Scheme 2 Synthesis of  $\alpha$ -C-galactopyranosyl aldehyde 7.Scheme 3 Synthesis of  $\beta$ -C-galactopyranosyl aldehyde 4c.

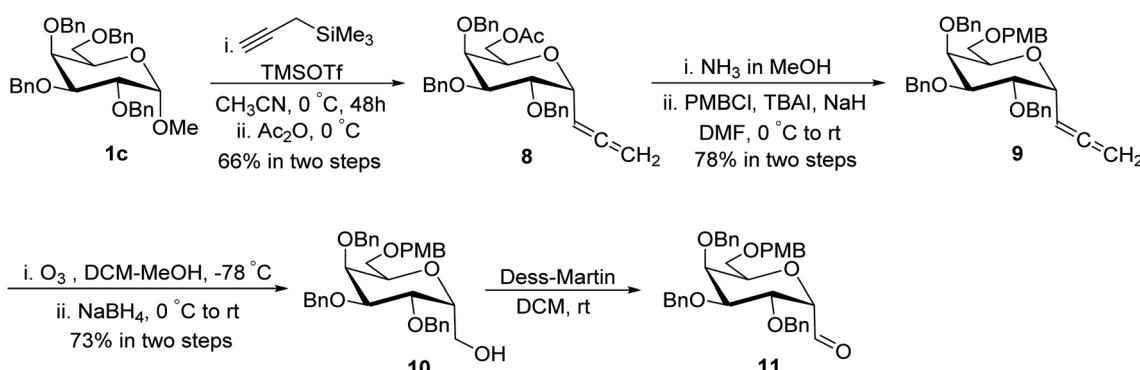
methoxide (NaOMe)/methanol followed by the protection of generated hydroxyl groups with benzyl bromide in the presence of sodium hydride in DMF. Further, compound **2c** was converted into  $\beta$ -C-galactopyranosyl aldehyde **4c** by following the methodology developed by Kobertz *et al.*<sup>24</sup>

Guillaume *et al.*<sup>27</sup> designed a route for the synthesis of C-glycopyranosyl aldehyde **11** initiating from perbenzylated  $\alpha$ -methyl galactoside **1c**. The aim for the synthesis of orthogonally protected C-glycopyranosyl aldehyde **11** was to be utilized for the synthesis of C6-modified  $\alpha$ -C-GalCer analogues (Section 3.1, Scheme 32a). Thus, treatment of galactoside **1c** with propargyl trimethylsilane and trimethylsilyl triflate in acetonitrile at 0 °C for 48 hours followed by acetylation using acetic anhydride yielded sugar allene **8** in 66% yield. Deprotection of the C6-OBn group in **1c** under condition propargyl trimethylsilane and trimethylsilyl triflate in acetonitrile at 0 °C for 48 was due to the excess use of Lewis acid, *i.e.* trimethylsilyl triflate and longer reaction time. Acetyl protection of compound **8** was replaced

with PMB on treatment with ammonia in methanol followed by protection of alcohol with PMBCl resulting in allene **9** in 78% yield, which upon ozonolysis and *in situ* reduction with sodium borohydride afforded primary alcohol **10** in 73% yield. The  $\alpha$ -C-galactopyranosyl aldehyde **11** was obtained by re-oxidation of alcohol **10** *via* the Dess–Martin reaction.  $\alpha$ -C-Galactopyranosyl aldehyde **11** was also found labile and further used without isolation (Scheme 4).

## 2.2 Thiazole approach

Thus, the allene approach carried out by these researchers concluded that the use of both Lewis acids  $\text{BF}_3\text{-Et}_2\text{O}$ -TMSOTf produced allene in good yield from sugar precursors. Excess use of Lewis acids furnished deprotection of the C6-OBn group and it was also observed that  $\alpha$ -C-glycopyranosyl aldehydes are less stable than  $\beta$ -C-glycopyranosyl aldehydes and the earlier one could be easily converted into later on treatment with base triethylamine in *iPrOH*-DCM. However, the synthesis of C-

Scheme 4 Synthesis of  $\alpha$ -C-galactopyranosyl aldehyde 11.

glycopyranosyl aldehydes *via* the allene approach has posed the limitation of using expensive reagents such as propargyl trimethylsilane, troublesome cleavage by ozonolysis and a long reaction time. So, a more convenient approach was developed by Dondoni *et al.*<sup>28</sup> in which *C*-glycopyranosyl aldehyde was synthesized using sugar thiazole as a key synthetic intermediate.

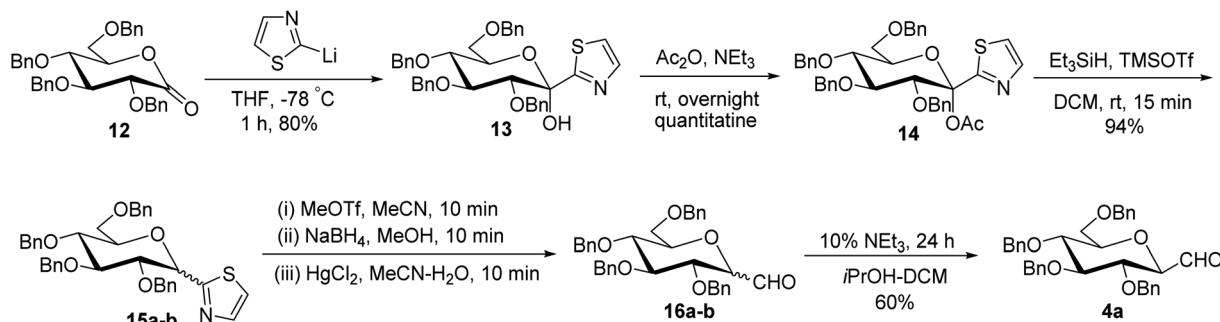
In this approach, the sugar thiazole was synthesized *via* the nucleophilic addition reaction followed by reductive dehydroxylation. The nucleophilic addition of 2-lithiothiazole (2-LTT, prepared *in situ* by the reaction of 2-bromothiazole and butyl lithium) on 2,3,4,6-tetra-*O*-benzyl-*D*-glucono-1,5-lactone 12 at  $-78^{\circ}\text{C}$  in THF yielded 2,3,4,6-tetra-*O*-benzyl- $\beta$ -1-*C*-(2-thiazolyl)-*D*-glucopyranose (13) in 80% yield. On acetylation, compound 13 yielded anomERICALLY activated compound 14, which on further reduction with triethylsilane in trimethylsilyl triflate (TMSOTf) at room temperature for 15 minutes gave an anomERIC mixture of  $\alpha$ - and  $\beta$ -linked 2-thiazolyl-*C*-glycopyranosides 15a-b in 1:1 ratio. The anomERIC mixture 15a-b when subjected to *N*-methylation followed by reduction and then hydrolysis in the presence of corresponding reagents produced  $\alpha$ - and  $\beta$ -linked *C*-glycopyranosyl aldehydes 16a-b in the ratio of 1:1. Treatment of 16a-b with 10% triethylamine afforded  $\beta$ -*C*-glycopyranosyl aldehyde 4a in 60% yield (Scheme 5).

Further, Dondoni *et al.*<sup>29</sup> applied the same approach to other sugar precursors to study the kinetic and thermodynamic aspects of improving the stereochemical control and chemical efficacy (Scheme 6). Different sugar precursors such as 2,3,4,6-tetra-*O*-benzyl-glucose/-mannose/-galactose and 2-azido-3,4,6-

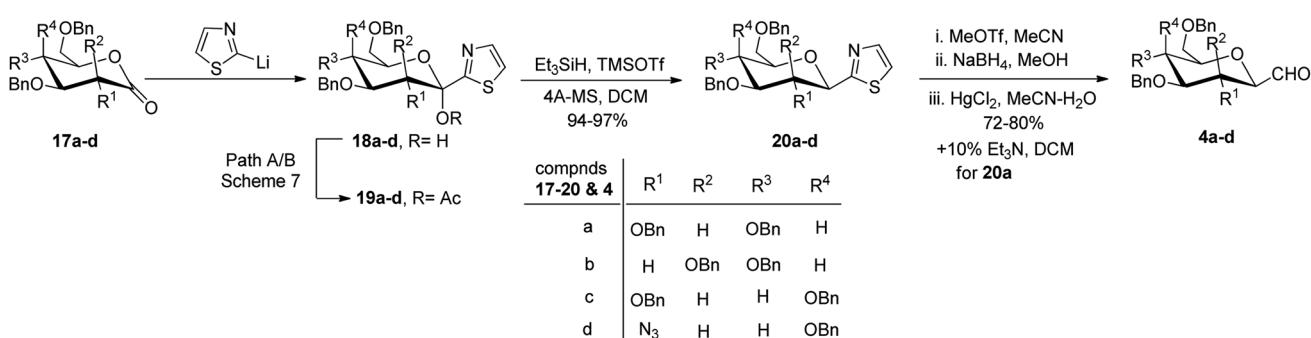
tri-*O*-benzyl-2-deoxy-galactose 17a-d were examined for the given approach where thiazole was used as a formyl group equivalent to synthesize *C*-glycopyranosyl aldehyde 4a-d. A mixture of  $\alpha$ - and  $\beta$ -isomers of *C*-glucopyranosyl aldehyde 4a was obtained in a 1:1 ratio, while, on the other hand, remaining *C*-glycopyranosyl aldehydes 4b-d were formed preferentially in  $\beta$ -configuration.

Ketol acetates 19a-d were synthesized by stereoselective addition of 2-lithiothiazole to sugar lactones 17a-d, resulting in ketol molecules and further acetylation of the corresponding hydroxy group *in situ* or after isolation. Two pathways have been studied for the conversion of 17a-d into 19a-d (Scheme 7). These two pathways produced an anomERIC mixture in different yields along with different ratios as shown in Table 2.

Thus, ketols 18a-d were found as a mixture of kinetically and thermodynamically controlled products where the kinetic products were attributed to the steric effect of substituent and the thermodynamic products to the electronic effect of ring oxygen. On the further reaction of compounds 19a-d with triethylsilane and trimethylsilyl triflate (TMSOTf), the acetate group was reduced yielding thiazolyl *C*-glycoside 20a-d in excellent yield, which is independent of stereochemistry at *C*-1 position of glycosyls 19a-d. Further, a reaction sequence of *N*-methylation followed by reduction of hydride and hydrolysis gave  $\beta$ -linked *C*-glycopyranosyl aldehydes 4a-d in 72-80% yields. The use of thiazole ring as a masked formyl group has been proven to be very efficient and flexible as it worked well on four different substrates, which is further supported by good overall yields (52-65%) of the isolated products. Also, the

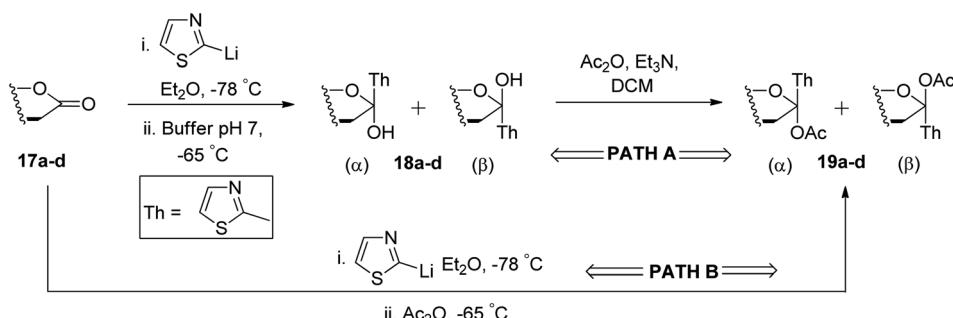


Scheme 5 Synthesis of  $\beta$ -*C*-glycopyranosyl aldehyde 4a.



Scheme 6 Synthesis of *C*-glycopyranosyl aldehydes 4a-d.



Scheme 7 The conversion process of **17a-d** into **19a-d** via two pathways, A and B.Table 2 Conversion of **17a-d** into **19a-d** via pathways A and B

Lactone	Ketol acetate	Condition (path)	$\alpha : \beta$	Yield (%)
<b>17a</b>	<b>19a</b>	A	1:0	80
		B	1:7	87
<b>17b</b>	<b>19b</b>	A	1:0	73
		B	0:1	78
<b>17c</b>	<b>19c</b>	A	1:0	78
		B	1:10	75
<b>17d</b>	<b>19d</b>	A	1:0	77
		B	0:1	80

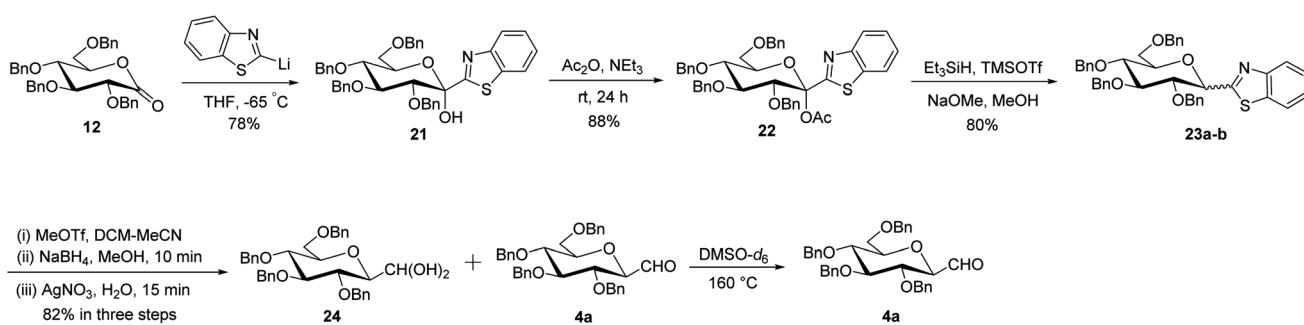
thiazolyl-masked precursor was indefinitely stable and tolerated the synthetic elaboration of the product to yield delicate sugar aldehydes.

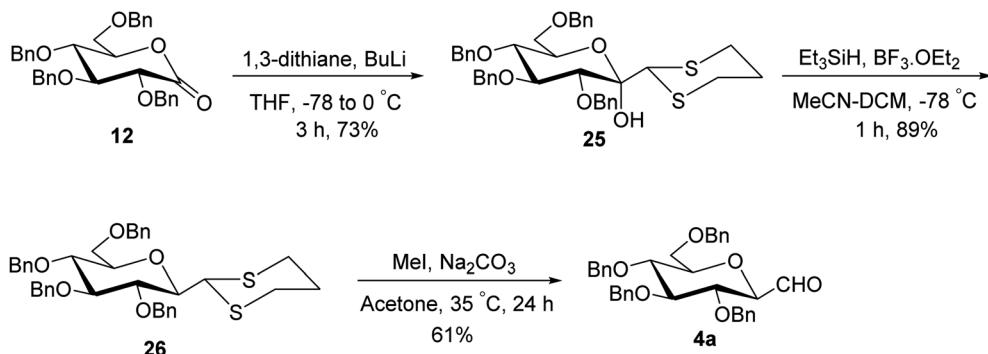
Later, Dondoni *et al.*<sup>30</sup> reported a multigram scale synthesis of *C*-glucopyranosyl aldehyde, where benzothiazole was used in place of thiazole as a formyl group equivalent. The precursor ketose **21** was prepared as a single anomer by the reaction of 2-lithiobenzothiazole (prepared *in situ* by the reaction of butyl lithium and benzothiazole) with 2,3,4,6-tetra-*O*-benzyl-*D*-glucopyran-1,5-lactone **12** in 78% yield. The anomeric position was activated by *O*-acetylation with acetic anhydride in triethylamine to afford compound **22** in 88% yield. Next, compound **22** was reacted with triethylsilane in the presence of trimethylsilyl triflate (TMSOTf) underwent silane-based deoxygenation, and afforded benzothiazolyl  $\alpha$ - and  $\beta$ -*C*-glucosides **23a-b** in 4:6 ratio in 80% yield. After the recovery of  $\beta$ -*C*-glucoside, the benzothiazole ring was converted to a formyl

group by a multistep sequence starting with *N*-methylation, followed by hydride reduction and then hydrolysis to give hydrated *gem*-diol compound **24** along with formyl *C*-glucopyranosyl aldehyde **4a** in 82% yield. A mixture of compounds **24** and **4a**, when heated with DMSO-*d*<sub>6</sub> at 160 °C produced almost pure  $\beta$ -linked *C*-glucopyranosyl aldehyde **4a** (Scheme 8).

### 2.3 Dithiane approach

Although the above-described thiazole approach proved efficient in respect of the overall yield obtained, the lack of diastereofacial selectivity arises during the addition of 2-lithiothiazole to sugar lactones and the formation of the anemic mixture of *C*-glucopyranosyl aldehyde has been the major limitation. However, it has been observed that kinetic and thermodynamic conditions control the diastereoselectivity of thiazole attack on sugar lactones. Hence, for stereoselective formylation, Sanchez *et al.*<sup>31</sup> introduced the sugar dithiane as the key intermediate and synthesized single  $\beta$ -anomer of *C*-glucopyranosyl aldehyde using anucleophilic addition reaction followed by Lewis acid-catalysed stereospecific reductive dehydroxylation. 2,3,4,6-Tetra-*O*-benzyl-*D*-glucopyran-1,5-lactone (**12**) on reaction with 2-lithio-1,3-dithiane gave a single diastereoisomer, sugar lactol **25** in 73% yield. This transformation indicated an equatorial attack on carbonyl to generate corresponding equatorial dithiane substituted sugar and hence compound **25** was assumed to be  $\beta$ -*C*-glucopyranosyl dithiane. Further, in the presence of boron trifluoride diethyl etherate ( $\text{BF}_3 \cdot \text{Et}_2\text{O}$ ) at -40 °C, the hydroxyl group was stereoselectively removed by triethylsilane yielding 2,3,4,6-tetra-*O*-benzyl- $\beta$ -1-*C*-

Scheme 8 Synthesis of *C*-glucopyranosyl aldehyde **4a**.

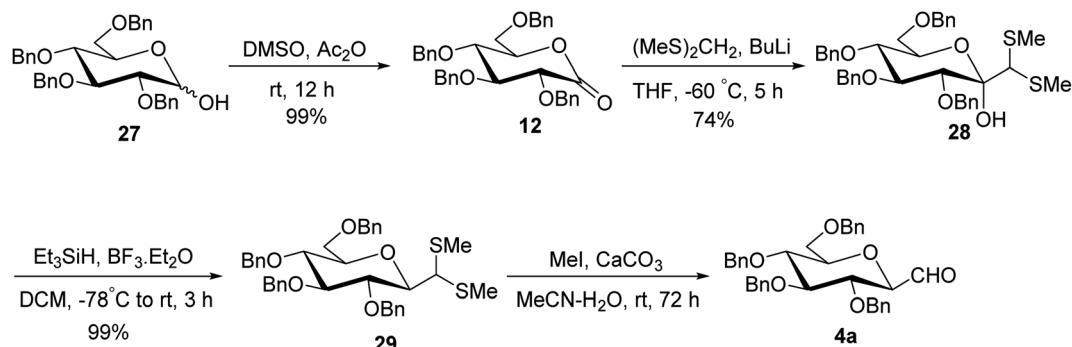
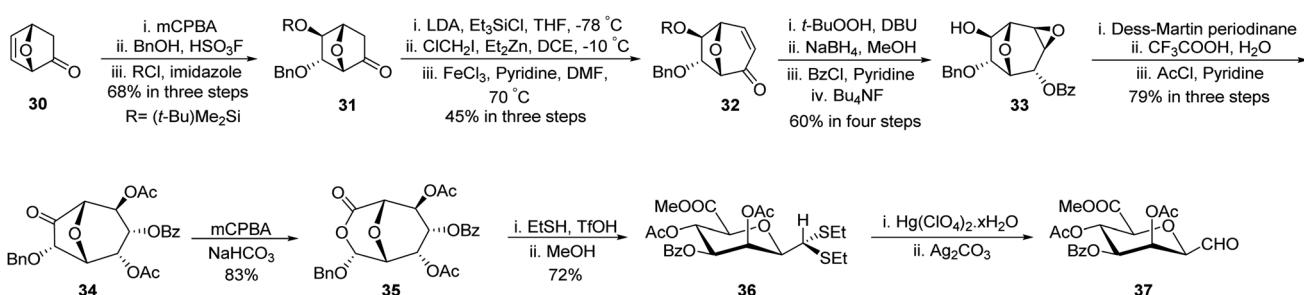
Scheme 9 Synthesis of  $\beta$ -C-glucopyranosyl aldehyde 4a.

(2-dithianyl)-D-glucopyranose (26) in 89% yield. Subsequently, compound 26 was hydrolysed to give  $\beta$ -C-glucopyranosyl aldehyde 4a in the presence of sodium carbonate ( $\text{Na}_2\text{CO}_3$ ) and methyl iodide (MeI) in acetone at 35 °C in 61% yield along-with 20% of unreacted starting material (Scheme 9).

Later on, Labeguere *et al.*<sup>32</sup> reported another route for the highly diastereoselective synthesis of  $\beta$ -C-glucopyranosyl aldehyde with improved overall yield. The commercially available precursor 2,3,4,6-tetra-O-benzyl-D-glucopyranose (27) underwent oxidation in the presence of dimethyl sulfoxide (DMSO) in acetic anhydride to produce 2,3,4,6-tetra-O-benzyl-D-glucono-1,5-lactone 12 in 99% yield. Under Umpolung Seebach reaction condition, compound 12 was transformed into 1-C-[bis(methylthio)methyl]- $\alpha$ -D-glucopyranose (28) in 74% yield *via* in

*in situ* formation of bis(methylthio)methyl carbanion. In the presence of  $\text{BF}_3\text{-Et}_2\text{O}$  and triethylsilane ( $\text{Et}_3\text{SiH}$ ) in DCM at -78 °C, the anomeric hydroxyl group of 28 was reduced to obtain the single  $\beta$ -anomer, *i.e.*  $\beta$ -1-bis(methylthio)methyl-tetra-O-benzyl-D-glucopyranoside (29) with 99% yield. Finally, treatment with methyl iodide and calcium carbonate in a solvent mixture of acetonitrile-water afforded single  $\beta$ -linked glucopyranosyl aldehyde 4a (Scheme 10).

Gerber *et al.*<sup>33</sup> developed a unique protocol for the stereoselective synthesis of  $\beta$ -C-manno-pyranosyl aldehyde (Scheme 11). Here, 7-oxabicyclo[2.2.1]hept-5-en-2-one (30) was converted into (-)-6-*endo*-(benzyloxy)-5-*exo*-hydroxy-7-oxabicyclo[2.2.1]heptane-2-one (31) in 68% yield using epoxidation by mCPBA followed by nucleophilic attack on the epoxide ring by  $\text{BnOH}$

Scheme 10 Synthesis of  $\beta$ -C-glucopyranosyl aldehyde 4a.Scheme 11 Synthesis of  $\beta$ -C-glycopyranosyl aldehyde 37.

and hydroxy group protection using *tert*-butyldimethylsilyl chloride. Further, treatment with triethylsilyl chloride followed by  $\text{ClCH}_2\text{I}/\text{Et}_2\text{Zn}$  in DCE and subsequent oxidation with  $\text{FeCl}_3/\text{pyridine}$  afforded enone 32 in 45% yield. Epoxidation using  $t\text{-BuOOH}$ , DBU followed by reduction with sodium borohydride after that protection with benzoyl chloride and deprotection of the silyl group using fluoride donor  $\text{Bu}_4\text{NF}$  afforded 33 in 60% yield. Dess–Martin Periodinane oxidation and epoxide ring opening using  $\text{CF}_3\text{COOH}-\text{H}_2\text{O}$  and acetyl protection produced 34 in 79% yield, which on Baeyer–Villiger treatment using mCPBA furnished lactone 35 in 83% yield. Further, treatment with ethanethiol in acidic media ( $\text{EtSH-TfOH}$ ) and then with methanol produced dithioacetal 36, which on hydrolysis using  $\text{Hg}(\text{ClO}_4)_2 \cdot x\text{H}_2\text{O}$  and then  $\text{Ag}_2\text{CO}_3$  liberated unstable *C*-glycopyranosyl aldehyde 37.

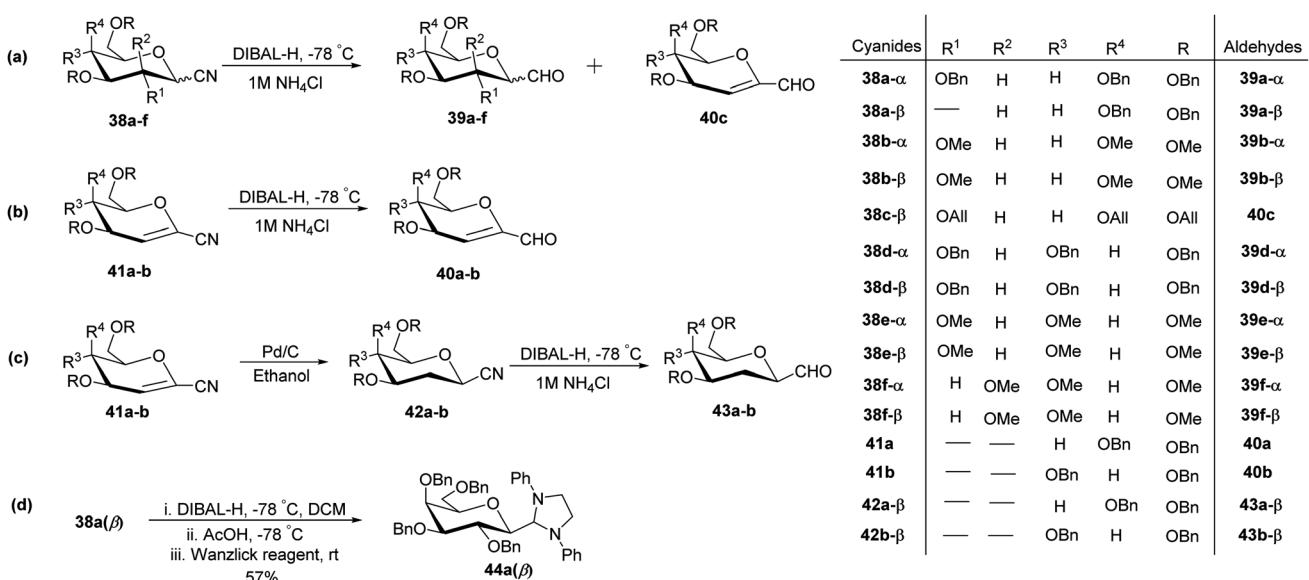
#### 2.4 Cyanide approach

In the dithiane approach, both cyclic and acyclic 1,3-dithiane were used, and it was observed that the acyclic dithiane could be easily removed in the last step for the synthesis of desired *C*-glycopyranosyl aldehydes. The cyclic 1,3-dithiane removal consists of a lower yield and has a longer reaction time along with the recovery of the starting material. Therefore, Sipos *et al.*<sup>34</sup> introduced a new approach to synthesise  $\beta$ -*C*-glycopyranosyl aldehyde by reductive hydrolysis of *C*-glycosyl cyanides. All glycosyl cyanides (38a–f) except 38c( $\beta$ ) were transformed into the expected aldehydes (39a–f) on direct treatment with DIBAL-H in ammonium chloride at  $-78^\circ\text{C}$ . On the other hand, 1-*C*-formyl glycal product 40c was formed from galactosyl cyanide (38c( $\beta$ )) (Scheme 12a). Similarly, the benzylated glycalnitriles 41a–b were reduced using DIBAL-H under the same reaction conditions to afford 2-deoxy glycopyranosyl aldehyde derivatives 40a–b, which were observed to be very stable (Scheme 12b). The corresponding reaction was

carried out by taking the same precursors 41a–b where reduction using Pd/C in ethanol resulted in the formation of 2-deoxy- $\beta$ -*C*-glycopyranosyl cyanides 42a–b, which on further reduction with DIBAL-H in ammonium chloride at  $-78^\circ\text{C}$  afforded  $\beta$ -*C*-glycopyranosyl aldehydes 43a–b (Scheme 12c). While compounds 40a–c and 43a–b were found to be very stable and could be stored, compounds 39a–f in the case of *gluco*-, *manno*- and *galacto*-derivatives were very sensitive to the elimination of 2-alkoxy group and a one pot strategy was developed to store them (Scheme 12d). In this process, 38a( $\beta$ ) was treated with DIBAL-H at  $-78^\circ\text{C}$  and excess hydride was quenched with acetic acid after 30 min followed by the addition of Wanzlick's reagent to afford 44a( $\beta$ ) in 57% yield.

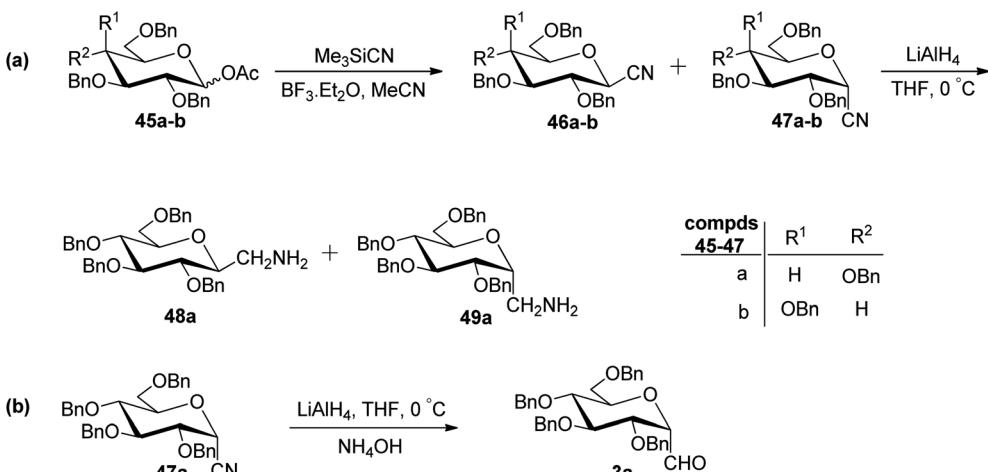
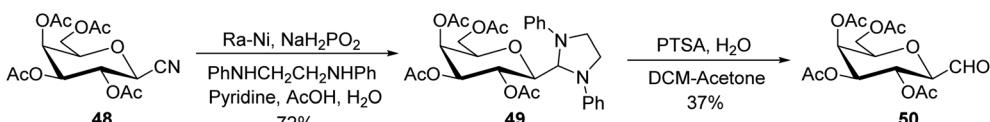
Lopez *et al.*<sup>35</sup> reported the synthesis of  $\alpha$ -*C*-glucopyranosyl aldehyde *via* sugar cyanide as a key intermediate. Here, 1-*O*-acetyl-2,3,4,6-tetra-*O*-benzyl-*D*-glycopyranose 45a–b on reaction with trimethylsilyl cyanide and boron trifluoride etherate in acetonitrile afforded anomeric mixture of  $\beta$ - and  $\alpha$ -glycopyranosyl cyanide 46a–b and 47a–b in 80–90% yield, which could be separated by column chromatography. Further, the reaction of glucopyranosyl cyanide 46a and 47a with lithium aluminium hydride in THF produced 1-amino-2,6-anhydro-3,4,5,7-tetra-*O*-benzyl-1-deoxy-*D*-glycero-*D*-gulo-heptitol 48a and 1-amino-2,6-anhydro-3,4,5,7-tetra-*O*-benzyl-1-deoxy-*D*-glycero-*D*-ido-heptitol 49a (Scheme 13a). *C*-Glucopyranosyl aldehyde 3a was obtained by direct reduction of  $\alpha$ -glucopyranosyl cyanide 47a with lithium aluminium hydride in THF followed by hydrolysis with ammonium hydroxide (Scheme 13b).

Dettinger *et al.*<sup>36</sup> designed a protocol for the synthesis of  $\beta$ -*C*-galactopyranosyl aldehyde 50 by a series of reactions starting from 2,3,4,6-tetra-*O*-acetyl-*D*-galactopyranosyl cyanide 48. Acetyl-protected cyanide 48 underwent a reduction in the presence of RANEY®-Nickel followed by protection with *N,N*-diphenylethylenediamine in pyridine to yield 49 in 72% yield. Subsequently, compound 49 on treatment with



Scheme 12 Synthesis of *C*-glycopyranosyl aldehydes 39a–f, 40a–c, 43a–b.



Scheme 13 Synthesis of  $\alpha$ -C-glycopyranosyl aldehyde 3a.Scheme 14 Synthesis of  $\beta$ -C-galactopyranosyl aldehyde 50.

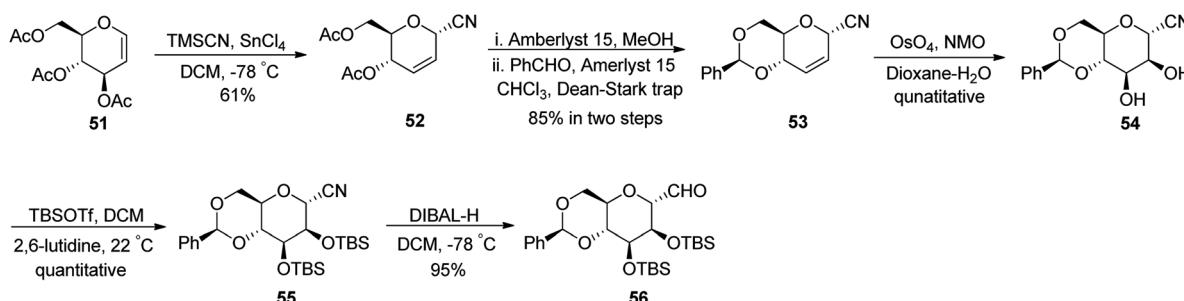
PTSA in DCM-acetone afforded  $\beta$ -C-galactopyranosyl aldehyde 50 in just 37% yield (Scheme 14).

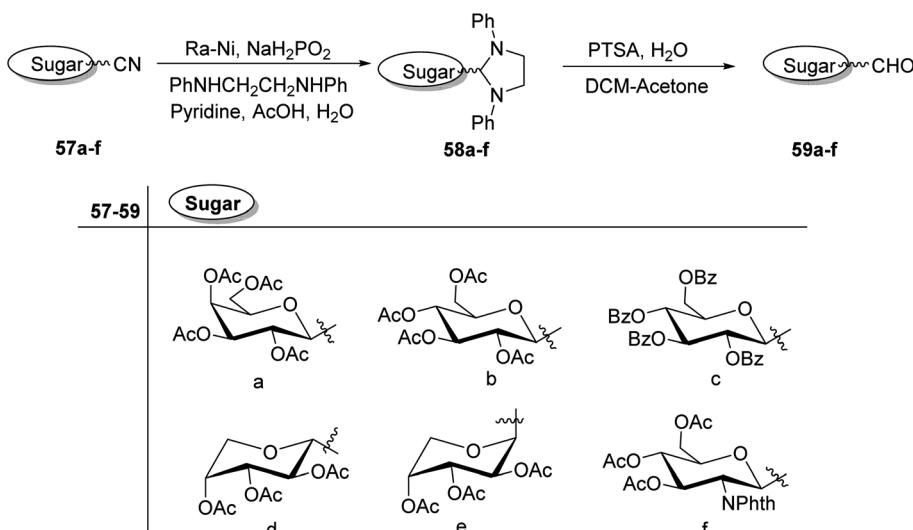
Fujiwara *et al.*<sup>37</sup> synthesised  $\beta$ -C-glycopyranosyl aldehyde starting from tri-O-acetyl-D-glucal (Scheme 15). Acetyl-protected D-glucal 51 was converted into 52 by treatment with TMSCN, SnCl<sub>4</sub> in DCM at  $-78^\circ\text{C}$  in 61% yield, which transformed into benzylidene-protected compound 53 by using solid support acid (Amberlyst 15) in methanol followed by benzaldehyde in chloroform, which was refluxed using Dean-Stark apparatus to afford benzylidene protection. The yield obtained in two steps was 85%. Alkene 53 underwent dihydroxylation by treatment with osmium tetroxide, NMO in dioxane-water to furnish diol 54 in quantitative yield. Silyl protection was carried out using TBSOTf in the presence of 2,6-lutidine in DCM to afford protected cyanide 55 quantitatively, which was further subjected to DIBAL-treatment to furnish benzylidene-protected pyranosyl aldehyde 56 in 95% yield.

C-Glycopyranosyl aldehydes from cyanide precursors were also obtained by Toth *et al.*<sup>38</sup> using Dettinger *et al.*<sup>36</sup> protocol where reduction of glycosyl cyanides 57a-f was achieved by RANEY® nickel and sodium hypophosphite in pyridine-aqueous acetic acid in the presence of *N,N*-diphenylethylenediamine to obtain imidazolidine derivatives 58a-f. Further, by using PTSA in DCM-acetone under acidic reaction conditions C-glycopyranosyl aldehydes 59a-f were obtained (Scheme 16). Further, the synthesized C-glycopyranosyl aldehydes 59a-f were used for the synthesis of *exo*-glycals.

## 2.5 Enoxysilane approach

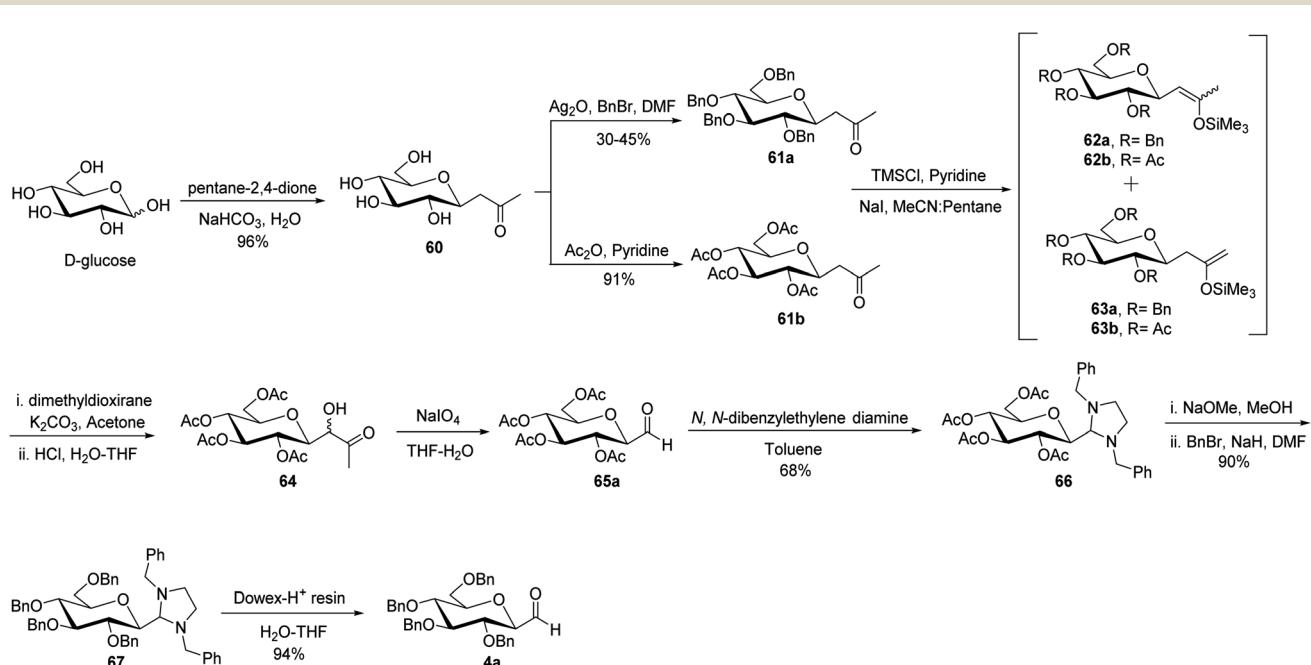
The cyanide approach furnished the desired C-glycopyranosyl aldehyde in just one step, *i.e.* protection of the cyanide group with *N,N*-diphenylethylenediamine in pyridine followed by treatment with PTSA and direct reduction of cyanide using reducing agents DIBAL-H or LiAlH<sub>4</sub>. However, the increased

Scheme 15 Synthesis of  $\alpha$ -C-glycopyranosyl aldehyde 56.

Scheme 16 Synthesis of  $\beta$ -C-glycopyranosyl aldehydes 59a–f.

interest in the synthesis of  $\beta$ -C-glycopyranosyl aldehydes due to their demanding application as intermediates in the formation of various complex C-glycosides led Zeitouni *et al.*<sup>39</sup> to introduce a new synthetic approach using enoxysilanes as a key intermediate. In this approach, the  $\beta$ -D-glucosidic ketone **60** was synthesised from D-glucose in 96% yield using pentane-2,4-dione. Next, compound **60** was subjected to benzylation (reagents:  $\text{Ag}_2\text{O}$ ,  $\text{BnBr}$  in DMF) and acetylation (reagents:  $\text{Ac}_2\text{O}$  in pyridine) individually yielding **61a** and **61b** with a yield of 30–45% and 91%, respectively, which on enolization using  $\text{TMSCl}$  in pyridine formed structural isomers **62a** and **63a** (from **61a**) and similarly, compounds **62b** from

**61b**. However, better regioselectivity was observed for compound **61b** as compared to compound **61a**. It has been observed that it was difficult to perform benzylation with the classical benzylation process ( $\text{NaH}$ , benzyl bromide, DMF) as compounds had ketone functional group present in the molecule, which further resulted in non-regioselective enolisation of compound **61a**. Subsequently, the scheme further proceeded with the reaction of enoxysilane **62b** with a freshly prepared solution of dimethyldioxirane (DMDO) to yield  $\alpha$ -hydroxy ketone **64**, which on further treatment with sodium metaperiodate in THF–water produced desired  $\beta$ -C-glycopyranosyl aldehyde **65a**. Compound **65a** turned out to be

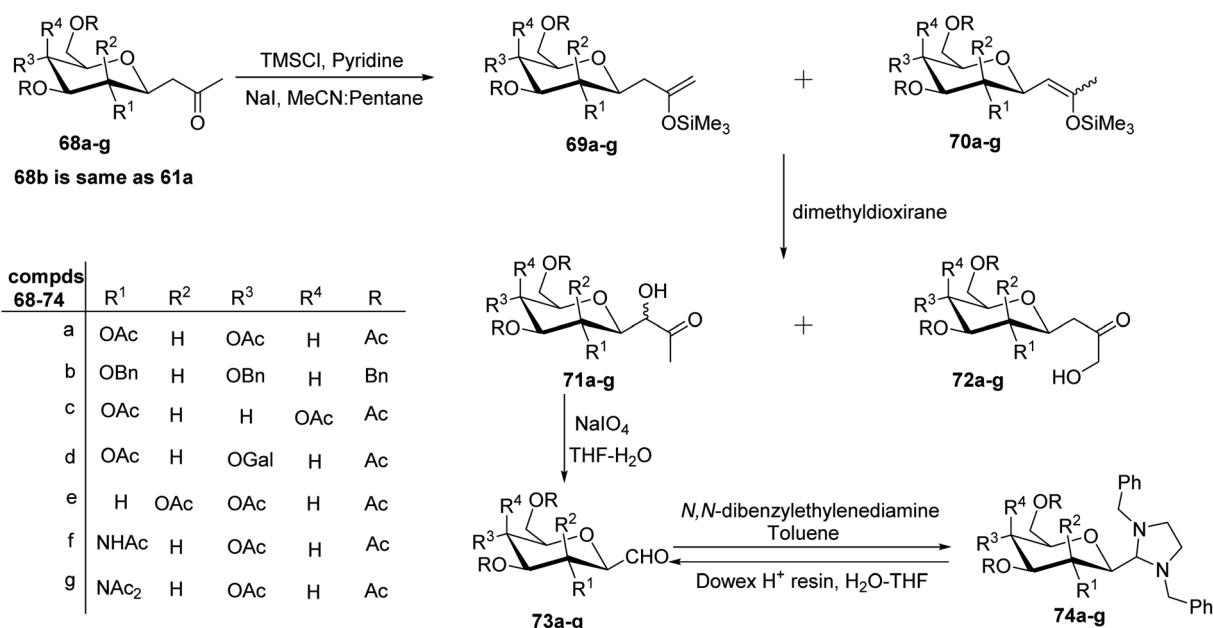
Scheme 17 Synthesis of  $\beta$ -C-glucopyranosyl aldehydes **65a** and **4a**.

unstable and less pure, so it was stored as aminal **66** using *N,N*-dibenzylethylene diamine in toluene. Compound **66** obtained in a yield of 68% was in turn benzylated to give **67** in a yield of 90%. On the deprotection of compound **67** with Dowex-H<sup>+</sup> resin quantitatively led to the formation of extremely pure  $\beta$ -C-glycopyranosyl aldehyde **4a** with a yield of 94% (Scheme 17).

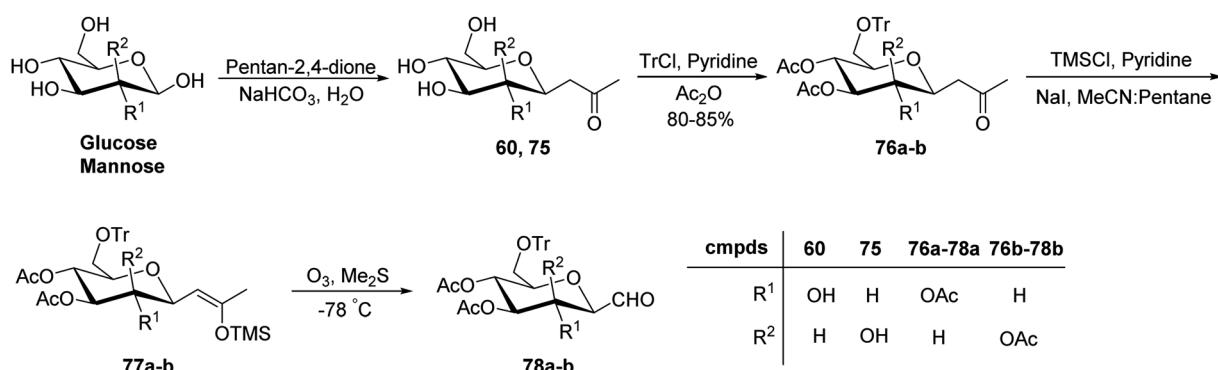
Later, Norsikian *et al.*<sup>40</sup> applied this effective approach to introduce the formyl group at the anomeric position of other sugar precursors and reported it to be very efficient for all sugars except D-mannose.  $\beta$ -C-Glycosyl ketones **68a–g** were treated with trimethylsilyl chloride in pyridine followed by sodium iodide in acetonitrile to afford enolized products **69a–g** and **70a–g**. The enoxysilanes thus produced were subjected to oxidation with DMDO, which produced  $\alpha$ -hydroxy ketones **71a–g** as major products. Further,  $\alpha$ -hydroxy ketones **71a–g** on treatment with sodium metaperiodate in THF–water gave the desired  $\beta$ -C-glycopyranosyl aldehydes **73a–g**. Due to the less

stability of  $\beta$ -C-glycopyranosyl aldehydes and with an aim to achieve a more pure form of it, they were stored as aminal **74a–g**, which on deprotection with Dowex-H<sup>+</sup> resin yielded the purest forms of  $\beta$ -C-glycopyranosyl aldehydes **73a–g** (Scheme 18).

Xia *et al.*<sup>41</sup> reported synthesis of L-glucose and L-galactose starting from D-glucose and D-mannose, respectively. In this synthesis, C-glycopyranosyl aldehyde was achieved as an intermediate, which was further converted into L-glucose and L-galactose sugars (Section 3.8, Scheme 81). Thus, both sugars, *i.e.* D-glucose and D-mannose were treated with pentan-2,4-dione, sodium bicarbonate in water to afford ketones **60** and **75**, respectively. The primary hydroxyl group was selectively protected with trityl chloride followed by acetylation of the secondary hydroxyl group to afford **76a–b** in 80–85% yield. Further, the Norsikian<sup>40</sup> condition was applied on ketone **76a–b** to produce silyl enol ether **77a–b**, which upon ozonolysis furnished C-glycopyranosyl aldehyde **78a–b** (Scheme 19).



Scheme 18 Synthesis of  $\beta$ -C-glycopyranosyl aldehydes **73a–g**.



Scheme 19 Synthesis of C-glycopyranosyl aldehydes **78a–b**.

## 2.6. Alkene approach

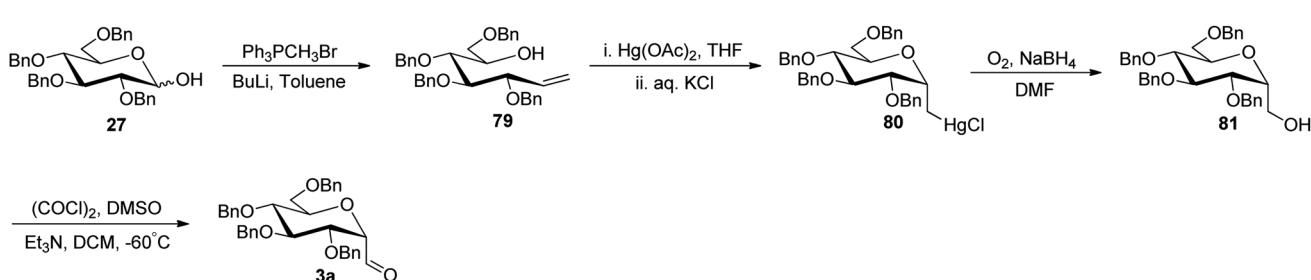
The approaches using allene and thiazole ring as a masked formyl group were low yielding and in addition, the thiazole deprotection involved a lengthy process. Besides, enoxysilane approach incriminated difficult synthesis of benzylated glycopyranosyl aldehydes due to by-product formation during DMDO treatment and the use of DMDO, which made this synthetic procedure cumbersome. Dietrich *et al.*<sup>42</sup> utilized Wittig reaction conditions to carry out a reaction between commercially available 2,3,4,6-tetra-*O*-benzyl-*D*-glucopyranose (27) and methylenetriphenylphosphorane to afford alkene 79 following the reported procedure.<sup>43</sup> Further, mercury-mediated cyclisation of compound 79 afforded oxymercuration product 80 with the known procedure.<sup>44</sup> Then, oxidative demercuration of 80 using  $O_2$ -NaBH<sub>4</sub> produced alcohol 81,<sup>45</sup> which was subjected to Swern oxidation to afford  $\alpha$ -C-glycopyranosyl aldehyde 3a (Scheme 20). The obtained compound 3a was found to be very labile and immediately used for the synthesis of benzyl- $\alpha$ -C-glucosides and anilinomethyl- $\alpha$ -C-glucosides, which act as  $\alpha$ -glucosidase inhibitors (Section 3.5, Scheme 62).

Sanchez *et al.*<sup>31</sup> introduced the sugar alkene as a key synthetic intermediate, which was obtained *via* nucleophilic addition and reductive dehydroxylation. This approach provided the stereochemical control during reductive dehydroxylation, before unmasking of the formyl group, unlike allene and thiazole approaches where both  $\alpha$ - and  $\beta$ -isomer were formed. Sugar lactone 12 on treatment with phenyl-acetyllyllithium at  $-78^\circ\text{C}$  gave a diastereomeric mixture (1 : 1) of lactol 82 in 84% yield, which furnished single isomer  $\beta$ -C-glycoside 83 in 88% yield after stereoselective removal of the hydroxyl group by triethylsilane in the presence of Lewis acid.

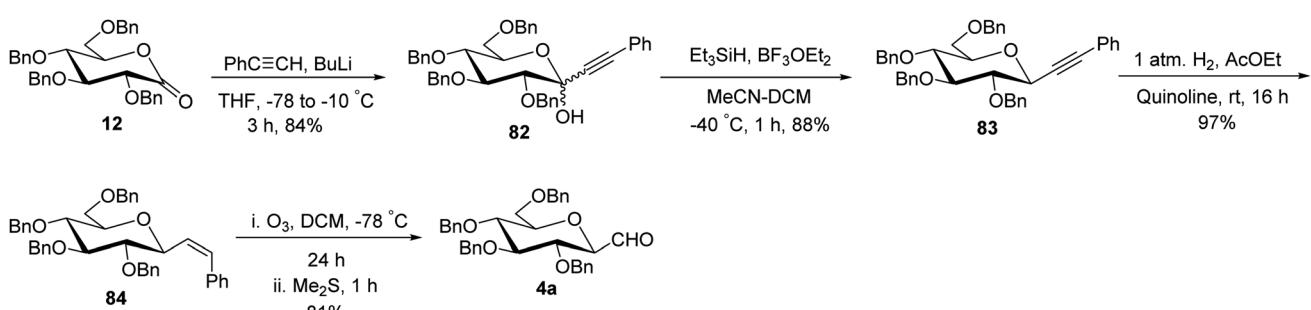
After the stereoselectivity was achieved, Lindlar's catalyst was used in the presence of quinoline for hydrogenation, resulting in *cis*-alkene 84 in 97% yield. Further, alkene 84 was subjected to ozonolysis to afford exclusively  $\beta$ -C-glycopyranosyl aldehyde 4a in 81% yield (Scheme 21).

Leclerc *et al.*<sup>46</sup> prepared the  $\alpha$ -C-glycopyranosyl aldehyde 90 from easily available galactosyl bromide 85. Galactosyl bromide 85 undergoes allylation in the presence of allyltributylstannane and Et<sub>3</sub>B/air and yielded  $\alpha$ -C-allyl galactose derivative 86 in 70% yield and a trace amount, *i.e.* 6% of compound 87 resulting from *in situ* acyl migration. Terminal alkene 86 in the presence of a catalyst (Ph<sub>2</sub>MeP)<sub>2</sub>Ir(COD)PF<sub>6</sub> isomerised into internal alkene 2-propenyl derivative 88 using the designed protocol.<sup>47</sup> Initial attempts to produce desired *C*-glycopyranosyl aldehyde from acetyl-protected alkene 88 failed, so deprotection of acetate of compound 88 with K<sub>2</sub>CO<sub>3</sub> in methanol followed by protection with iso-propylidene using 2-methoxypropane, TsOH in DMF afforded compound 89 in 75% yield, which on ozonolysis yielded  $\alpha$ -C-glycopyranosyl aldehyde 90 in good yield (Scheme 22).

Chen *et al.*<sup>48</sup> incorporated easily and readily available starting material galactosyl pentaacetate 5. The galactosyl pentaacetate 5 was subjected to allylation at the anomeric position in the presence of allyl trimethylsilane in BF<sub>3</sub>·Et<sub>2</sub>O to afford compound 86 in 77% yield, which next underwent de-protection in the presence of sodium methoxide in methanol followed by benzyl protection in the presence of BnBr led to the formation of compound 91 in 93% yield. Palladium-mediated isomerisation of the terminal alkene of compound 91 was performed into internal sugar alkene 92 with a 90% yield. Subsequently, compound 92 on ozonolysis followed by *in situ* reduction and

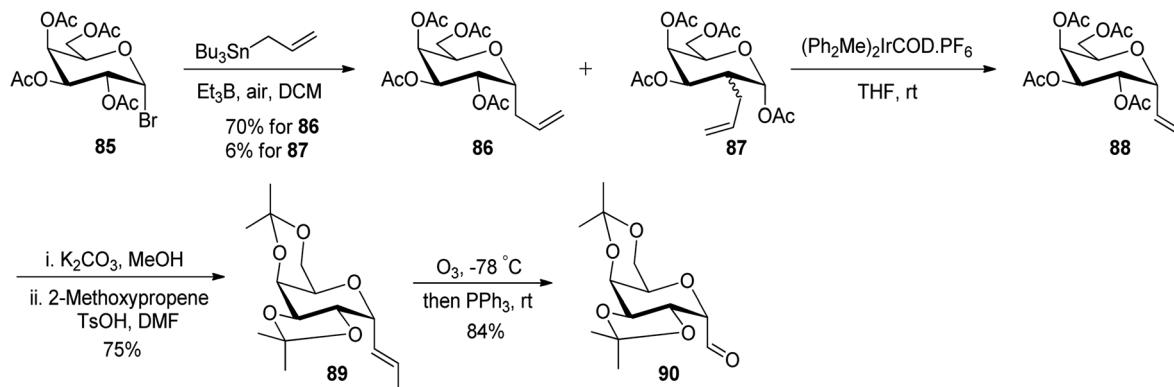
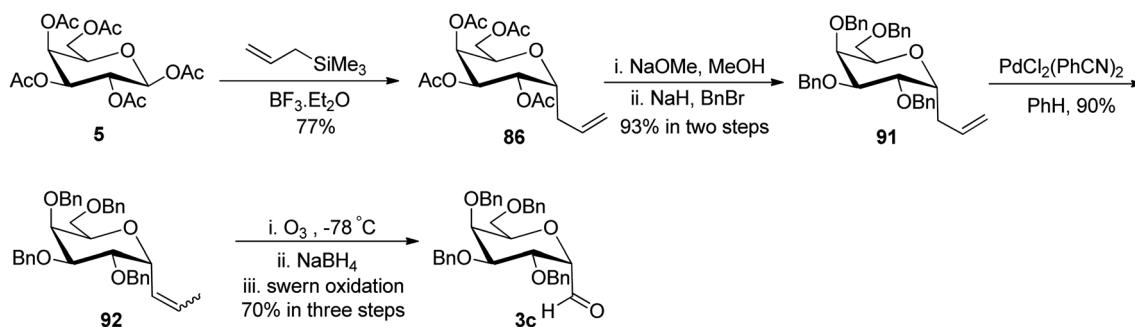


Scheme 20 Synthesis of  $\alpha$ -C-glycopyranosyl aldehyde 3a.



Scheme 21 Synthesis of  $\alpha$ -C-glycopyranosyl aldehyde 4a.



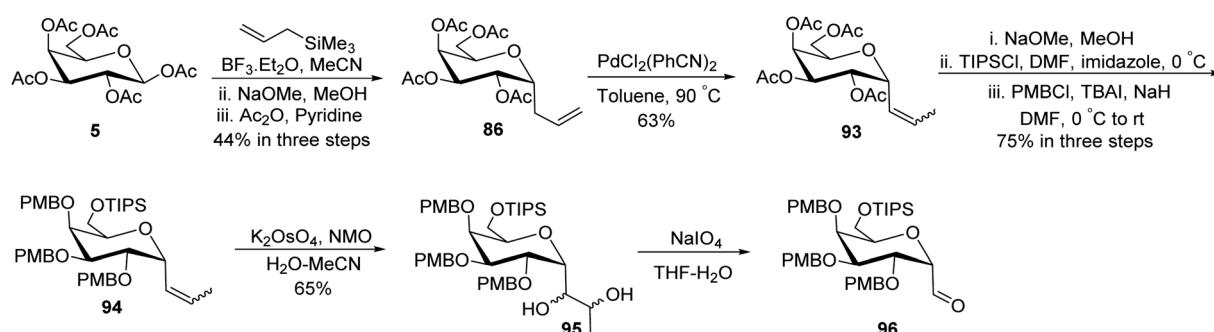
Scheme 22 Synthesis of  $\alpha$ -C-glycopyranosyl aldehyde **90**.Scheme 23 Synthesis of  $\alpha$ -C-galactopyranosyl aldehyde **3c**.

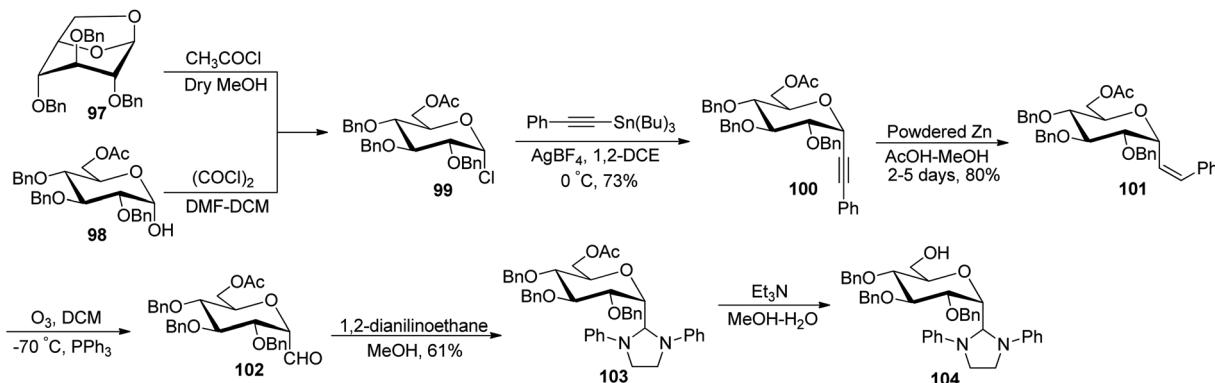
further treatment with Swern oxidation resulted in the formation of  $\alpha$ -C-galactopyranosyl aldehyde (Scheme 23).

Guillaume *et al.*<sup>27</sup> designed a strategy to synthesise  $\alpha$ -C-galactopyranosyl aldehyde **96** using galactosyl pentaacetate **5**, which is a readily available starting material. The C-glycosylation of compound **5** was performed with allyl trimethylsilane using conditions of Chen *et al.*<sup>48</sup> to afford terminal sugar alkene **86** in 44% yield, which on palladium catalysed double bond isomerisation resulted in propene **93** in 63% yield. Compound **93** upon Zemplen deacetylation with sodium methoxide in methanol followed by selective protection of primary alcohol with tri-isopropylsilyl ether and secondary alcohol were masked in the presence of  $\text{PMBCl}$  to obtain compound **94** in 75% yield.

Alkene **94** on osmium-catalysed dihydroxylation resulted in vicinal diol **95**, which underwent further reaction with sodium periodate resulting  $\alpha$ -C-galactopyranosyl aldehyde **96** (Scheme 24), which was further utilized for the synthesis of C6-modified  $\alpha$ -C-GalCer analogues.

Desire *et al.*<sup>49</sup> reported synthesis of  $\alpha$ -C-glucopyranosyl aldehyde *via* alkene as a key intermediate (Scheme 25). 6-O-Acetyl-2,3,4-tri-O-benzyl- $\alpha$ -D-glucopyranosyl chloride (**99**) was synthesised by ring opening of 1,6-anhydro-2,3,4-tri-O-benzyl- $\beta$ -D-glucopyranose (**97**) or from 6-O-acetyl-2,3,4-tri-O-benzyl-D-glucopyranose (**98**) by following reported literature.<sup>50</sup> Further treatment of compound **99** with tributyl(phenylethynyl)tin in the presence of silver tetrafluoroborate in 1,2-dichloroethane at

Scheme 24 Synthesis of  $\alpha$ -C-galactopyranosyl aldehyde **96**.

Scheme 25 Synthesis of  $\alpha$ -C-glucopyranosyl aldehyde 102.

0 °C produced selectively ( $\alpha$ -D-glucopyranosyl) phenylacetylene **100** in 73% yield. Hydrogenation of compound **100** was carried out by using powdered zinc in AcOH–MeOH for a long time of 2–5 days to give Z-alkene **101** in 80% yield, which underwent ozonolysis to afford  $\alpha$ -C-glucopyranosyl aldehyde **102**, which was found to be prone to decomposition; therefore, it was masked by *N,N'*-diphenylethylenediamine as stable 1,3-diphenylimidazolidines **103** with 61% yield and could be regenerated by mild acidic treatment. Deacetylation was achieved using triethylamine in methanol–water to afford **104**.

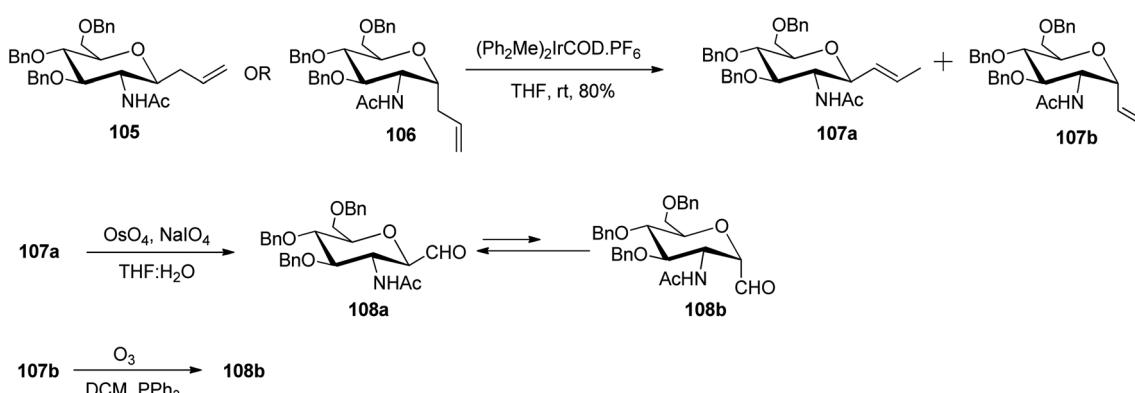
Among the other alkene approaches, the metal-catalysed isomerisation of allyl species was also achieved by McGarvey *et al.*<sup>51</sup> where the benzyl protected  $\beta$ -isomer, **105** and the  $\alpha$ -isomer, **106** on exposure to iridium catalyst,  $(\text{Ph}_2\text{Me})_2\text{IrCOD}\cdot\text{PF}_6$  (10 mol%) yielded isomeric vinyl glycosides **107a** and **107b** in 80% yield. These isomeric vinyl glycosides further gave  $\beta$ - and  $\alpha$ -linked C-glycopyranosyl aldehydes, where the  $\beta$ -linked isomer was the major product. Substrate **107b** upon ozonolysis gave the desired **108b** isomer with >90% yield. Similarly, compound **107a** underwent oxidative cleavage using Lemieux reaction conditions yielding **108a** analogue. The aldehydes **108a** and **108b** thus obtained acted as intermediates for various further syntheses (Scheme 26).

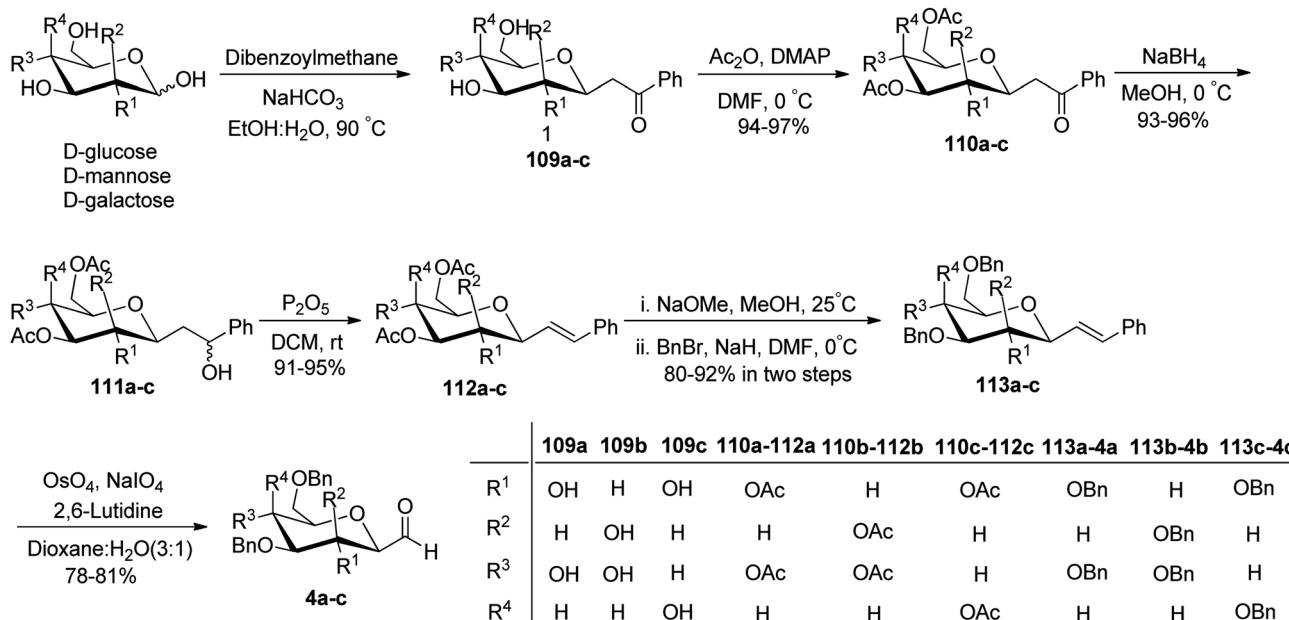
Khatri *et al.*<sup>52</sup> reported another synthesis of stereoselective  $\beta$ -linked C-glycopyranosyl aldehyde *via* an alkene approach using

easily available precursors *i.e.*, D-galactose, D-glucose, and D-mannose. The native sugars were treated under a developed procedure,<sup>53</sup> *i.e.* reaction with dibenzoylmethane–sodium bicarbonate in aqueous alcoholic solution gave  $\beta$ -C-glycosyl benzoylmethane **109a–c**, which further reacted with acetic anhydride–DMAP in DMF yielding the peracetylated derivatives of  $\beta$ -C-glycosyl benzoylmethane **110a–c** in 94–97% yield. Compounds **110a–c** upon reduction with NaBH<sub>4</sub> gave corresponding alcohols **111a–c** in 93–96% yield, which was followed by dehydration reaction with dehydrating reagent P<sub>2</sub>O<sub>5</sub> in dichloromethane to obtain alkene derivatives **112a–c** in 91–95% yield. The peracetylated C-glycosides **112a–c** were converted to the corresponding perbenzylated sugar alkene **113a–c** since the former gave very unstable products on oxidation. Hence, **112a–c** were firstly deacetylated using sodium methoxide followed by perbenzylation using benzyl bromide in NaH to obtain the perbenzylated sugar alkene **113a–c** in 80–92% yield. These perbenzylated analogues **113a–c** upon oxidation with OsO<sub>4</sub>–NaIO<sub>4</sub> resulted in  $\beta$ -C-glycopyranosyl aldehydes **4a–c** in 78–81% yield (Scheme 27).

## 2.7 Nitromethane approach

In the above-discussed approaches, the alkene approach was found to be most efficient in respect of overall yield obtained and selectivity due to the formation of only one anomeric

Scheme 26 Synthesis of C-glycopyranosyl aldehydes **108a–b**.

Scheme 27 Synthesis of  $\beta$ -C-glycopyranosyl aldehydes 4a-c.

isomer of *C*-glycopyranosyl aldehydes. Moreover, the synthetic routes consisted of cheap and easily available starting materials. Now we are moving towards the end of approaches developed for the synthesis of *C*-glycopyranosyl aldehydes and at last we are discussing nitromethane as a key synthetic intermediate. So, Martin *et al.*<sup>54</sup> developed a synthetic route for the synthesis of the  $\beta$ -*C*-glycopyranosyl aldehyde 65a starting from  $\beta$ -D-glucosylnitromethane 114, which in turn can be synthesized from readily available D-glucose following two steps.<sup>55</sup> The  $\beta$ -D-glucosylnitromethane 114 on reaction with *tert*-butyldimethylsilyl chloride, DBU in DCM, yielded the silyl nitronate derivative 115 in 95% yield, which on ozonolysis afforded the 2,3,4,6-tetra-*O*-acetyl- $\beta$ -*C*-glucopyranosyl aldehyde 65a (Scheme 28).

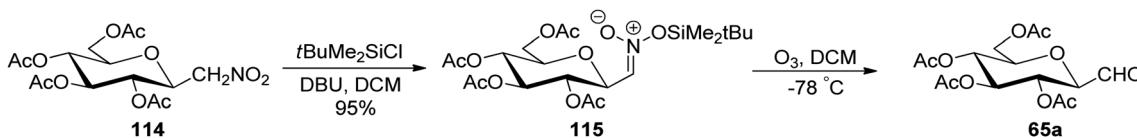
Simo *et al.*<sup>56</sup> achieved the synthesis of *C*-glycopyranosyl aldehyde starting from nitromethane sugar precursor (Scheme 29). Here, *C*-(4,6-*O*-benzylidene- $\beta$ -D-glucopyranosyl) nitromethane (116) was reduced to hydroxylamino derivative 117 using  $H_2$ , Lindlar catalyst in methanol which was difficult to isolate and directly oxidised in the air under basic condition ( $NH_4OH$ ) to obtain *cis-trans* mixture of oxime 118 in 70% yield. The oxime 118 reacted with  $H_2$  in the presence of RANEY® nickel affording the dimeric aminal 119 in 79%, which on reaction with 1,2-dianilinoethane (Wanzlick base) produced imidazolidine 120 in 90% yield. Acetylation was carried out using acetic anhydride in pyridine to afford 121, which was

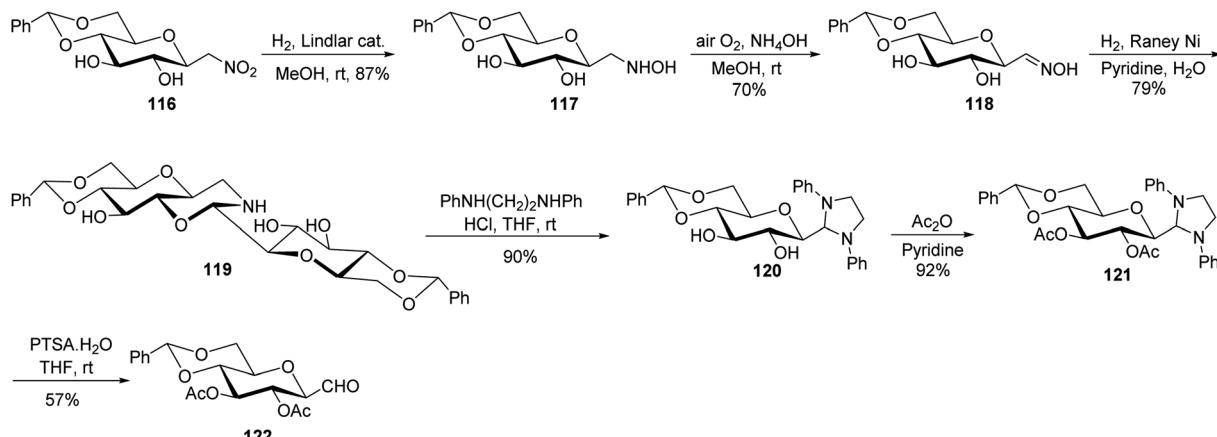
hydrolysed by *p*-toluenesulfonic acid monohydrate in dry THF to furnish *C*-glycopyranosyl aldehyde 122 in 57% yield.

Petrusova *et al.*<sup>57</sup> designed a one-step protocol for the synthesis of  $\beta$ -*C*-glycopyranosyl aldehydes from  $\beta$ -D-glucosylnitromethane (Scheme 30). 2,6-Anhydro-7-deoxy-7-nitro-*L*-glycero-*L*-galacto-heptitol 123a-d treated with an aqueous alkaline solution followed by ozonolysis at room temperature to give  $\beta$ -*C*-glycopyranosyl aldehydes 124a-d. It was observed that in an aqueous solution, the compound 124a-d exists in its hydrate form predominantly. Thus, the resulting native *C*-glycopyranosyl aldehydes 124a-d were found very much labile and were used further for the synthesis of 2- $\beta$ -D-glycopyranosyl-nitroethenes and -nitroethanes (Section 3.8, Scheme 82).

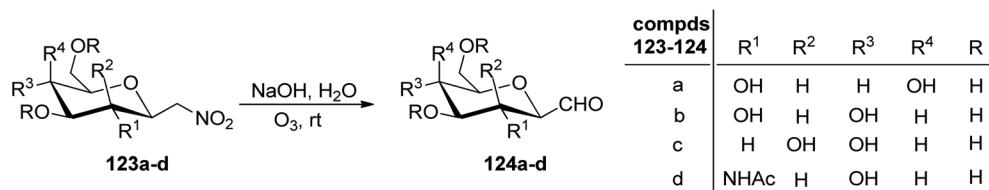
### 3. Synthesis of *C*-glycoconjugates

The availability of numerous methods to bring diversity in the formation of aldehyde at the anomeric position of sugar benefited the development of *C*-galactosphingo lipid analogues, *C*-glycopyranosyl disaccharides, *C*-glycopyranosyl amino acid precursors, *C*-glycopyranosyl-amino acids and dipeptides, glycopyranosyl phenyl methane and its fluoro derivatives, *C*-glycopyranosyl heterocycles, glycopyranosyl bis-amides, several natural product fragments, and many other *C*-linked glycoconjugates. Some of them play important roles in biological systems, for instance, glycoconjugate 125 is a potent inhibitor of

Scheme 28 Synthesis of  $\beta$ -C-glucopyranosyl aldehyde 65a.



Scheme 29 Synthesis of C-glycopyranosyl aldehyde 122.



Scheme 30 Synthesis of β-C-glycopyranosyl aldehydes 2a-d.

ice recrystallization and could protect embryonic liver cells from cryo-injury;<sup>46</sup> the acyl- and benzyl-C- $\beta$ -D-glucosides (126 and 127) work as glucose uptake promotor;<sup>58</sup> C-mannosides analogues (128a-b) block uropathogenic *Escherichia coli* from colonizing the lower urinary tract;<sup>59</sup> C-glycosides 129a-c were determined by ELISA of a blood sample obtained from mice stimulated by a 1  $\mu$ g injection of glycolipid in the buffer. It was found that *E*-isomer 129b is superior to *Z*-isomer 129c as a ligand for CD1d/NKT immunity pathway;<sup>48</sup> C-linked galactosphingo lipid analogue (130) blocks the interaction of HIV-1 gp120 with GalCer;<sup>60</sup> C-linked disaccharide analogue (131a) of TF epitope induces a strong immune response in mice, which imparts it a possibility to be developed as a therapeutic vaccine;<sup>61</sup> C-linked disaccharide (132a) mimics *O*- $\beta$ -D-galactopyranosyl-(1-3)-D-galactopyranosides and proved to be a suitable agent for *O*-glycosidation and construction of glycoconjugates;<sup>62</sup> carbohydrate amino acids mimetic (133) shows *in vivo* stability towards  $\alpha$ -galactosidase enzyme and might function as glycosidase inhibitor (Fig. 4).<sup>25</sup> Henceforth, we describe the following synthetic processes for the development of structurally diversified and complex C-glycoconjugates.

### 3.1 C-Glycolipid analogues

Bertozzi *et al.*<sup>60</sup> designed a range of water-soluble, C-linked galactosphingo lipid derivatives, which bind specifically to HIV-1 gp120, inhibiting its interaction with CD4 of host cells. The designed compounds have  $\beta$ -linked galactose mimicking galactosyl ceramide (GalCer) antibodies, which inhibit the infection of two CD4-negative neural cell lines. The synthesis of

these C-linked galactosphingo lipids was initiated from  $\beta$ -C-galactopyranosyl aldehyde 4c, which upon condensation with Wittig reagent 134 furnished oxazolidinone 135 in 34% yield. Next, alkene was reduced by tosyl hydrazine and sodium acetate in DME-H<sub>2</sub>O producing compound 136 in 92% yield, which was transformed into compound 137 using the reaction condition of Boc-anhydride/triethylamine in DMF, and further calcium carbonate in methanol. Upon oxidation with Jones reagent, compound 138 was achieved in 95% yield, which was transformed to its amide derivative 139 by reaction with tetradecylamine in the presence of coupling reagent (EDC and HOBr). The deprotection of Boc and benzyloxy group was achieved on treatment with TFA and H<sub>2</sub> in Pd/C to afford C-linked galactosphingo lipid 130 quantitatively (Scheme 31). Similarly, other derivatives 140, 141, 142, and 143 were also synthesized from the condensation of acid derivative 138 and different varieties of amines (Table 3). The introduction of different amines displayed different inhibition range against gp120 GalCer binding at 1 mg mL<sup>-1</sup> as given in Table 3.

It was observed that compound 130 (entry 1) showed the highest affinity for recombinant gp120 at IC<sub>50</sub> = 120  $\mu$ M and slightly better than their *O*-linked glycolipid analogue 143 (entry 5). A decrease in inhibitory activity was observed with a decrease in the length of hydrocarbon.

Guillaume *et al.*<sup>27</sup> designed a strategy to synthesise immunogenic glycolipids due to their importance in the medical field. These have the potential to act as vaccine adjuvants to fight cancer and other microbial infections. One such glycolipid synthesised is  $\alpha$ -GalCer analogues starting from C-



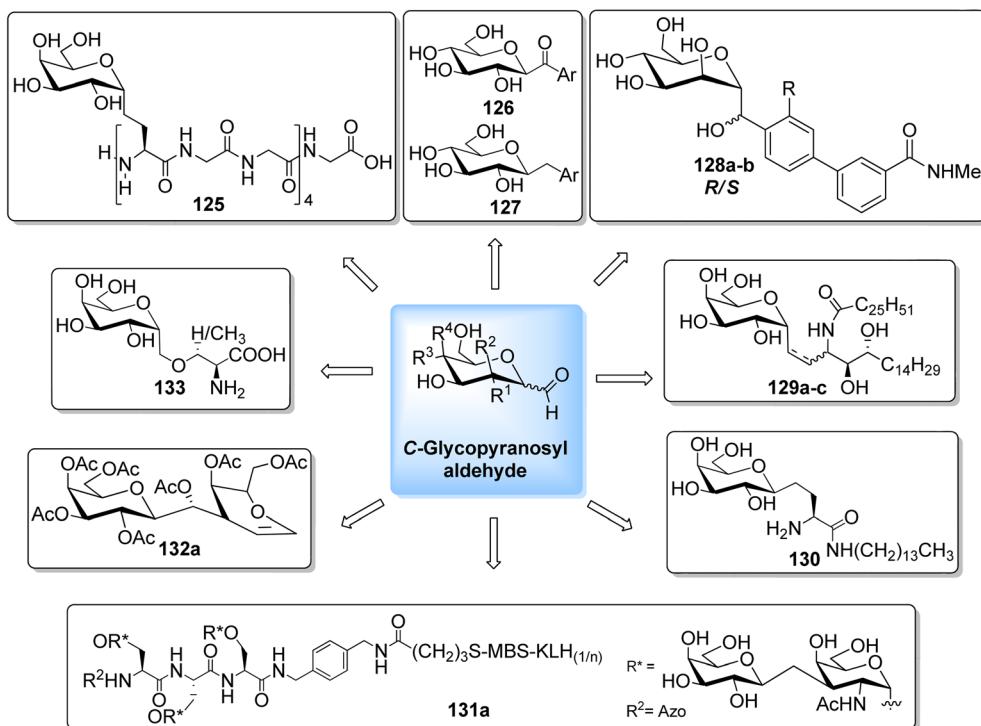
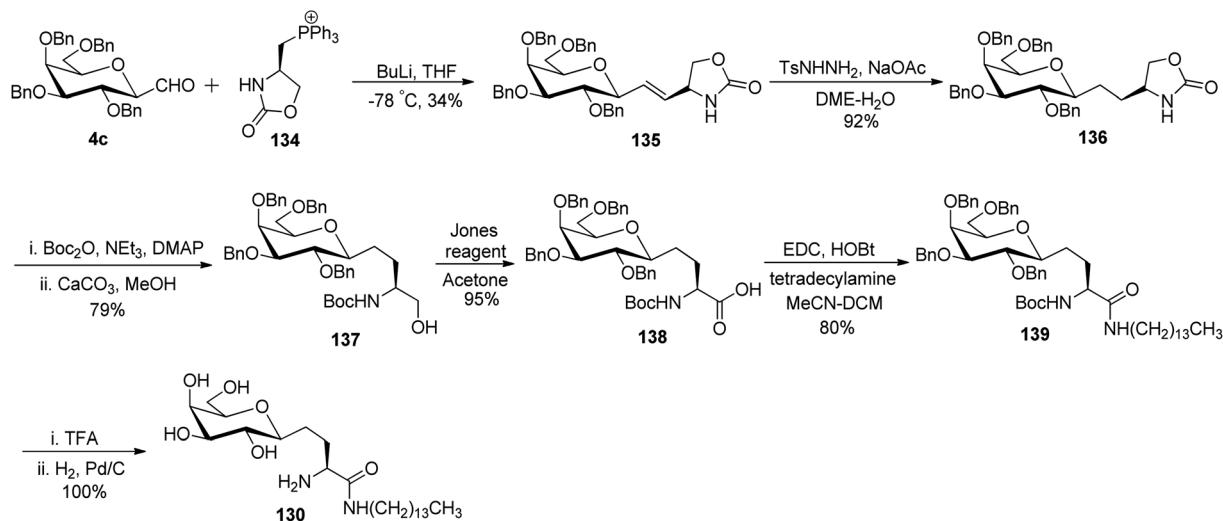


Fig. 4 Structures of various biologically important C-glycoconjugates derived from C-glycopyranosyl aldehyde.



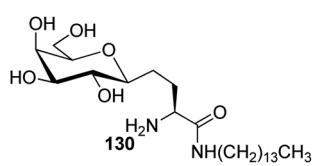
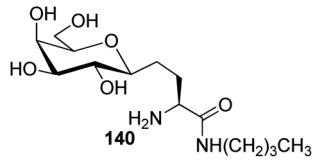
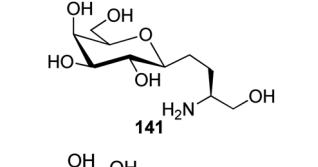
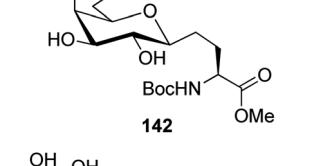
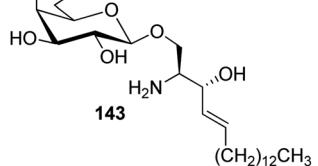
Scheme 31 Synthesis of galactosphingo lipid 130.

galactopyranosyl aldehyde **96** (Scheme 32a). Aldehyde **96** upon Julia–Kocienski olefination with the known benzothiazole **144** yielding inseparable  $\alpha$ - $\beta$  anomers of olefin **145a–b** in just 44% yield. Olefin **145a–b** underwent deprotection of silyl ethers on treatment with tetrabutylammonium fluoride, leading to the separation of both anomers and  $\alpha$ -anomer alcohol **146** in 65% yield was subjected to Mitsunobu reaction with phthalimide to afford compound **147** in 88% yield. This compound **147** on treatment with methylhydrazine did not reduce the double bond, while the same compound on treatment with hydrazine

monohydrate reduced the alkene and liberated free ammonia. Further treatment of both analogues with 1-naphthyl isocyanate furnished corresponding urea derivatives **148** and **150**, in 66% and 77% yields, respectively. Further, deprotection of compounds **148** and **150** was achieved by treatment of 4 M HCl in dioxane after that acylation with cerotoyl chloride in a biphasic mixture of THF and 1 M KOH solution gave  $\alpha$ -C-GalCer derivatives **149** and **151** in 29% yield, respectively.

Further, for the synthesis of  $\alpha$ -GalCer analogues **153** and **156**, the alcohol **146** on treatment with *p*-nitrophenyl chloroformate

Table 3 Different amines displaying different inhibition ranges

Entry	Compounds	% inhibition of 1 mg mL <sup>-1</sup>
1		86 (IC <sub>50</sub> = 120 μM)
2		34
3		0
4		0
5		96 (IC <sub>50</sub> = 160 μM)

followed by the addition of 4-aminopyridine resulted in the 4-pyridylcarbamate intermediate **152** in 62% yield, while the same sequence when followed after the reaction with hydrazine and 1-naphthyl isocyanate afforded 4-pyridylcarbamate intermediate **155**. Both compounds **152** and **155** when treated with HCl followed by acetylation afforded the corresponding pyridinylcarbamate analogues **153** and **156** in 17% and 44% yields, respectively (Scheme 32b).

Chen *et al.*<sup>48</sup> reported the synthesis of *E* and *Z*  $\alpha$ -C-galactosyleceramides using Julia–Lythgoe–Kocienski reaction as the key step between *C*-glycopyranosyl aldehyde **3c** and sulfones **157** or **158** using lithium hexamethyldisilazide (LiHMDS) at  $-78\text{ }^\circ\text{C}$  to afford olefin **159** along with a trace amount of 1-C-formyl glycal (Scheme 33a). Only an *E*-isomer was formed in the case of BT-sulfone while in the case of PYR-sulfone *E/Z* ratio (39 : 61) was obtained. Further, the installation of fatty amide side chain was achieved by treatment of olefin **159** with trifluoro acetic acid (TFA), triethylsilane ( $\text{Et}_3\text{SiH}$ ) in DCM followed by di-isopropyl carbodiimide (DIC), DMAP in butyl alcohol to obtain the precursor of targeted compound **160** in 80% yield. The *trans* isomer in amide **160** could be easily separated from its *cis* counterpart by flash chromatography. Finally, amide **160** was elaborated by either the retention or removal of double bonds. Hydrogenation of the double bond together with debenzylation

was achieved using  $\text{H}_2$ , Pd/C to afford *C*-glycoside **129a** in 80% yield, while unsaturated compounds **129b** and **129c** were prepared in 80% and 84% yield, respectively, by Birch reduction ( $\text{Na}-\text{NH}_3$ ).

IL-12, IFN- $\gamma$  and IL-4 levels of these synthetic *C*-glycosides **129a**, **129b**, and **129c** were determined by ELISA of blood samples obtained from mice stimulated by a  $1\text{ }\mu\text{g}$  injection of glycolipid in the buffer. It was found that *E*-isomer **129b** is superior to *Z*-isomer **129c** as a ligand for the CD1d/NKT immunity pathway.

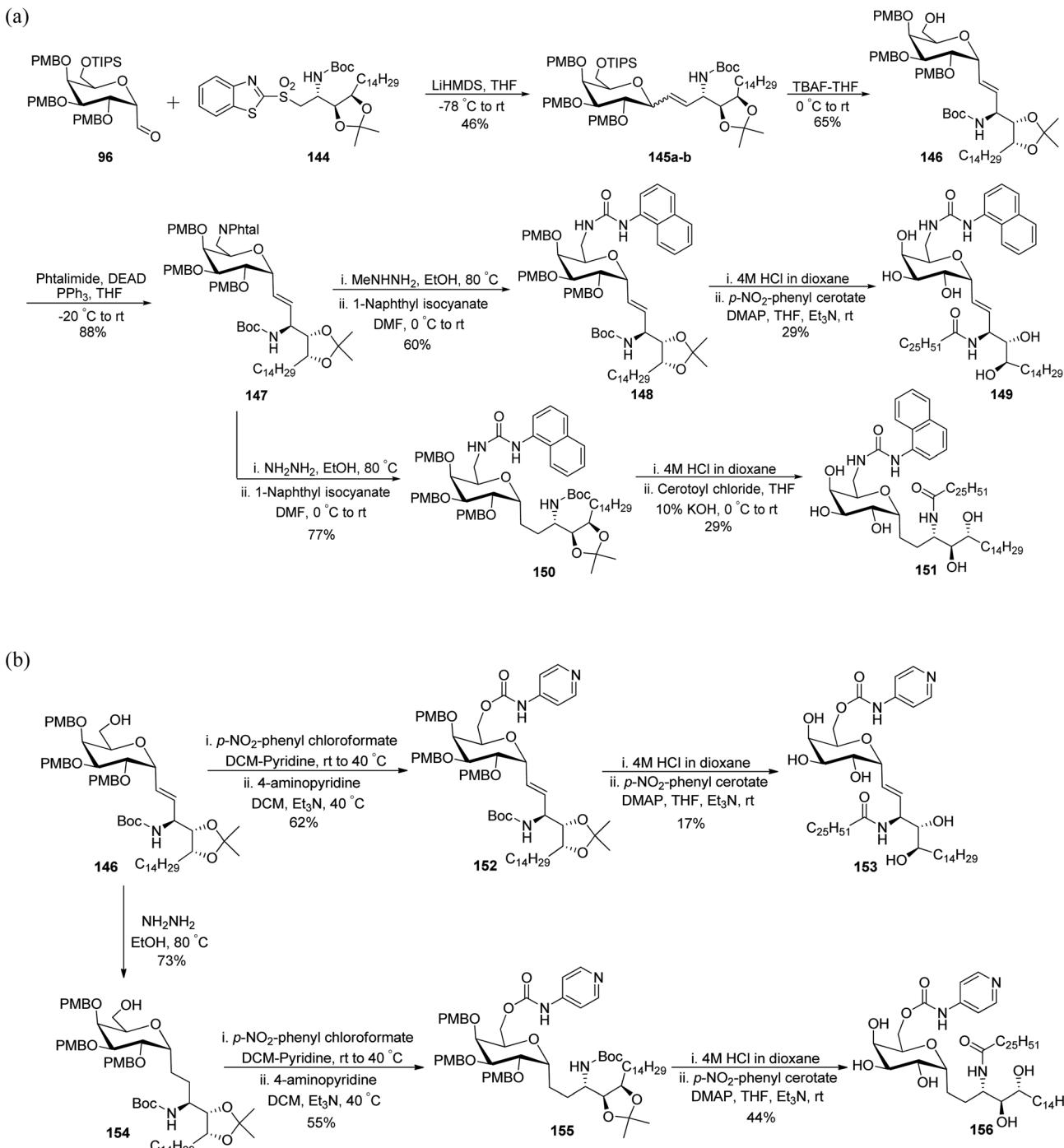
Both sulfones used in the above Julia–Lythgoe–Kocienski reaction were prepared from commercially available phytosphingosine (Scheme 33b). BOC protection was achieved from phytosphingosine to afford butyl carbamate **161** in 93% yield. Further, primary alcohol was temporarily blocked by the silyl protecting group (TBSCl) followed by isopropylidene protection of vicinal diol and deprotection of primary alcohol, producing precursor **162** in 87% yield. Mitsunobu transformation to thioether using  $\text{PPh}_3$ ,  $\text{BtSH}$ , and DIAD followed by oxidation with *m*-CPBA afforded BT-sulfone **157** in 95% yield. Similarly, the mesylation of the hydroxyl group in **162** followed by substitution with PYRSH afforded **164**, which on oxidation with *m*-CPBA produced PYR-sulfone **158** in 92% yield.

Dondoni *et al.*<sup>63</sup> developed a strategy for the synthesis of  $\beta$ -D-galactosyl ceramide methylene isostere starting from *C*-galactopyranosyl aldehyde (**4c**) (Scheme 34). First, *C*-galactopyranosyl aldehyde **4c** was transformed into alkyloxazolidine **164** by a sequence of reactions.<sup>64</sup> Acetonide protective group removal was achieved by  $\text{AcOH}-\text{H}_2\text{O}$  to afford *N*-Boc amino alcohol, which on further oxidation under Swern conditions obtained aldehyde **165** in 55% yield. Addition of lithium 1-pentadecyne in anhydrous THF produced alcohol **166** as a mixture of *S/R* (*syn/anti*) isomer in a 70 : 30 ratio. Due to the isomer formation, oxidation–reduction steps were carried out with **166**. First, Swern oxidation afforded ketone **167** followed by reduction with *L*-selectride in THF afforded *anti* isomer **168** as a major product with *S/R* (*syn/anti*) isomer in a 5 : 95 ratio. BOC deprotection was carried out with 4.8 M HCl in dioxane-afforded amino alcohol **169** in 90% yield. Further, stereoselective hydrogenation of triple bond using lithium aluminium hydride produced alkene **170** where installation of *N*-palmitoyl group produced benzyl protected  $\beta$ -D-galactosyl ceramide methylene isostere **171** in 80% yield. Switching of the protective group produced another  $\beta$ -D-galactosyl ceramide methylene isostere **172** in 55% yield. Isostere **172** with a 45% yield was also obtained from **169** via another sequence of reactions (Scheme 34).

### 3.2 *C*-Glycopyranosyl di- and polysaccharides

Due to the presence of ubiquitous glycosidases and their ability to carry out hydrolysis, a short lifetime of the usual *O*-linked disaccharide conjugates was observed in the bloodstream whereas *C*-linked disaccharides are stable enough towards hydrolysis so that they could be utilised as a disaccharide-based vaccine. Due to the immense potential of *C*-linked disaccharides, Kobertz *et al.*<sup>65</sup> described the synthesis of *C*-linked disaccharide using nitro aldol condensation between *C*-



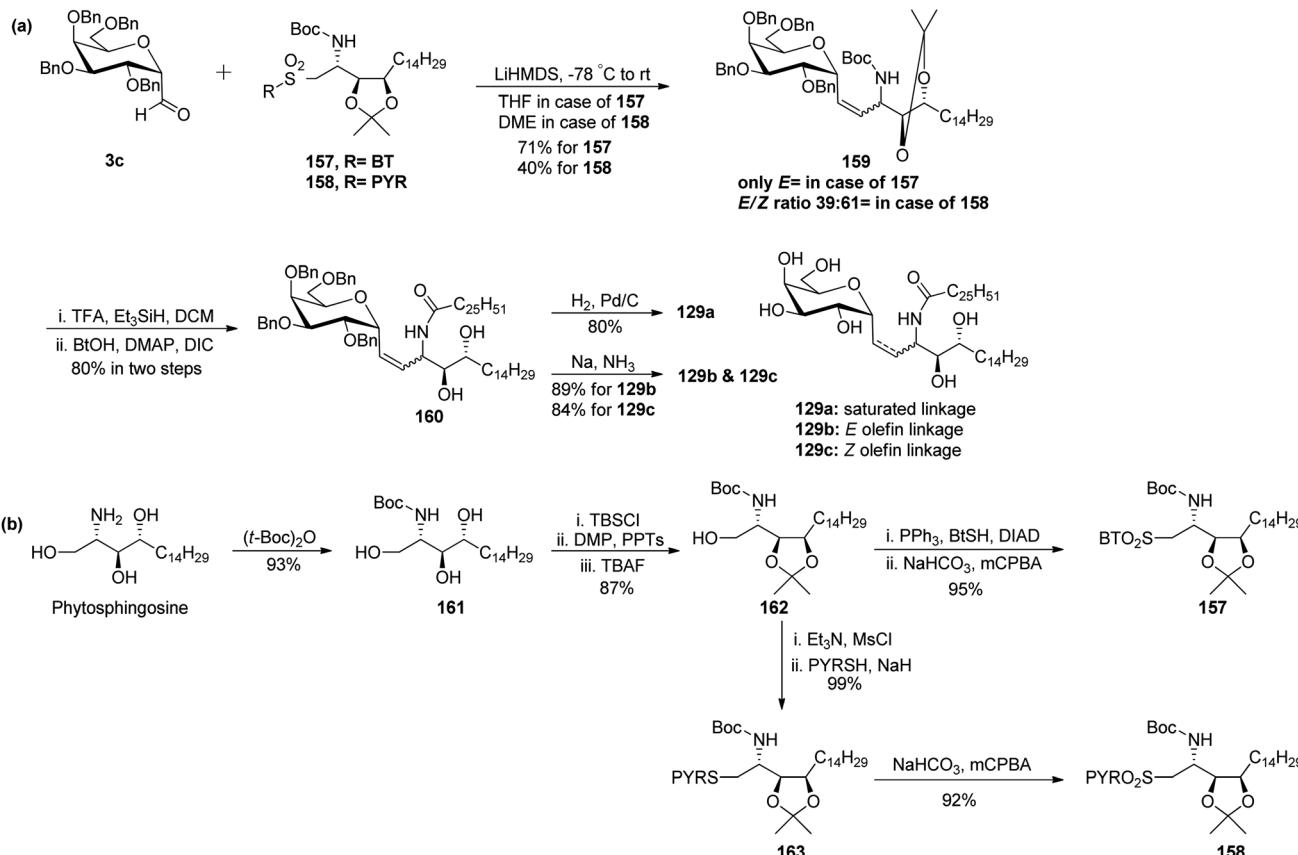
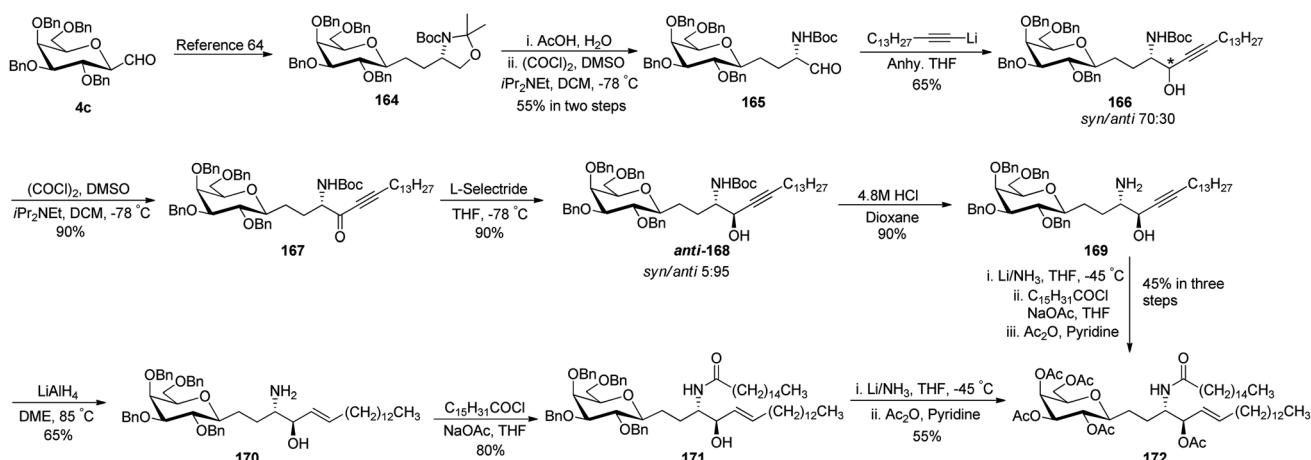


Scheme 32 (a) Synthesis of  $\alpha$ -GalCer analogues 149 and 151. (b) Synthesis of  $\alpha$ -GalCer analogues 153 and 156.

galactopyranosyl aldehyde **4c** and nitro sugar **175** in the presence of KF in acetonitrile, which afforded compound **176** as a diastereomeric mixture in 52% yield (Scheme 35). Nitro sugar derivative **175** used herein was prepared from compound **1a** by acid catalysed selective debenzylation followed by substitution with the azide group to obtain **174**. Next, compound **174** was subjected to reduction followed by oxidation to afford compound **175** in 61% yield. Compound **176** was converted into completely protected compound **177** using *n*-butyl lithium

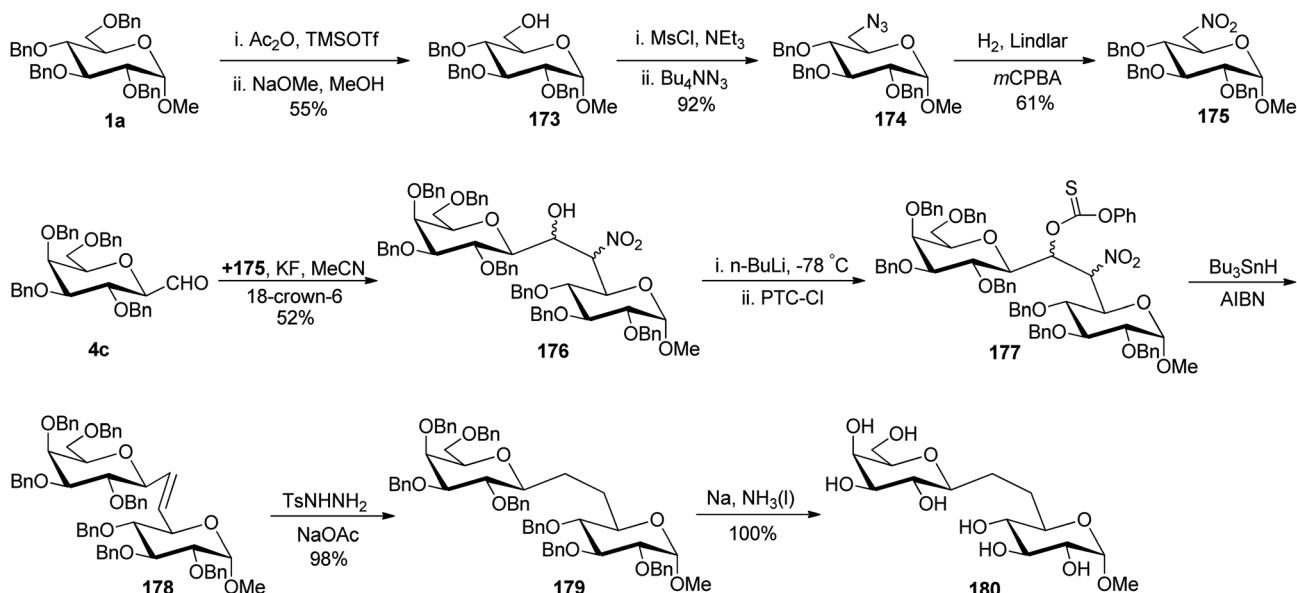
followed by phenyl chlorothionocarbonate (PTC-Cl), which was used in the next step without isolation. Further, a radical-assisted elimination reaction using  $\text{Bu}_3\text{SnH}$ -AIBN was carried out to afford alkene **178** in 10% yield calculated from compound **176**. The reduction of olefin **178** was carried out by diimide (generated *in situ* from tosyl hydrazine and sodium acetate) to obtain disaccharides **179** in 98% yield. The debenylation of **179** was carried out by dissolving metal reduction in liquid ammonia to obtain compound **180** in quantitative yield.



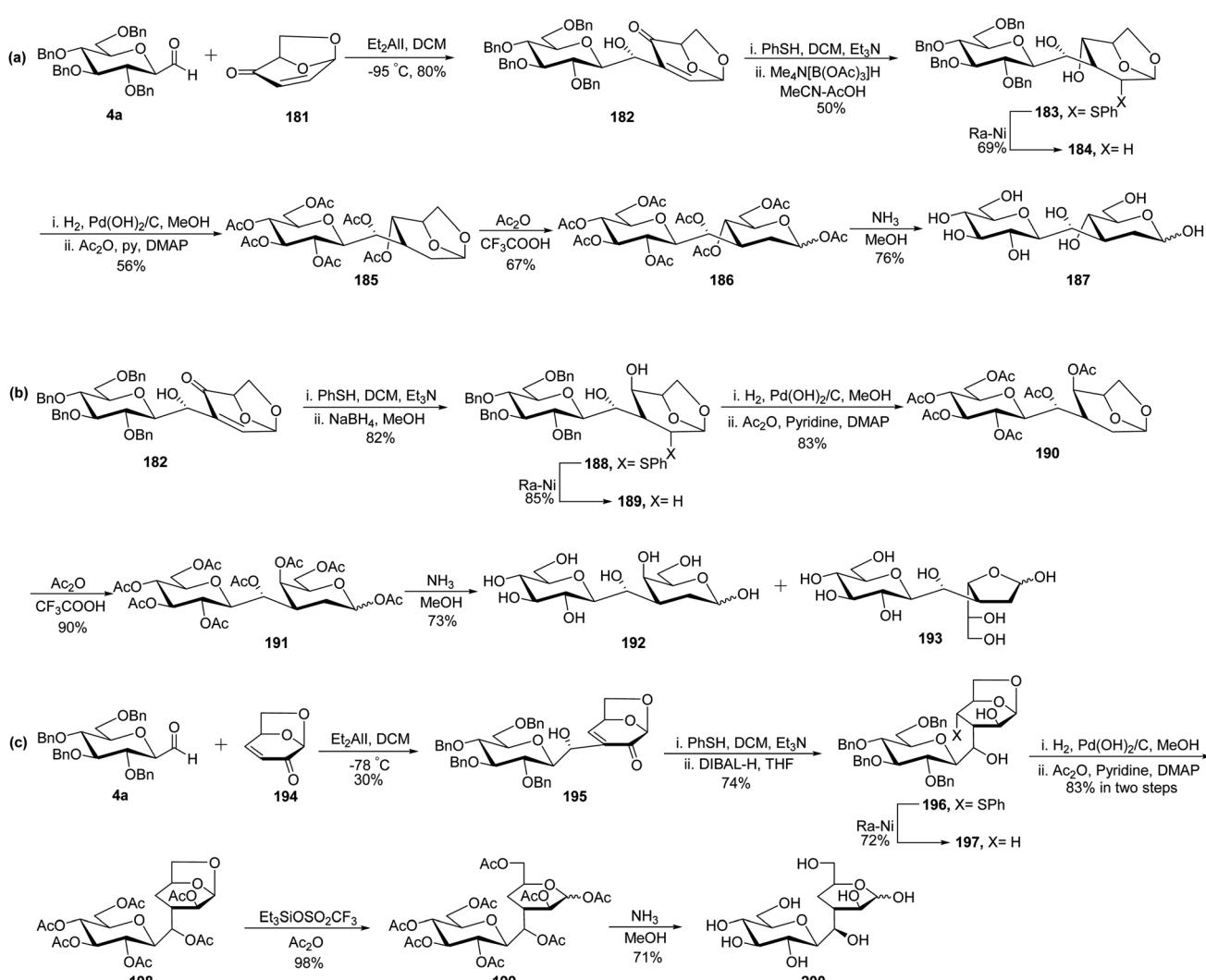
Scheme 33 Synthesis of  $\alpha$ -C-galactosylceramides 129a–c.Scheme 34 Synthesis of  $\beta$ -D-galactosyl ceramide methylene isostere 171 and 172.

Demange *et al.*<sup>66</sup> designed a synthesis of  $C(1 \rightarrow 3)$ -linked disaccharides *via* the Oshima–Nozaki condensation of  $\beta$ -C-glucopyranosyl aldehyde with isolevoglucosenone and levoglucosenone (Scheme 36). In both condensations, an exclusively ( $1'R$ )-hydroxymethano linker was formed.  $\beta$ -C-Glucopyranosyl aldehyde **4a** was condensed with isolevoglucosenone **181** using  $Et_2AlI$  in DCM at  $-95^{\circ}C$  to generate enone **182** in 80% yield. Further, the addition of

thiophenol was taken using base  $Et_3N$  followed by direct reduction with  $Me_4N[B(OAc)_3]H$  in MeCN–AcOH to give **183** in 50% yield. Treatment with RANEY®-Nickel produced **184** in 69% yield, where debenylation followed by acetylation was achieved to obtain compound **185** in 56% yield. Further, treatment with  $Ac_2O$ – $CF_3COOH$  afforded an anomeric mixture **186** where ammonolysis was carried out to give pure  $C$ -disaccharide **187** in 76% yield (Scheme 36a).



Scheme 35 Synthesis of disaccharide 180.



Scheme 36 Synthesis of C-linked disaccharides 187, 192, 193, and 200.

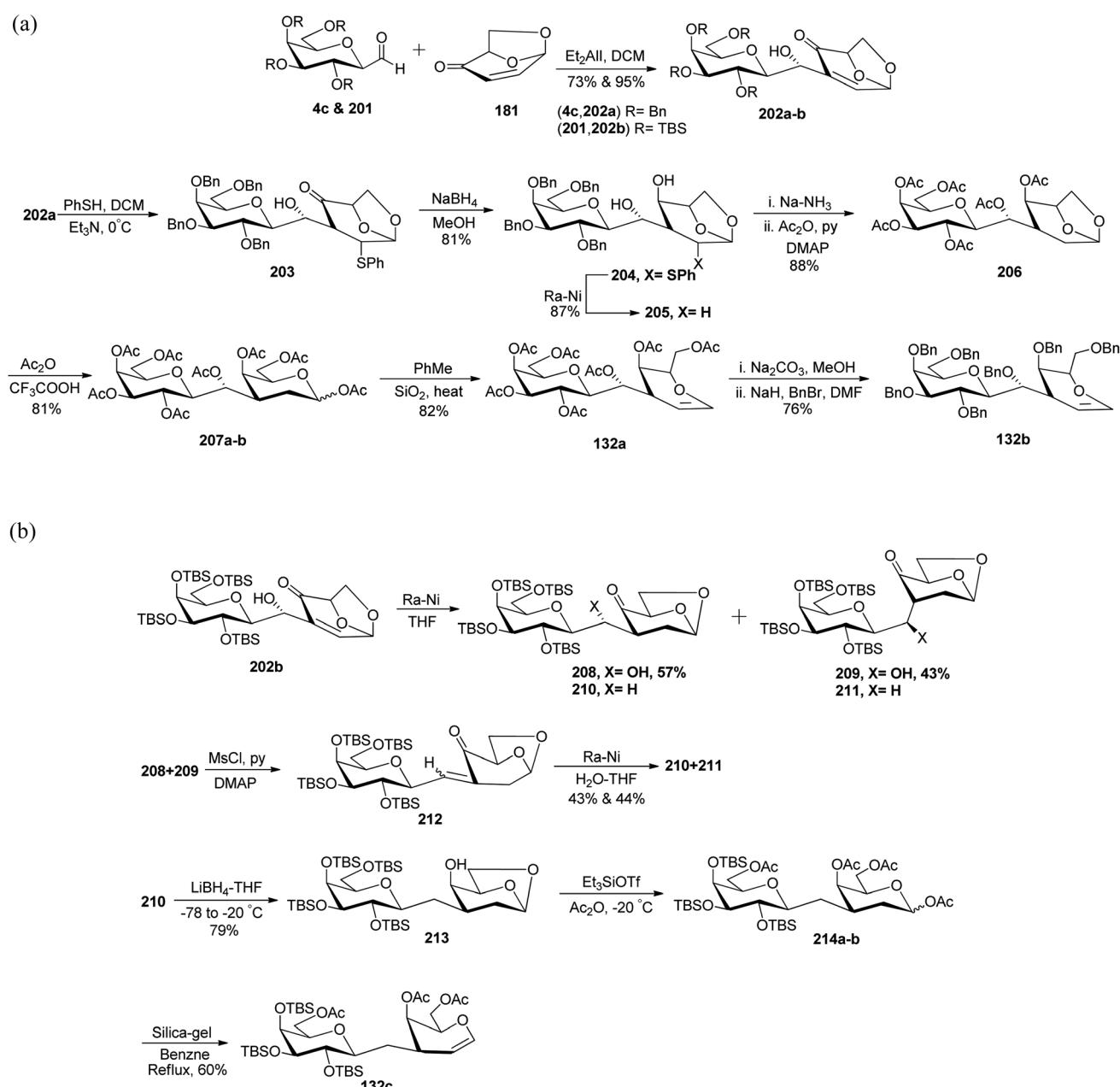


The addition of thiophenol to enone **182** was followed by a reduction with  $\text{NaBH}_4$  instead of  $\text{Me}_4\text{N}[\text{B}(\text{OAc})_3]\text{H}$  to obtain **188** in 82% yield, which on reduction with RANEY®-Nickel afforded compound **189** in 85% yield. *C*-Disaccharides **192** and **193** were obtained by applying the same sequence of reactions as carried out for the synthesis of *C*-disaccharide **187**. Exchange of the benzyl protective group with acetyl produced **190**, which on acetolysis afforded anomer mixture **191** in 90% yield. Further, deacetylation was achieved by  $\text{NH}_3\text{-MeOH}$  to produce the mixture of **192** and **193** in 73% yield (Scheme 36b).

*C*-Glucopyranosyl aldehyde **4a** and levoglucosenone **194** were subjected to Oshima–Nozaki condensation, which produced enone **195** in just 30% yield. The addition of thiophenol

followed by reduction with DIBAL-H afforded **196** in 74% yield, which was further treated with RANEY®-Nickel to obtain **197** in 72% yield. The debenzylation of compound **197** followed by acetylation was carried out to obtain **198** in 83% yield. Further, acetolysis was carried out using triethylsilyl trifluoromethanesulfonate in acetic anhydride to obtain an anomeric mixture **199** in 98% yield, which was deacetylated using  $\text{NH}_3\text{-MeOH}$  to give *C*-disaccharide **200** in 71% yield (Scheme 36c).

Demange *et al.*<sup>62</sup> reported the synthesis of *C*-linked disaccharides, which mimics *O*- $\beta$ -D-galactopyranosyl-(1 $\rightarrow$ 3)-D-galactopyranosides starting from *C*-galactopyranosyl aldehyde. Three *C*-linked disaccharides **132a**, **132b**, and **132c** were



Scheme 37 (a) Synthesis of disaccharides **132a–b**. (b) Synthesis of  $\beta$ -D-galactopyranosyl-D-galactal **132c**.

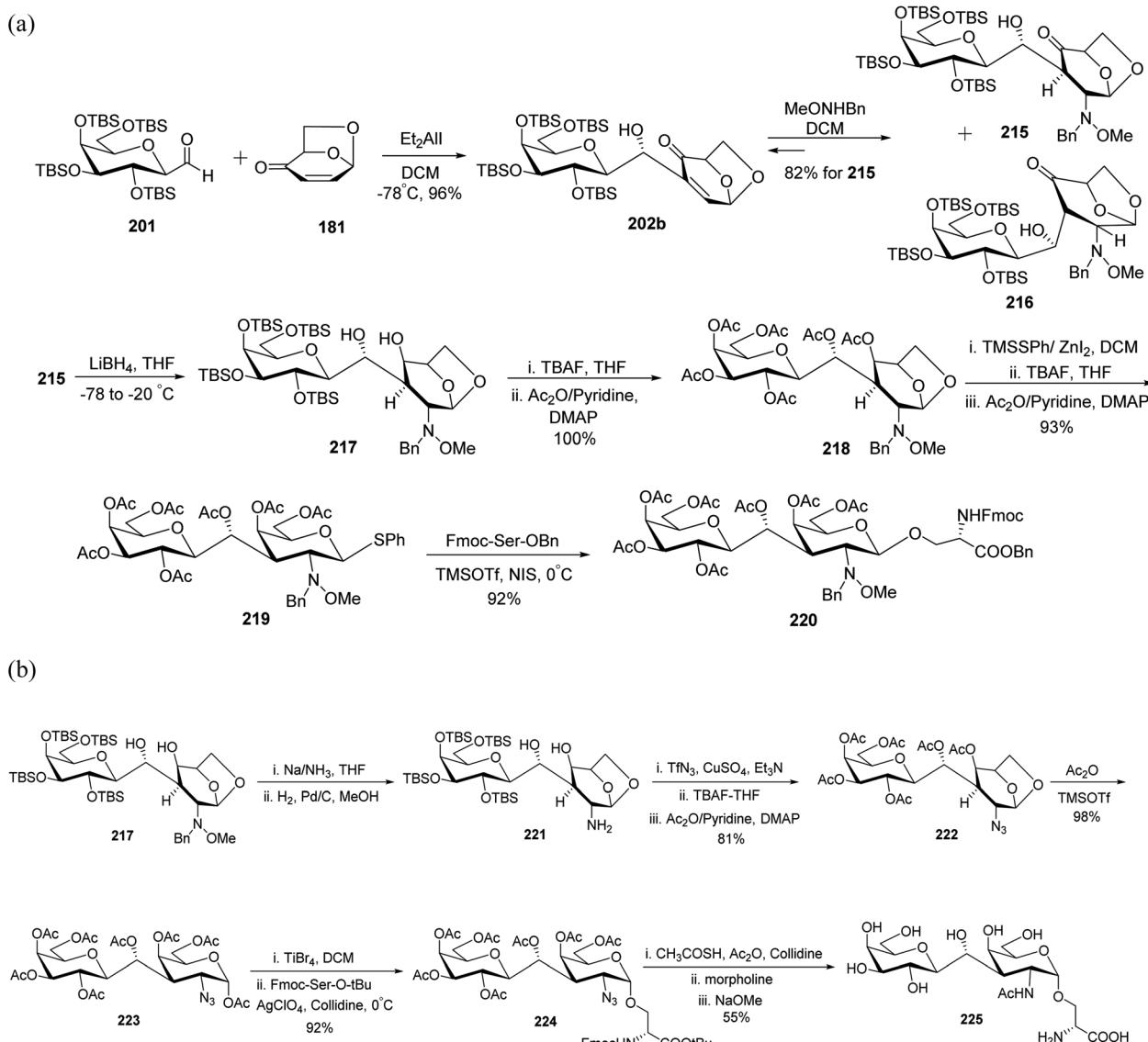


synthesized, out of which **132a** was found to be a suitable agent for *O*-glycosidation and for the construction of conjugates (Scheme 37). *C*-galatopyranosyl aldehyde **4c** and **201** reacted with **181** to prepare **202a** and **202b** in 73% and 95% yields, respectively. Michael addition of thiophenol to **202a** afforded **203**, which was directly converted into **204** with 81% yield by reduction using sodium borohydride in methanol. Treatment with RANEY®-nickel converted compound **204** into compound **205** in 87% yield, which on debenzylation following the acetylation furnished peracetylated **206** in 88% yield. Treatment of **206** with  $\text{Ac}_2\text{O}$ -TFA gave **207a–b** as a mixture of anomers ( $\alpha : \beta$ , 1 : 0.3) in 81% yield, which on refluxing in toluene afforded **132a** in 82% yield. Further replacement of acetyl protection with the benzyl group produced **132b** in 76% yield (Scheme 37a).

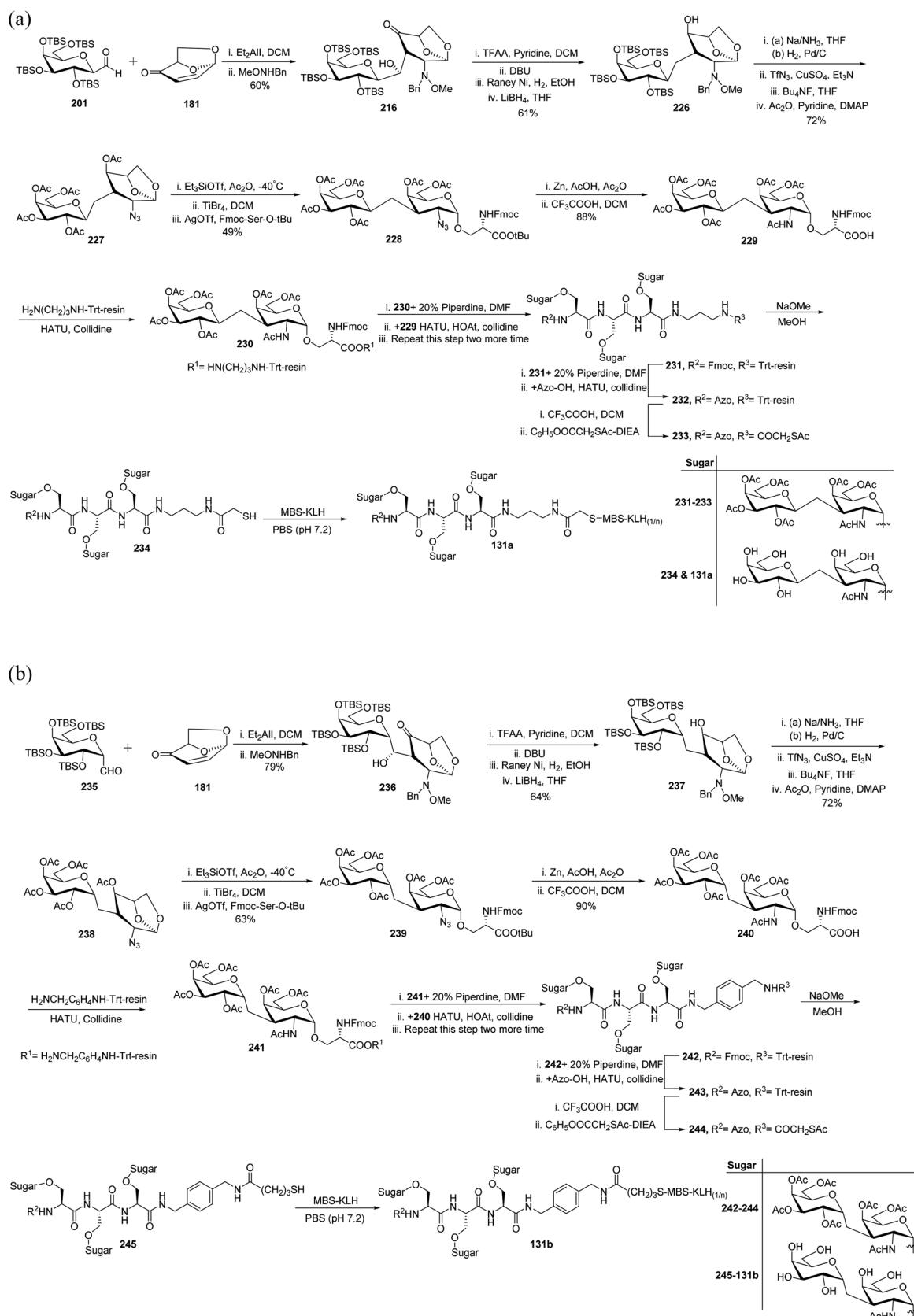
*C*-Galactoside **202b** on reduction with RANEY®-nickel produced a mixture of aldols **208–211** in quantitative yield. From this mixture, compounds **208** and **209** were isolated by

flash chromatography in 57% and 43% yield, respectively. This mixture of aldols **208** and **209** when treated with  $\text{CH}_3\text{SO}_2\text{Cl}$ /pyridine and DMAP formed unstable enone **212**, which when reduced with Ra-Ni in aq. THF produced a mixture of ketones **210** and **211** in 43% and 44% yield, respectively. The ketone **210** thus produced when reduced with lithium borohydride in THF at low temperature formed alcohol **213** in 79% yield, which on treatment with triethylsilyltrifluoromethanesulfonate( $\text{Et}_3\text{SiOTf}$ ) and acetic anhydride underwent ring opening of 1,6-anhydro moiety followed by acylation to give a mixture of  $\alpha$ - and  $\beta$ -pyranosides **214a–b**. Anomeric mixture **214a–b** was directly treated with silica gel in benzene and heated under refluxing conditions, which resulted in a *C*-linked analogue of  $\beta$ -D-galactopyranosyl-D-galactal **132c** in 60% yield (Scheme 37b).

In 2001, Zhu *et al.*<sup>67</sup> and in 2005, Awad *et al.*<sup>68</sup> reported the synthesis of a *C*-linked disaccharide analogue of epitope T. First, Oshima–Nozaki condensation<sup>69</sup> was carried out



Scheme 38 (a) Synthesis of  $\beta$ -C-galactopyranosyl disaccharide 220. (b) Synthesis of  $\beta$ -C-glycopyranosyl disaccharide 225.



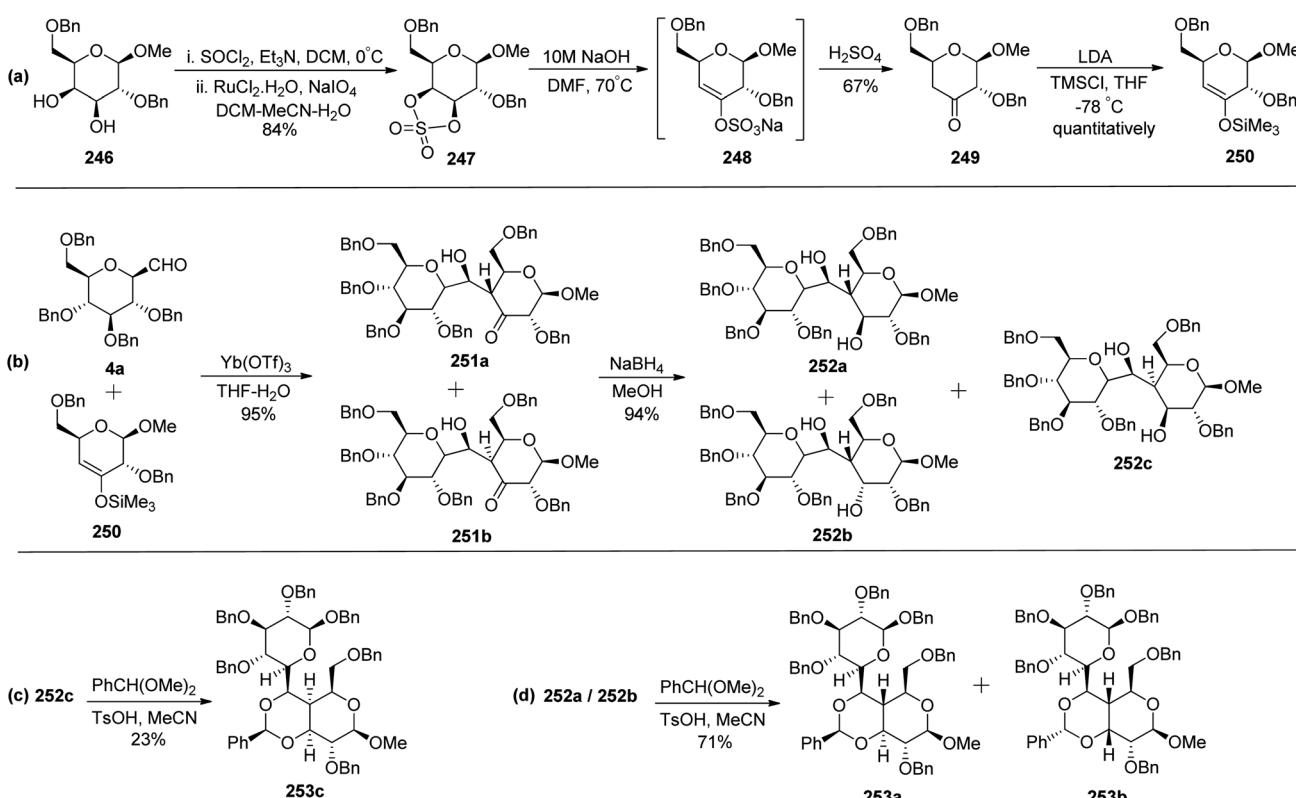
Scheme 39 (a) Synthesis of antigen 131a. (b) Synthesis of antigen 131b.

between *C*-glycopyranosyl aldehyde **201** and commercially available isolevoglucosenone **181** using  $\text{Et}_2\text{AlI}$  in DCM to afford **202b** in 96% yield. Further conjugate addition of  $\text{MeONHBn}$  to enone **202b** produced a stereoisomeric mixture of **215** and **216**, which were isomerised during column chromatography, and adduct **215** was recovered in 82% yield. Reduction of **215** was carried out with lithium borohydride in THF at  $-78^\circ\text{C}$  to afford compound **217**, which was directly treated with TBAF in THF following acetylation to furnish **218** quantitatively. Treatment of peracetylated compound **218** with  $\text{TMSSPh/ZnI}_2$ -DCM followed by TBAF and acetylation furnished **219** in 93% yield, which was reacted with protected serine to afford  $\beta$ -*C*-glycopyranosyl disaccharide **220** in 92% yield (Scheme 38a).

The bulky 2-MeONBn group present on compound **219** enforced the reaction to undergo  $\beta$ -glycosylation, which afforded compound **220** (Scheme 38a). To achieve  $\alpha$ -glycosylation, 2-MeONBn group was removed initially from compound **217** using  $\text{Na}/\text{NH}_3$  reduction conditions followed by hydrogenation with  $\text{H}_2$ -Pd/C to afford compound **221** (Scheme 38b). Further, compound **221** was treated without isolation with  $\text{TfN}_3\text{-CuSO}_4$  following treatment with TBAF in THF and acetic anhydride in pyridine to furnish **222** in 81% yield. The peracetylated compound **222** on treatment with  $\text{Ac}_2\text{O-TMSOTf}$  afforded **223**, which reacted with protected serine to afford  $\alpha$ -glycosylated product **224** in 92% yield. The treatment of compound **224** with  $\text{CH}_3\text{COSH-Ac}_2\text{O}$  followed by further deacetylation afforded targeted compound **225** in 55% yield.

In 2012, Awad *et al.*<sup>61</sup> reported another interesting application of *C*-glycopyranosyl aldehyde by synthesizing *C*-linked disaccharide, which was found to induce a strong immune response in mice. The TBS-protected *C*-galactopyranosyl aldehyde **201** and isolevoglucosenone **181** were condensed followed by a reaction with  $\text{MeONHBn}$  to afford **216** in 60% yield. Compound **216** on treatment with TFA in pyridine following DBU furnished dehydration, further reduction of the double bond with RANEY®-nickel, and then by  $\text{LiBH}_4$  converted the keto group to afford compound **226** in 61% yield. Compound **227** was achieved in 72% yield by reduction of the 2-MeONBn group, its conversion into azide by diazo transfer, and desilylation following acetylation of **226**.  $\alpha$ -O-Galactosidation was achieved with protected serine to afford compound **228**, which on reaction with  $\text{Zn-AcOH}$  followed by treatment with TFA in DCM afforded compound **229** in 88% yield, which was coupled with trityl polymer to give **230**. Compound **231** was obtained first by removal of Fmoc protection from **230** and then by coupling it with the  $-\text{COOH}$  group of **229**.

The deprotection of Fmoc from compound **231** followed by capping with 4-(dimethylamino)-azobenzene-4'-carboxylic acid (Azo-OH) gave compound **232**. Coupling with pentafluorophenylacetylthioacetate after the liberation of protected triglycopeptides from the polymer furnished **233**, which was treated with sodium methoxide to give peptide **234**. Finally, the reaction of peptide **234** with MBS-KLH under the Michael addition reaction condition furnished antigen **131a** (Scheme 39a).



Scheme 40 Synthesis of *C*-linked disaccharide **253a–c**.



A similar synthetic protocol was developed for TBS protected  $\alpha$ -C-galactopyranosyl aldehyde 235 (Scheme 39b). In this strategy, trityl resin-monoprotected diamine 1,4-di( $\alpha$ -aminomethyl)benzene was coupled with compound 242. So, following the same sequence of reactions, antigen 131b was prepared.

Zeitouni *et al.*<sup>70</sup> introduced a new class of *C*-linked disaccharides 253a–c, which were obtained by the Mukaiyama aldol<sup>71</sup> reaction between  $\beta$ -C-glucopyranosyl aldehyde 4a and trimethylsilyl enol ether 250. This enol ether was synthesised from readily available methyl 2,6-di-O-benzyl- $\beta$ -D-galactopyranoside 246 (Scheme 40a). The diol 246 was reacted with  $\text{SOCl}_2\text{-Et}_3\text{N}$  followed by reaction with  $\text{RuCl}_3\cdot\text{H}_2\text{O-NaIO}_4$  to afford 3,4-cyclic sulfate 247 in 84% yield, which on treatment with 10 M NaOH gave unstable compound 248 and subsequent acidic hydrolysis furnished ketone 249 in 67% yield. Final enol ether 250 was obtained quantitatively by treatment with LDA-TMSCl in THF.

Condensation of 4a and 250 in the presence of  $\text{Yb}(\text{OTf})_3$  in  $\text{THF-H}_2\text{O}$  furnished diastereomeric mixture 251a and 251b in a 59 : 41 ratio out of four possible diastereomers in 95% yield. The diastereomers could not be separated by column chromatography so they were further reduced with sodium borohydride to furnish three diol products 252a, 252b, and 252c in 94% yield (Scheme 40b). Here, only 252c could be separated by column chromatography which was reacted with benzaldehyde dimethyl acetal in acetonitrile in the presence of PTSA to give 253c in 23% yield (Scheme 40c). The same reaction was also carried out on the 253a/253b mixture to give 253a and 253b in 71% yield, they could be separated easily (Scheme 40d).

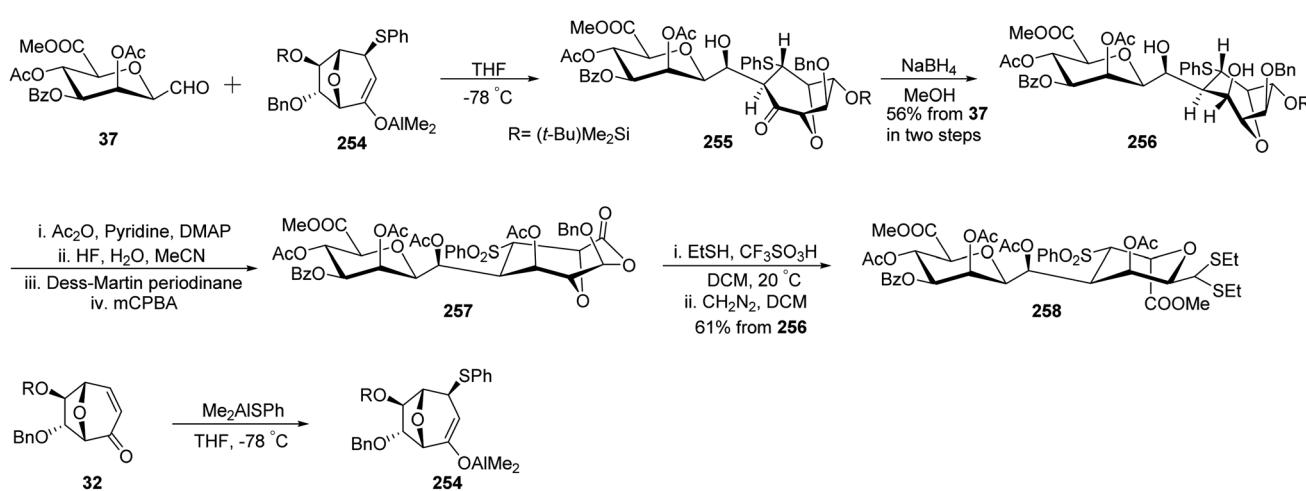
Gerber *et al.*<sup>33</sup> designed a stereoselective synthesis of *C*-linked disaccharides and oligosaccharides due to their advantage of being resistant to acidic and enzymatic hydrolysis. The enolate 254, which in turn was synthesised from enone 32 using  $\text{Me}_2\text{AlSPh}$  was reacted with *C*-glycopyranosyl aldehyde 37 in tetrahydrofuran to furnish aldol 255, which turned out to be unstable and hence was reduced with  $\text{NaBH}_4$  in methanol to afford diol 256 with 56% yield. Diol 256 on

acetylation with  $\text{Ac}_2\text{O}$  in pyridine, followed by desilylation with HF in  $\text{H}_2\text{O}$  and  $\text{MeCN}$ , and then undergoing Dess–Martin periodinane oxidation furnished a ketone, which upon Baeyer–Villiger oxidation afforded compound 257. Compound 257 on treatment with  $\text{EtSH/CF}_3\text{SO}_3\text{H/CH}_2\text{Cl}_2$  and with  $\text{CH}_2\text{N}_2$  in DCM afforded  $\beta$ -D-*C-manno*-pyranoside 258 in 61% yield (Scheme 41).

Levoirier *et al.*<sup>72</sup> developed a strategy for the synthesis of  $\beta$ -(1  $\rightarrow$  4)-*C*-disaccharides using Barbier-type allylation catalysed by indium in aqueous media (Scheme 42). *C*-Glucopyranosyl aldehyde was reacted with 6-bromo-4,6-dideoxy- $\alpha$ -D-*threo*-4-enopyranoside 259 using indium in  $\text{THF}$ -phosphate buffer to obtain an inseparable mixture of *C*-disaccharide 260 and 261 in 45% yield, which was acetylated using acetic anhydride in pyridine affording 262 and 263, respectively which could be separated easily. Hydroboration with diborane-tetrahydrofuran followed by oxidation with hydrogen peroxide in phosphate buffer and then acetylation was carried out on 262 and 263 to obtain protected *C*-disaccharides 264 and 265 in 91% and 83% yields, respectively (Scheme 42a).

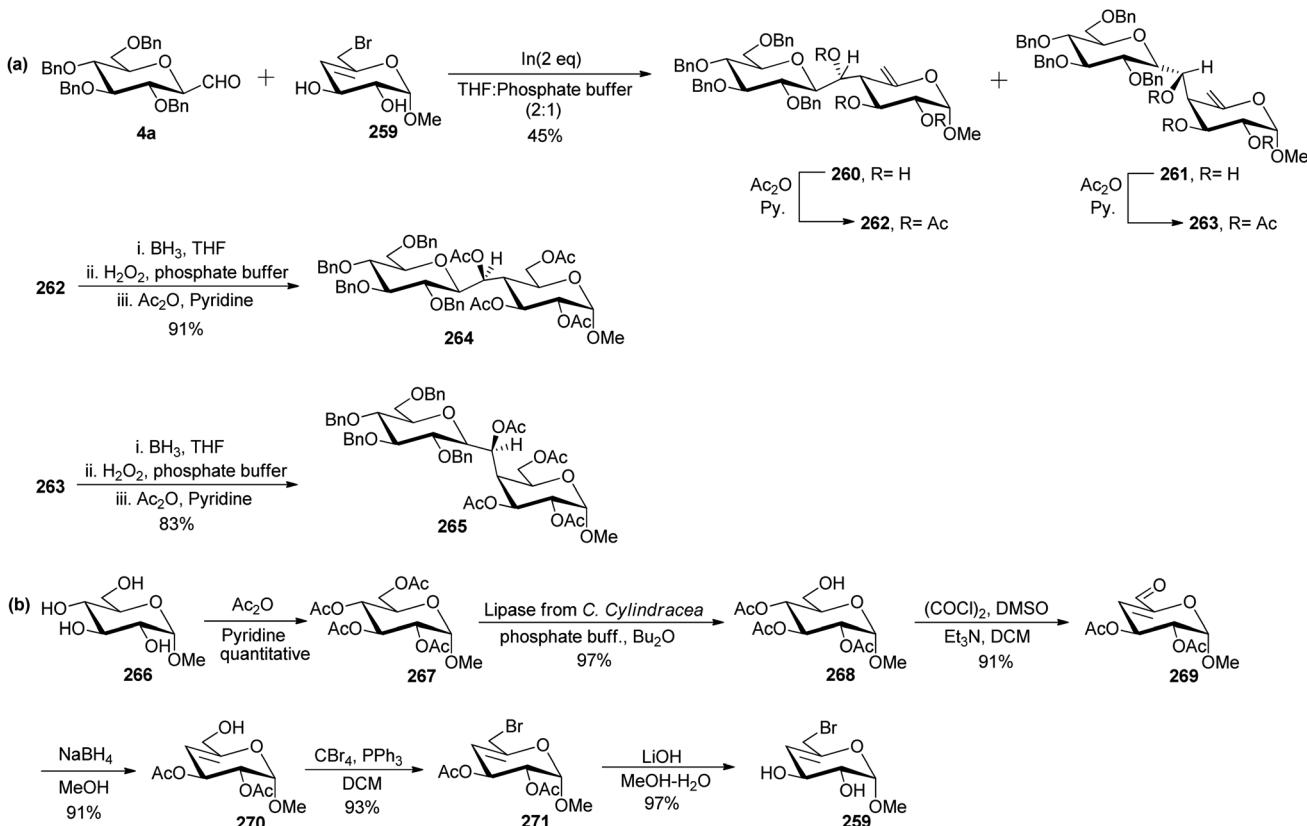
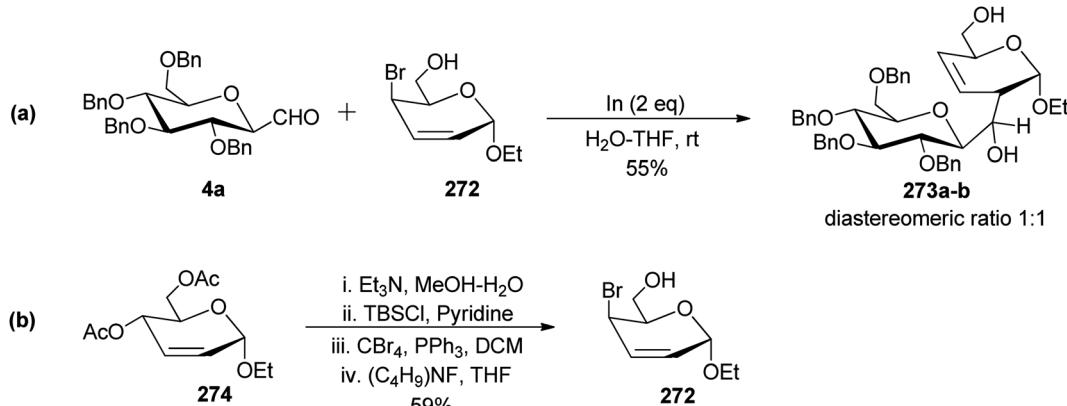
6-Bromo-4,6-dideoxy- $\alpha$ -D-*threo*-4-enopyranoside 259 used in the above Barbier-type allylation was synthesised from methyl  $\alpha$ -D-glucopyranoside 266, which on acetylation produced peracetylated derivative 267 quantitatively. Selective deacetylation of peracetylated derivative was performed after treatment with lipase from *C. Cylindracea* in a mixture of phosphate buffer and di-*n*-butyl ether produced methyl 2,3,4-tri-O-acetyl- $\alpha$ -D-glucopyranoside 268 in 97% yield. Compound 268 underwent Swern oxidation to afford unsaturated aldehyde 269 in 91% yield, which on further reduction with  $\text{NaBH}_4$  in  $\text{MeOH}$  produced allyl alcohol 270 in 91% yield. Treatment of allyl alcohol 270 with carbon tetrabromide and triphenylphosphine in DCM followed by deacetylation using  $\text{LiOH}$  in  $\text{MeOH-H}_2\text{O}$  afforded 259 in 97% yield (Scheme 42b).

Canac *et al.*<sup>73</sup> designed a protocol for the synthesis of *C*-disaccharides under indium-promoted Barbier-type allylation (Scheme 43). Here, *C*-glucopyranosyl aldehyde 4a was reacted with 4-bromo-2-enopyranoside 272 using indium in  $\text{H}_2\text{O-THF}$ .



Scheme 41 Synthesis of  $\beta$ -D-*C-manno*-pyranoside 258.



Scheme 42 Synthesis of  $\beta$ -(1-4)-C-disaccharides 264 and 265.

Scheme 43 Synthesis of C-disaccharide 273a-b.

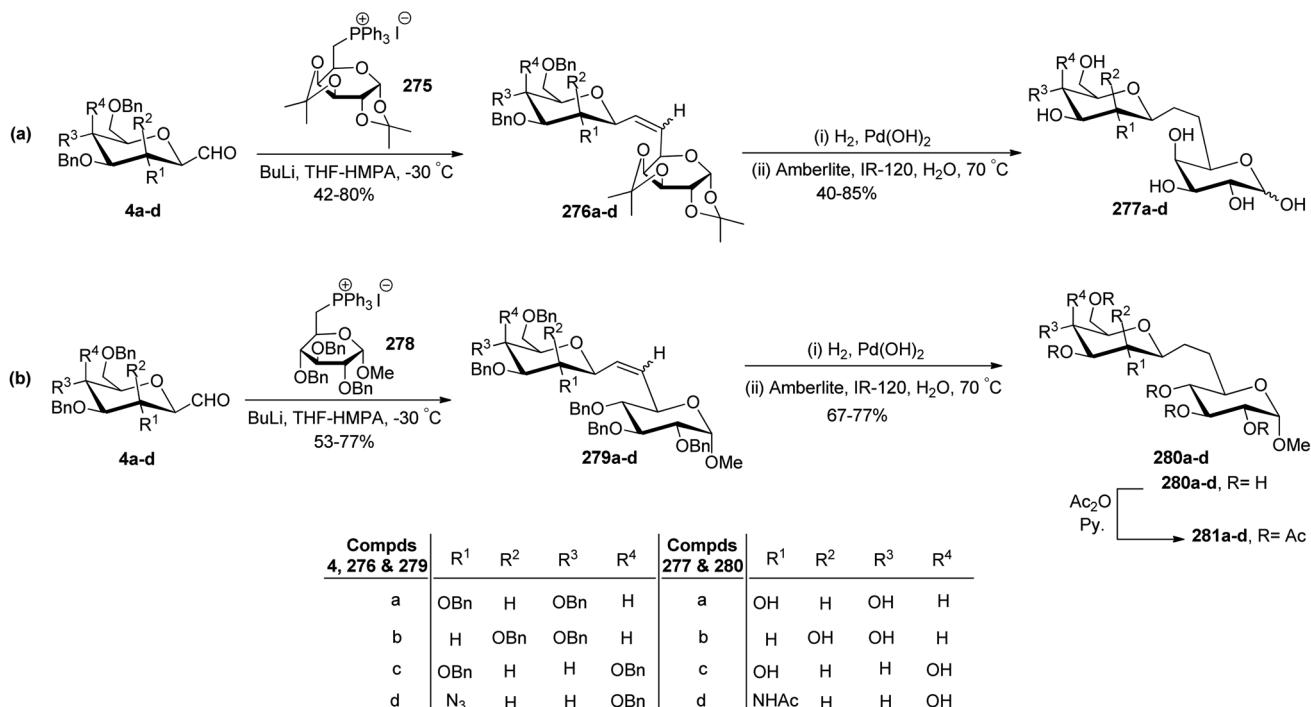
A mixture of diastereomers 273a-b with a ratio (1:1) in 55% yield was obtained.

The key compound 272 used in the above Barbier-type allylation was synthesised from 2-enopyranoside 274 using a sequence of deprotection of the acetyl group, selective protection of the primary hydroxyl group, bromination followed by deprotection reaction (Scheme 43b).

Dondoni *et al.*<sup>74</sup> achieved the synthesis of (1-6)-C-disaccharides by Wittig olefination reaction between C-glycopyranosyl aldehyde and pyranose 6-phosphoranes (Scheme 44).

First, C-glycosyl aldehydes 4a-d were reacted with galactose 6-phosphorane 275 using *n*-butyl lithium, THF-HMPA at -30 °C to afford alkenes 276a-d in 42-80% yield. In the case of manopyranosyl aldehyde 4b low yield (42%) was observed due to the formation of unexpected side products (formed by the elimination of BnOH from C1 and C2 of sugar). Further, treatment of alkenes 276a-d with H<sub>2</sub>, Pd(OH)<sub>2</sub> led to the debenzylation and reduction of the double bond, which on deprotection with amberlite IR-120 in water furnished  $\beta$ -D-(1-6)-C-disaccharides 277a-d in 40-85% yield.





Scheme 44 Synthesis of (1→6)-C-disaccharides 277 and 280.

Similarly, *C*-glycopyranosyl aldehydes **4a-d** were reacted with glucose 6-phosphorane **278** under Wittig conditions to furnish alkenes **279a-d** with 53–77% yield, which on treatment with  $\text{H}_2$ ,  $\text{Pd}(\text{OH})_2$  followed by Amberlite IR-120 resin produced disaccharides **280a-d**. Further, disaccharides **280a-d** were acetylated using acetic anhydride in pyridine to afford **281a-d** (Scheme 44b).

Dondoni *et al.*<sup>75–77</sup> worked on designing synthetic routes for oligosaccharides and glycoconjugates both being mediators in inflammation, fertilization, cancer metastasis, and viral and bacterial infections in human beings. For the synthesis of these oligosaccharides, two complementary routes were designed taking *C*-galactopyranosyl aldehyde **282** in the first route while in the second,  $\alpha$ -linked galactosylmethylenephosphorane **10** was taken as the starting material. The formyl group of *C*-galactopyranosyl aldehyde **282** on reaction with  $\text{NaBH}_4$  reduces to alcohol followed by iodination with  $\text{I}_2$  and  $\text{PPh}_3$  finally phosphination in the presence of  $\text{PPh}_3$  yielding galactosylmethylenephosphonium iodide **283** in 65% yield, which reacted with galactose derived aldehyde **284** in the presence of  $\text{BuLi}$ . The reaction afforded olefin **285** in a good yield, which further undergoes removal of the silyl protecting group followed by oxidation to primary alcohol to yield aldehyde **286** in 70% yield. The same sequence of addition of galactosylmethylenephosphonium iodide **283** followed by oxidation of alcohol to aldehyde with  $\text{Bu}_4\text{NF}$  and PCC resulted in the formation of the desired oligosaccharide chain **290** in very low overall yield (Scheme 45a). In the other route, galactosylmethylenephosphorane **292** was reacted with *C*-glycopyranoside **282** in the presence of  $\text{BuLi}$  in THF-HMPA, affording bis-olefin **293** in excellent yield. Further, olefin **293**

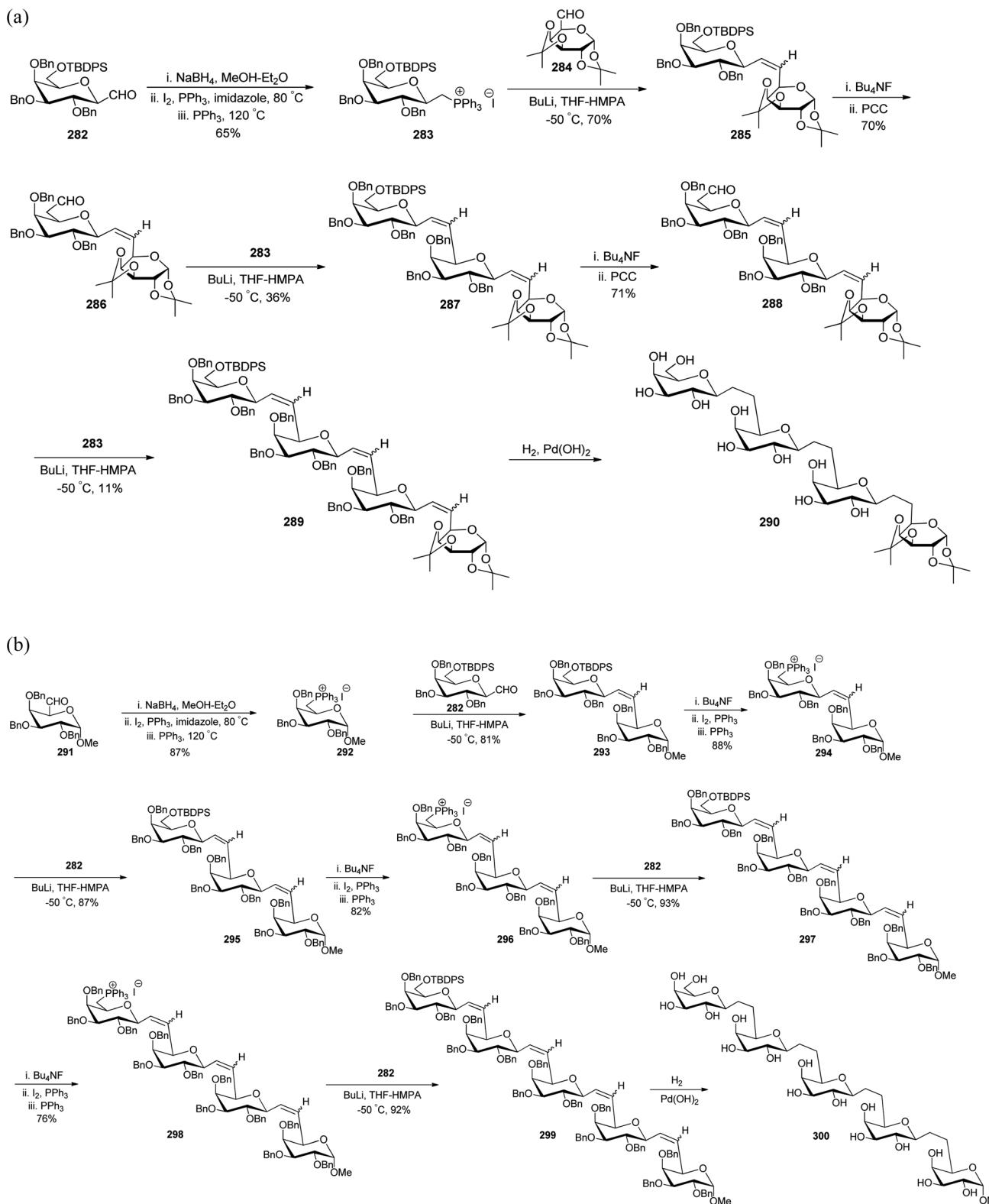
upon subsequent installation of the phosphonium group *via* desilylation ( $\text{Bu}_4\text{NF}$ ), followed by iodination ( $\text{I}_2$ ,  $\text{PPh}_3$ ), and phosphination ( $\text{PPh}_3$ ) yielded sugar phosphonium iodide **294** in 88% yield, which on further reaction with *C*-galactopyranosyl aldehyde **282** followed by the same sequence of steps yielded bis-olefin **295** in 87% yield and same steps were followed to obtain oligosaccharide **299**, which on debenzylation and hydrogenation produced oligosaccharide **300** with good overall yield (Scheme 45b).

### 3.3 *C*-Glycopyranosyl amino acid precursors

Sipos *et al.*<sup>78</sup> designed the synthesis of *C*-glycosyl-aminoacetonitriles **301a-b**, **302a-b**, and **303** under Strecker reaction conditions from various *C*-glycopyranosyl aldehydes. *C*-glycosyl aminoacetonitriles **301a-b** were formed in 67–70% yield by Strecker reaction upon **43a-b** with DCM for **43a** and THF for **43b**. The diastereomeric ratios for **301a-b** were 8.25 and 5.17, respectively. Similarly, **302a-b** were formed in 48–78% yield by Strecker reaction upon **40a-b** by reacting them with chiral amines such as *S*- or *R*-PEA or achiral amines such as benzylamine (BA), benzhydrylamine (BHA) in the presence of cyanide donor HCN. The diastereomeric ratio and yield obtained for *C*-glycosyl-aminoacetonitriles are shown in Scheme 46.

In addition, glycosyl-formaldehydes **39a**, **39d**, and **39f** also underwent Strecker reaction leading to the formation of *C*-glycosyl aminoacetonitriles **303a**, **303d**, and **303f** (Scheme 46b). The hydrolysis of these *C*-glycosyl- $\alpha$ -aminoacetonitrile led to the formation of *C*-glycosyl glycine, which can be used for the development of biologically-active glycol-peptidomimetics.

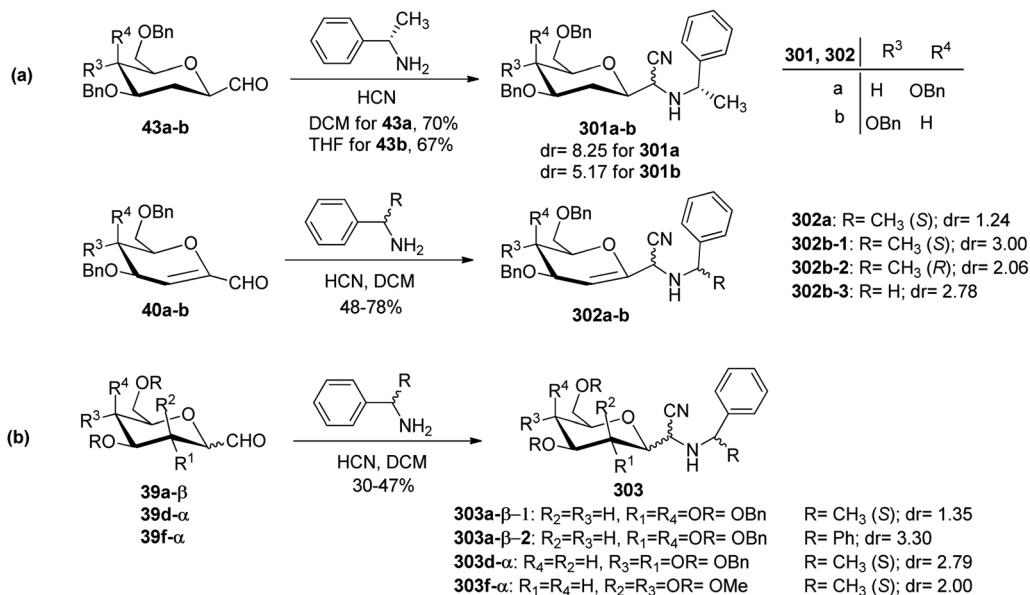
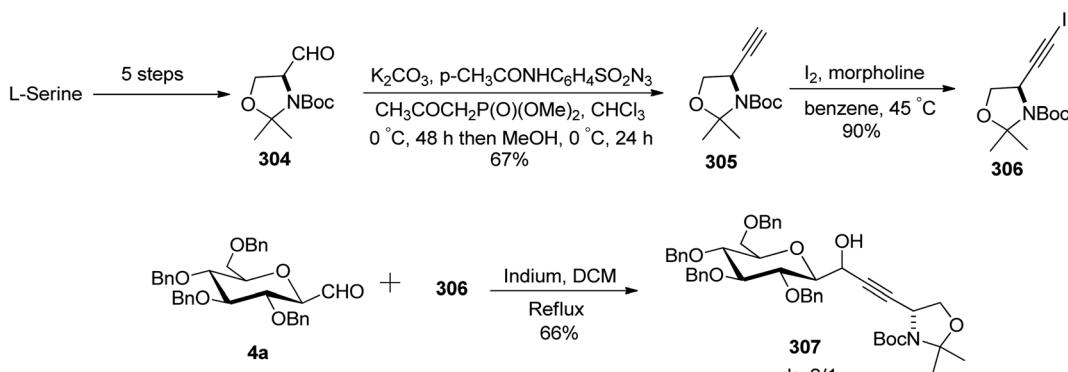




Scheme 45 (a) Synthesis of oligosaccharide 290. (b) Synthesis of oligosaccharide 300.

Charfedinne *et al.*<sup>79</sup> described the synthesis of some alkynes and iodoalkynes bearing protected amino alcohol moieties as amino acid precursors, which were used for the

alkynylation reaction of sugar derivatives. The alkynyl iodide 306 was obtained in a multi-step reaction process (Scheme 47). Garner's aldehyde 304 was synthesised from L-serine in

Scheme 46 Synthesis of 2-amino-2-C-β-glycosyl-acetonitriles **301a-b**, **302a-b**, **303**.Scheme 47 Synthesis of C-glycopyranosyl propargylic alcohol **307**.

a five-step procedure.<sup>80</sup> This aldehyde was then homologated into terminal alkyne **305** with 67% yield using Ohira–Bestmann reagents (Seydel–Colvin–Gilbert reaction). The alkyne derivative **305** when treated with iodine and morpholine in benzene at 45 °C resulted in iodinated *tert*-butyl-(*R*)-4-iodoethynyl-2,2-dimethylethazolidine-3-carboxylate (**306**) in 90% yield.

The reaction of alkynyl-iodide **306** with 2,3,4,5-tetra-O-benzyl-1-formylglucopyranose (**4a**) in the presence of metallic indium in dichloromethane resulted in a coupling reaction producing the corresponding propargylic alcohol **307** in 66% yield with a diastereomeric ratio of 2/1 (Scheme 47).

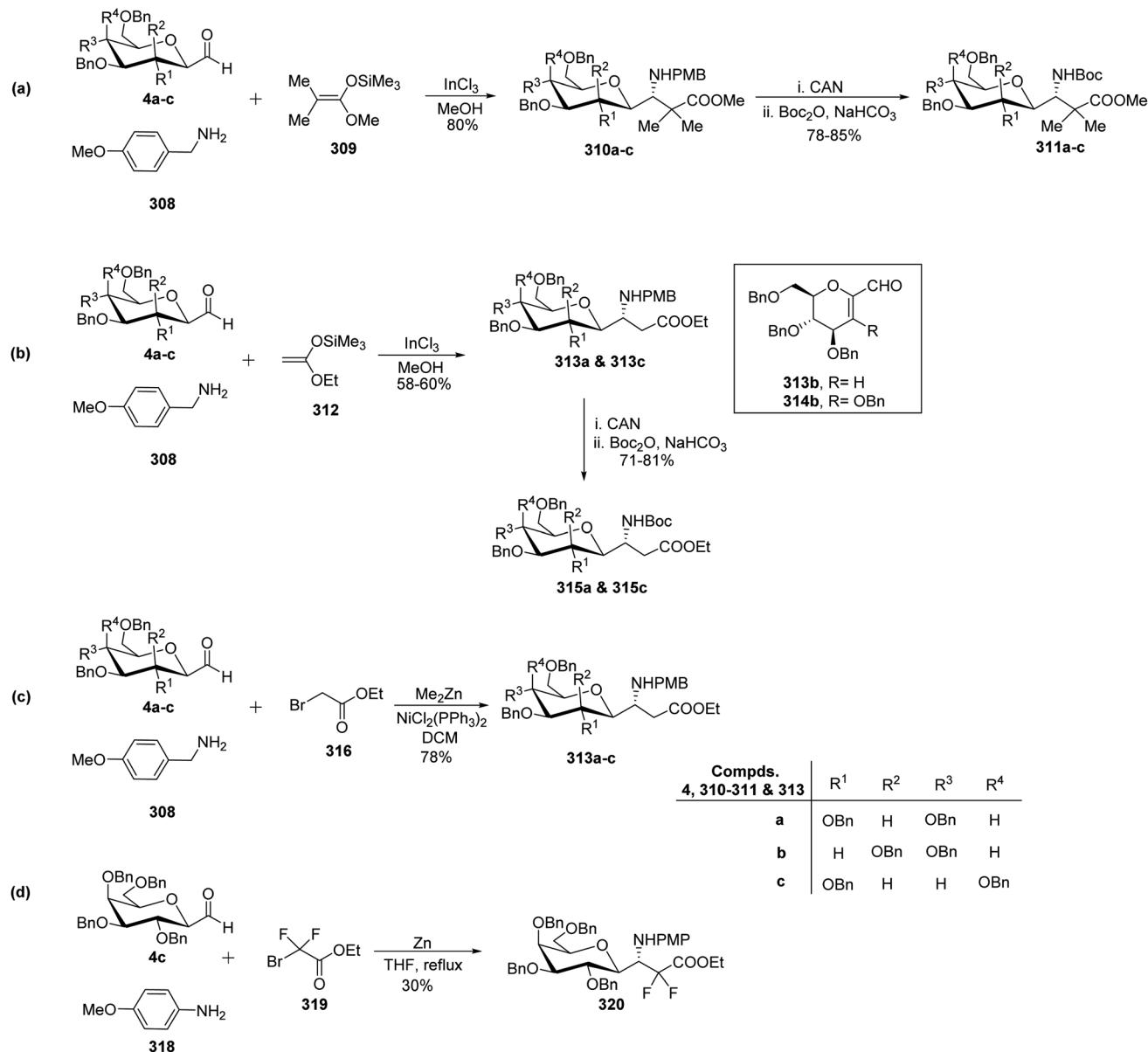
### 3.4 C-Glycopyranosylamino acids and dipeptides

Dondoni *et al.*<sup>81,82</sup> developed complementary one-pot Mannich- and Reformatsky-type multicomponent approaches to synthesise a library of *C*-glycosyl β-amino acids (Scheme 48). Both methods involved *C*-glycopyranosyl aldehydes **4a-c** as starting compounds.

Mannich route coupled *C*-glycopyranosyl aldehyde **4a-c**, *p*-methoxy benzylamine **308**, and commercially available ketene silyl acetal **309** in the presence of indium chloride in methanol to afford *C*-glycosyl β-amino ester **310a-c** as single diastereomer observed by <sup>1</sup>H NMR analysis with 80% yields. In the case of **4b** (*manno* sugar), DCM was chosen as the solvent because of the insolubility of the intermediate in methanol and also reaction was performed at 0 °C to avoid the formation of glycal amino ester (resulting from the elimination of BnOH from C-1 and C-2 of *manno* sugar). Further, for the reagent diversity ketene silyl acetal **312** was also chosen (Scheme 48b). Unfortunately, this process suffered from low yields of *C*-glycosyl β-amino esters **313a** and **313c** in 58–60% yield as well as undesired product formation **313b** and **314b** in case of **4b** (*manno* sugar).

In view of Boc-based peptide synthesis, all amino esters, **310a-c**, **313a**, and **313c**, were transformed into their corresponding *N*-Boc derivatives **311a-c**, **315a**, and **315c** by treatment of ceric ammonium nitrate (CAN) followed by  $\text{Boc}_2\text{O}$  and  $\text{NaHCO}_3$  in 78–85% and 71–81% yields, respectively (Scheme 48a–b).

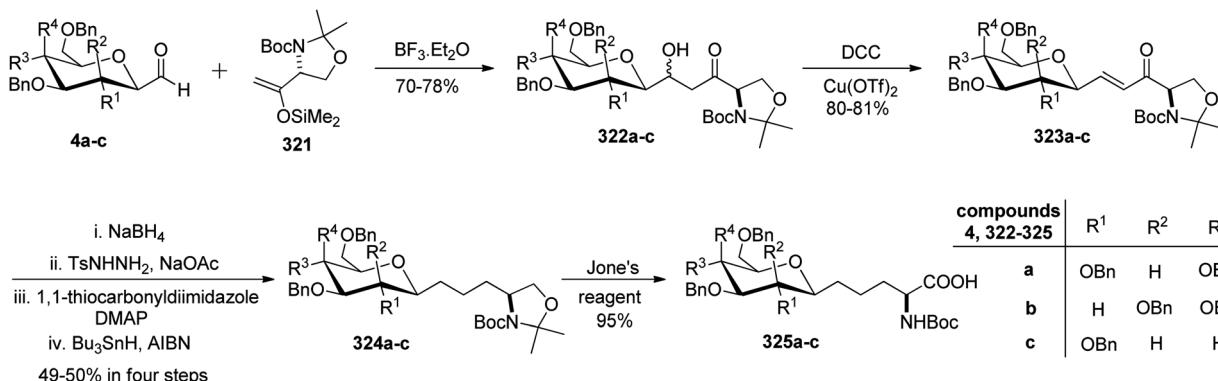


Scheme 48 Synthesis of C-glycopyranosyl  $\beta$ -amino acids 311, 313, 315, 320.

Due to some limitations in the above Mannich-type approach another route for the synthesis of *C*-glycosyl  $\beta$ -amino esters was performed. Here, ethyl bromoacetate 316 was taken in place of ketene silyl acetate (Scheme 48c). *C*-glycopyranosyl aldehyde 4a-c, *p*-methoxy benzylamine 308, and ethyl bromoacetate 316 were reacted in the presence of zinc donor  $\text{Me}_2\text{Zn}$ ,  $\text{NiCl}_2(\text{PPh}_3)_2$  as a catalyst in DCM to produce *C*-glycosyl  $\beta$ -amino esters 313a-c in 78% yield. Thus, the Reformatsky route demonstrated over the Mannich route in terms of overall yield and desired products.

Due to the application of fluorinated amino acids in biological and medicinal studies, synthesis of  $\alpha,\alpha$ -difluoro *C*-glycosyl  $\beta$ -amino acid 320 was also achieved by the Reformatsky-type reaction in 30% yield (Scheme 48d).

Dondoni *et al.*<sup>83,84</sup> employed threonine-derived silyl enol ethers 321 to serve as a synthetic equivalent of the homoalanine carbanion to introduce  $\alpha$ -amino side chains at the anomeric carbon position of sugar moieties. This functionalized silyl enol ether 321 was prepared from methyl *N*-Boc-L-threoninate in six steps with a 48% yield. Tetra-*O*-benzylated formyl *C*-glycopyranoside 4a-c upon condensation with 321 in the presence of Lewis acid boron trifluoride etherate underwrote Mukaiyama coupling in  $\text{CH}_2\text{Cl}_2$  at  $-30^\circ\text{C}$ , which afforded aldols 322a-c in 70–78% yield. The  $\alpha,\beta$ -enones 323a-c were obtained with 80–81% yield from dehydration of 322a-c using  $\text{DCC-Cu}(\text{OTf})_2$  for  $\alpha,\beta$ -elimination reaction. The carbonyl and carbon–carbon double bonds were then reduced by following a sequence of reactions on 323a-c to yield 324a-c with 49–50% yield in four steps. Next, when compounds 324a-c were subjected to Jones' reagent, they



Scheme 49 Synthesis of C-glycosyl amino acids 325a-c.

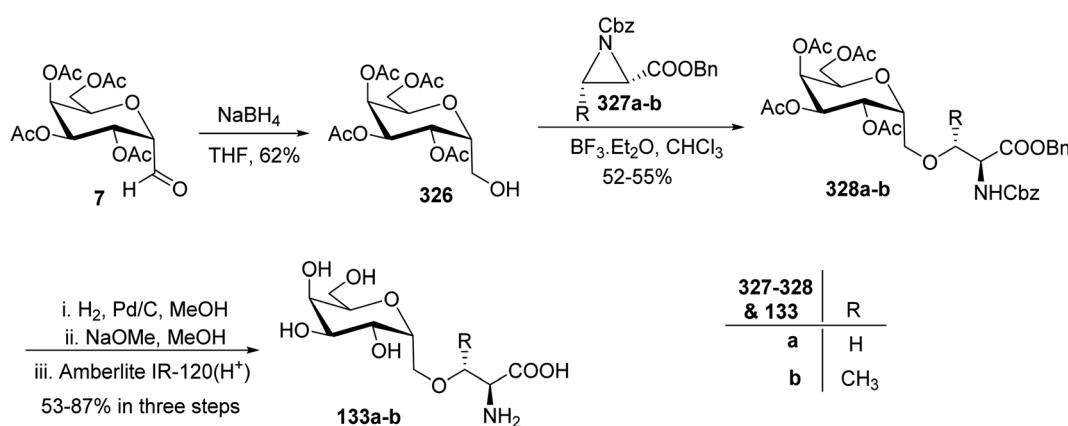
underwent oxidative cleavage of oxazolidine ring, which afforded C-glycosyl amino acids  $\beta$ -D-galactose ( $\text{CH}_2$ )<sub>2</sub>-asparagine ( $\beta$ -Gal-( $\text{CH}_2$ )<sub>2</sub>-Asn, 325c), and the corresponding *gluco*- and *manno*-isomers 325a and 325b, respectively in 95% yield (Scheme 49).

Kroger *et al.*<sup>25</sup> synthesised O-glycosyl amino acid mimetics 3'-O-(2,6-anhydro-D-glycero-L-glucopyranosyl)-L-serine (328a) and -L-threonine (328b), which acted as building blocks for O-glycopeptides. The synthesis proceeded *via*  $\alpha$ -D-galactopyranosyl aldehyde 7, which in turn was prepared from 1,2,3,4,6-penta-O-acetyl- $\beta$ -D-galactopyranose 5 *via* an allene approach. Aldehyde 7 on reduction with sodium borohydride gave C-glycosidic methylene galactitol 326 in 62% yield. Compound 326 in the presence of Lewis acid  $\text{BF}_3 \cdot \text{Et}_2\text{O}$  in toluene, reacted with the activated aziridine ring containing compounds 327a-b to form compounds 328a-b in 52-55% yield. The C-glycosyl amino acids 133a-b in 53-87% yields were obtained by hydrogenolytic deprotection followed by Zempen deacetylation of compounds 328a-b (Scheme 50). C-Glycosyl amino acids 133a-b were found to be a competitive inhibitor of  $\alpha$ -glycosidase from *Aspergillus niger*.

Risseeuw *et al.*<sup>85</sup> worked to design two synthetic pathways to obtain  $\delta$ -substituted pyranoid sugar amino acids (SAAs). This synthesis was initiated from easily and readily available C-glycopyranosyl aldehyde 4a. Condensation of formyl tetra-

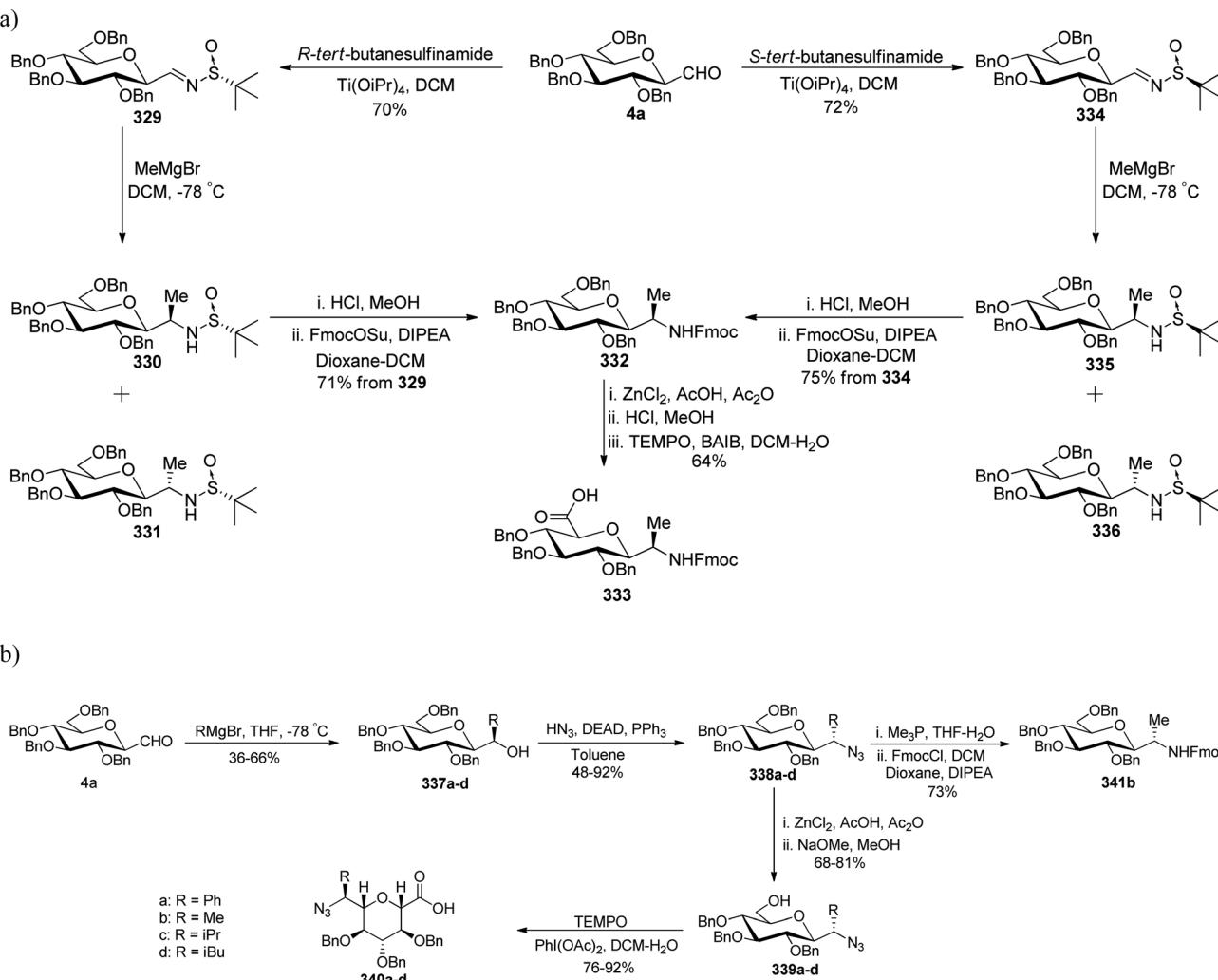
O-benzyl- $\beta$ -D-C-glucopyranoside 4a with *R*-tert-butanesulfinyl amide yielded *R*-tert-butanesulfamide 329 in 70% yield, which on alkylation in the presence of  $\text{MeMgBr}$  in DCM afforded *R*-methyl adduct 330 in excess over the corresponding *Z*-diastereoisomer 331. Adduct 330 on further acid-mediated hydrolysis and installation of Fmoc protecting group resulted in 332 in 70% yield, which on selective acidolysis of primary benzyl ether, ester hydrolysis, and oxidation afforded the carboxylate 333 in 64% yield. The same stereoisomer 332 was formed in 75% yield when the whole reaction sequence was repeated with *S*-tert-butanesulfinamide, and the final product obtained was carboxylate 333 (Scheme 51a).

Treatment of C-glycopyranosyl aldehyde 4a with different Grignard reagents afforded single isolated diastereomers 337a-d in 36-68% yield. Further, Mitsunobu displacement using  $\text{HN}_3$ , DEAD, and  $\text{PPh}_3$  in toluene afforded azide 338a-d in 48-92% yield, with inverted stereochemistry. The reduction of azide 338b using  $\text{Me}_3\text{P}$ ,  $\text{THF-H}_2\text{O}$  followed by Fmoc protection produced 341b in 73% yield. Selective acidolysis of primary benzyl protection of compounds 338a-d with  $\text{ZnCl}_2\text{-AcOH}$  yielded compounds 339a-d in 68-81% yield, which were further oxidized with TEMPO to afford L,L dipeptide isosters 340a-d in 76-92% yield (Scheme 51b).



Scheme 50 Synthesis of C-glycosyl amino acids 133a-b.





Scheme 51 (a) Synthesis of  $\delta$ -substituted pyranoid sugar amino acid 333. (b) Synthesis of  $\text{L,L}$ -dipeptides isosteres 340a-d.

Three-component reaction on *C*-glycopyranosyl aldehyde was achieved by Dondoni *et al.*<sup>86</sup> to synthesize *C*-glycopyranosyl- $\beta$ -lactams and further elaborated synthesis of *C*-glycosyl isoserines and dipeptide precursors. *C*-Galactopyranosyl aldehyde 4c was reacted with easily available primary amines and substituted with acetyl chlorides to give a small library of *C*-galactopyranosyl- $\beta$ -lactams 342a-g with 65-94% yield (Scheme 52a).

First, *C*-glycosylimine was generated by the reaction between *C*-galactopyranosyl aldehyde and an excess amount of primary amine derivatives in DCM, and thereafter resin supported sulfonyl chloride removed the excess of unreacted alkylamine from the solution. The resulting mixture was treated with substituted acetyl chloride in the presence of triethylamine to afford *C*-galactopyranosyl- $\beta$ -lactam. The amino-methylated resin was used to remove excess ketene and unreacted acetyl chloride from the reaction mixture. These  $\beta$ -lactams could be utilised to synthesise other classes of biologically active compounds, *i.e.*  $\beta$ -amino acids.

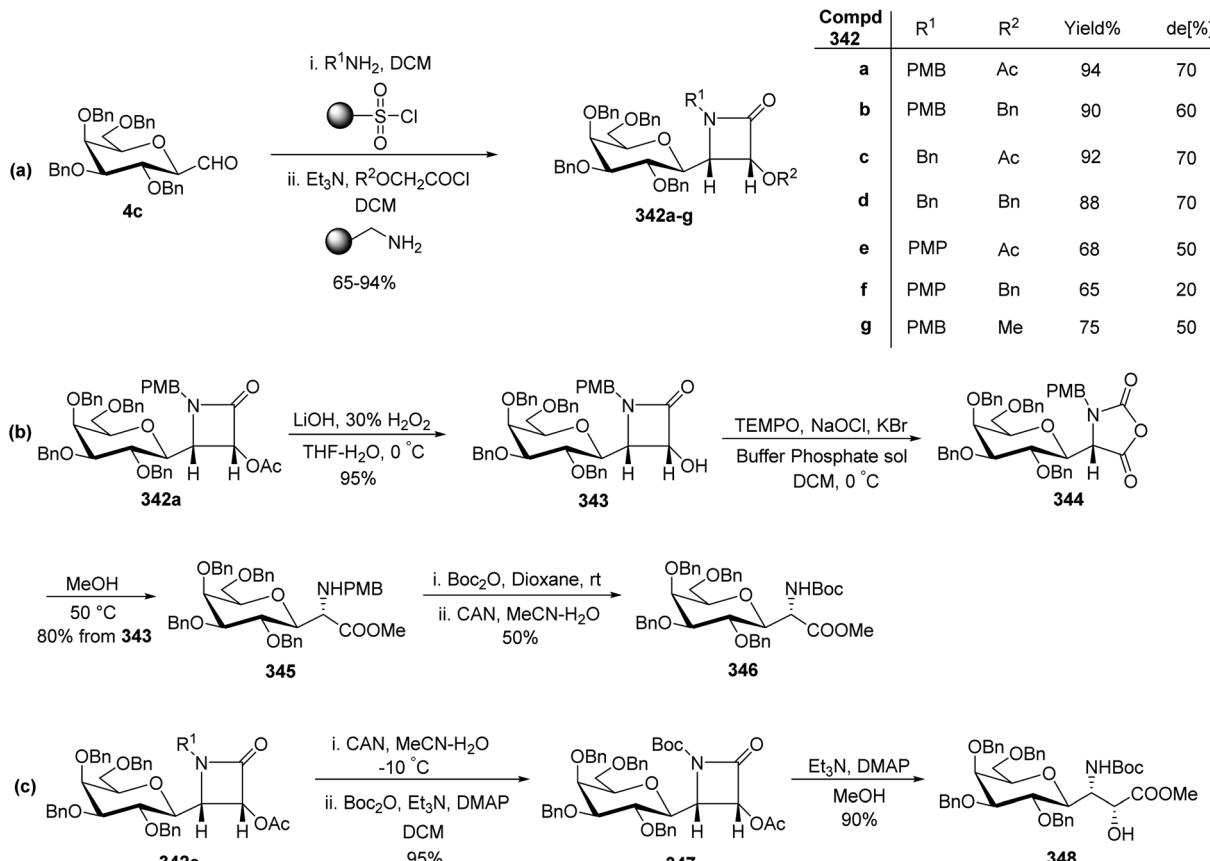
Deacetylation of *C*-glycosyl- $\beta$ -lactam 342a was achieved using LiOH-30%  $\text{H}_2\text{O}_2$  to afford 343 in 95% yield, which on oxidation

with TEMPO-NaOCl furnished *N*-carboxy anhydride 344 (Scheme 52). Ring-opening of 344 using methanol followed by protection of  $-\text{NH}$  with Boc group and deprotection of PMB functional group with CAN produced compound 346 in 50% yield (Scheme 52b).

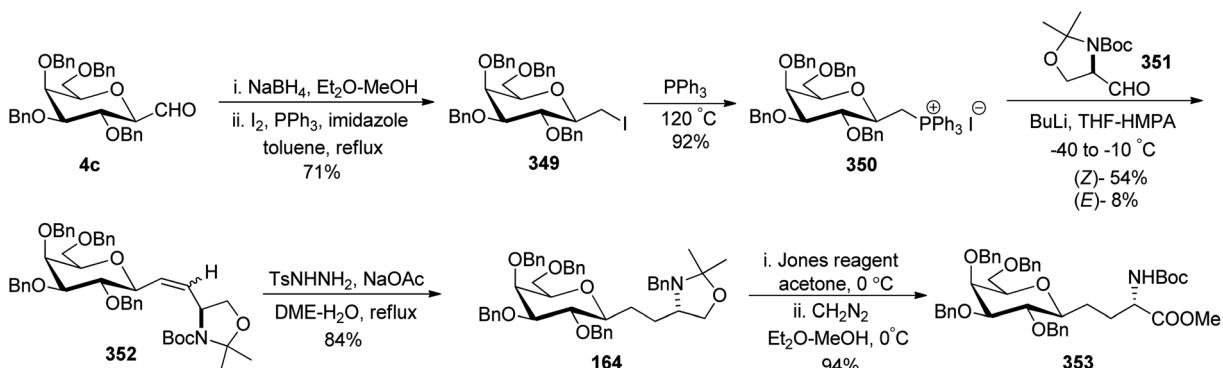
Synthesis of *C*-galactopyranosyl-*iso*-serine 348 was achieved with 90% yield by conversion of *C*-glycosyl- $\beta$ -lactam 342e into 347 with 95% yield *via* switching of *N*-protective group using  $\text{Et}_3\text{N}-\text{DMAP}$  in MeOH (Scheme 52c).

In 1998, Dondoni *et al.*<sup>64</sup> reported the synthesis of *C*-galactopyranosyl- $\alpha$ -amino acids *i.e.* *C*-analogue of  $\beta$ -D-galactopyranosyl-L-serine. First of all,  $\beta$ -*C*-galactopyranosyl aldehyde 4c was reduced using  $\text{NaBH}_4$  in MeOH followed by iodination with iodine- $\text{PPh}_3$ -imidazole furnished compound 349 in 71% yield, which was efficiently converted into sugar-based Wittig reagent 350 in 92% yield by reaction with  $\text{PPh}_3$ . Subsequently, Wittig coupling between 350 and 351 in the presence of butyl lithium-THF-HMPA afforded 352 with as a mixture of stereoisomers (Z-54%, E-8%). Reduction with diimide (generated *in situ*) gave 164 in 84% yield, which was





Scheme 52 Synthesis of C-galactopyranosyl-β-lactams 342a-g, α-amino ester 346, C-galactosyl isoserine methyl ester 348.



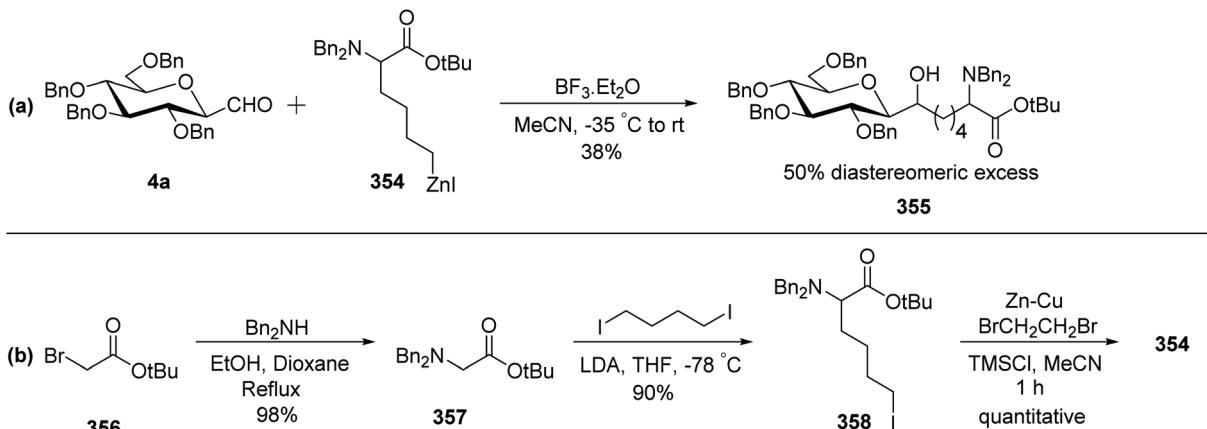
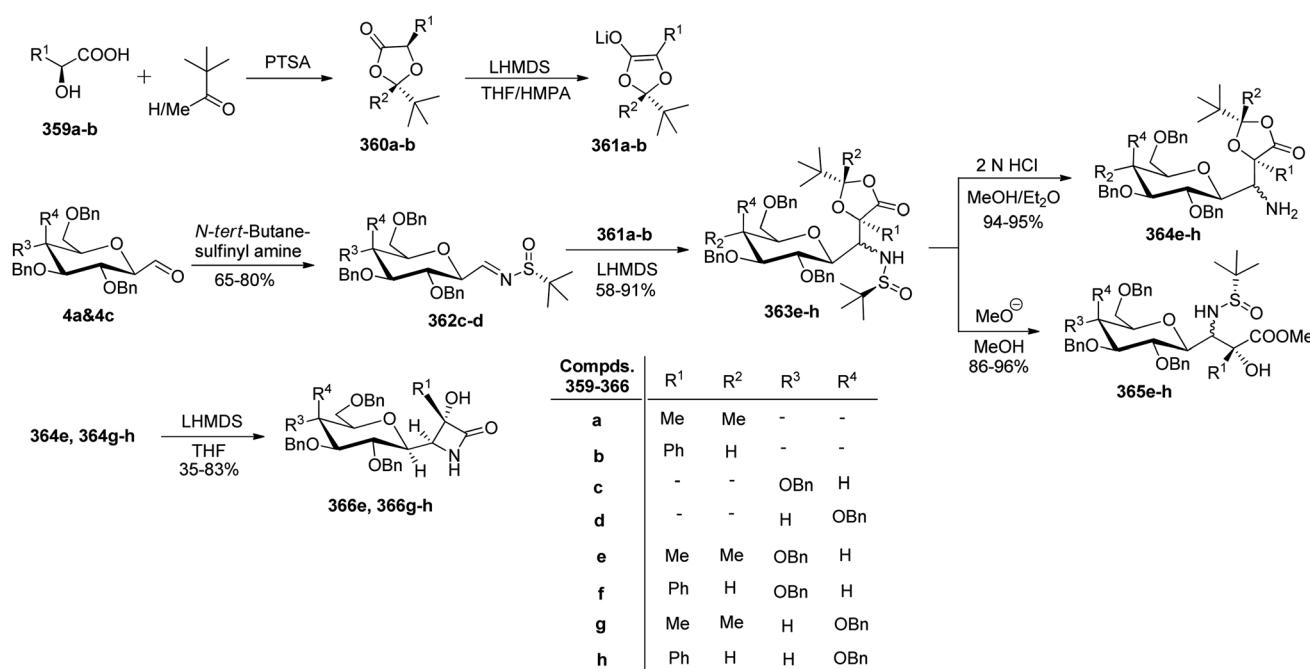
Scheme 53 Synthesis of β-D-galactopyranosyl-L-serine 353.

treated with Jones' reagent and then methylation with diazomethane afforded C-linked analogue of β-D-galactopyranosyl-L-serine 353 in 94% yield (Scheme 53).

Boutard *et al.*<sup>87</sup> synthesized C-glucopyranosyl-α-amino acids 355 in 38% yield with 50% diastereomeric excess where the reaction between C-glucopyranosyl aldehyde 4a and organozinc reagent of amino acid 354 was carried out in presence of Lewis acid  $\text{BF}_3 \cdot \text{Et}_2\text{O}$  in acetonitrile (Scheme 54a). Compound 354 was synthesized from α-bromo ester in three steps as shown in (Scheme 54b).

Guerrini *et al.*<sup>88</sup> designed one-pot synthesis of constrained N,O-orthogonally protected C-glycosyl norstatines (α-hydroxy-β-amino acids) 365e-h, which was formed by the reaction of enolates of dioxolanones 361a-b with (S)-N-sulfinyl azomethines 362c-d following Seebach's SRS (Self-Regenerating Stereocenters) principle (Scheme 55). In the compounds 363e-h, the N and O were orthogonally protected with the sulfinyl group at the nitrogen atom and the acetal moiety of the dioxolanone ring. The sulfinyl group present in the compounds 363e-h was removed by using 2 N HCl acidic condition in a solvent mixture



Scheme 54 Synthesis of C-glucopyranosyl- $\alpha$ -amino acid 355.Scheme 55 Synthesis of C-glycosyl norstatines ( $\alpha$ -hydroxy- $\beta$ -amino acids) 365e-h.

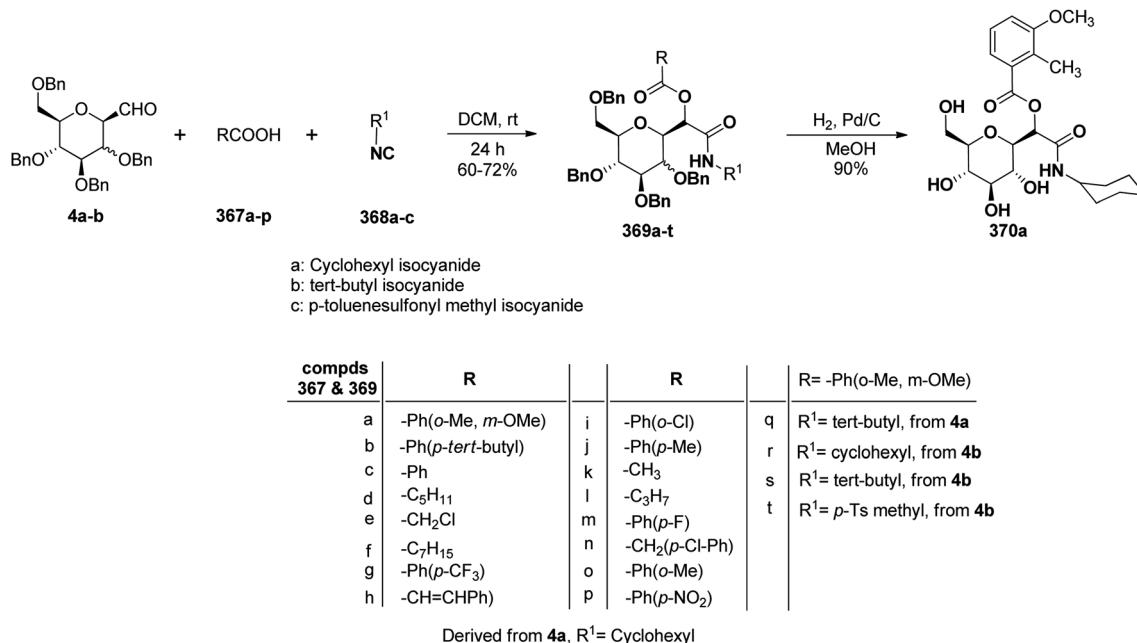
of methanol and diethyl ether (1 : 1) leading to the formation of *N*-deprotected 1-*C*-glycosyl amino-dioxolan-4-ones 364e-h in 94–95% yield. The acetal groups of 363e-h were removed by methoxide-induced methanolysis forming, corresponding methyl *C*-glycosyl-sulfinylamino-isoserinates 365e-h with 86–96% yield. Compounds 364e and 364g-h were converted into corresponding  $\beta$ -lactams 366e and 366g-h, respectively, with 35–83% yield using LHMDS in THF (Scheme 55).

Kumar *et al.*<sup>89</sup> recently designed a protocol based on the Passerini<sup>90</sup> multi-component reaction to synthesize a library of  $\beta$ -*C*-glycopyranosyl- $\alpha$ -acyloxy amides (Scheme 56). The component *C*-glycopyranosyl aldehyde 4a-b, aryl/alkyl acid derivatives 367a-p, and isocyanides 368a-c were reacted by using DCM as the solvent at room temperature to afford glucopyranosyl- $\alpha$ -acyloxy amides 369a-t in good to excellent yield (60–72%).

These glucopyranosyl  $\alpha$ -acyloxy amides are commonly known as depsipeptides and are biologically significant. Further, 369a was debenzylated using  $H_2$ , Pd/C in methanol to obtain 370a in 90% yield.

Raunkjaer *et al.*<sup>91</sup> synthesised highly functional, novel dipeptide isosteres *via* diastereoselective alkylation/arylation of sugar amino acids. This novel sugar amino acid (SAA) when applied in peptide synthesis protocol afforded a cyclic tetramer with excellent overall yield. The synthesis started with perbenzylated  $\beta$ -*C*-glucopyranosyl aldehyde 4a, which on condensation with (*R*)-*tert*-butylsulfinamide in the presence of anhydrous  $CuSO_4$  in DCM-derived sulfinimine 329 in 70% yield, which was treated with  $PhMgBr$  in toluene leading to the formation of sulfinamide 371 in >95% diastereomeric excess. Compound 371 was desulfinylated by  $HCl$  in methanol giving HCl salt of 372,





Scheme 56 Synthesis of depsipeptides 369a-t and 370a.

which was Boc protected using  $\text{Boc}_2\text{O}$ , DIPEA in DCM to produce corresponding *tert*-butoxycarbonylate, which underwent hydrogenolysis of benzyl ether group in the presence of Pd/C followed by removal of protecting group leading to the synthesis of compound 375 in 62% yield (Scheme 57a). The HCl salt of compound 372 was Fmoc protected to derive 373 with 63% yield in the presence of Fmoc-OSu, DIPEA, and DCM in dioxane. Compound 373 underwent selective debenzylation at the primary hydroxyl group on treatment with anhydrous  $\text{ZnCl}_2$  in  $\text{AcOH}$  and  $\text{Ac}_2\text{O}$ , followed by acid-catalyzed deacetylation ( $\text{HCl}$  in  $\text{MeOH}$ ) and oxidation using TEMPO and BAIB, leading to sugar amino acid 374 in 80% yield (Scheme 57b).

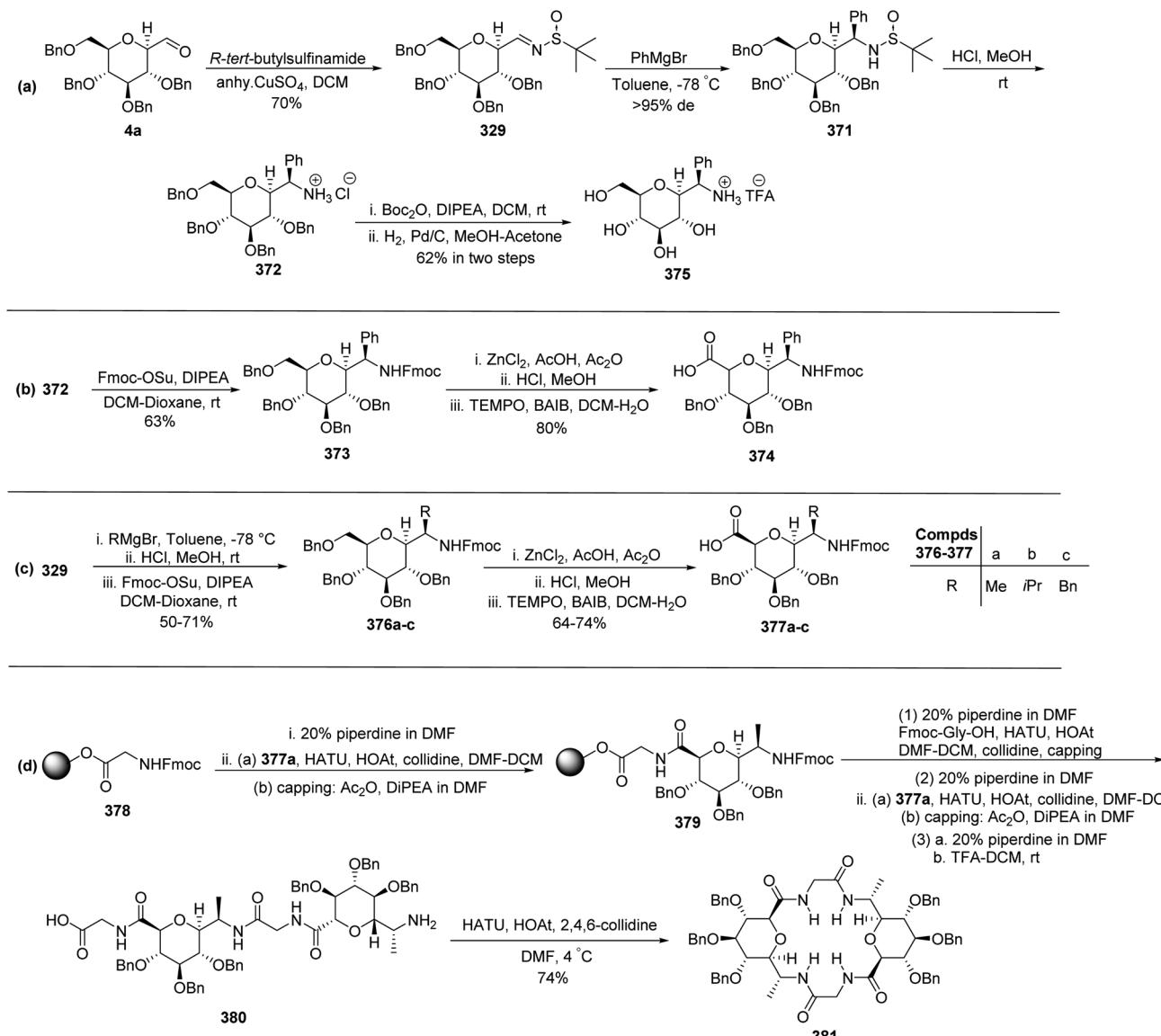
The sulfinimine derivative 329 was employed to synthesize a series of substituted SAAs 377a-c. Compound 329 was treated with  $\text{RMgBr}$  in toluene and  $\text{HCl}$  in methanol followed by the removal of the sulfoxyl auxiliary and Fmoc protection, which led to the production of compounds 376a-c in 50-71% yield. The primary benzyl-protected hydroxyl functionalities were converted into corresponding carboxylic acid groups following the reaction sequence leading to the formation of compounds 377a-c in 64-74% yield (Scheme 57c). The alkylated SAAs were synthesized for their incorporation into oligomeric sequences. SAA 377a was condensed with glycine-functionalized Wang resin 378 (Scheme 57d), thus producing immobilized product 379, which upon removal of the Fmoc protecting group, and repetition of coupling steps followed by TFA-mediated cleavage from the solid support transformed into the linear tetramer 380. This linear tetramer 380 was cyclized under high dilution to afford benzylated cyclic tetramer 381 in 74% yield.

Singh *et al.*<sup>92</sup> reported the synthesis of sugar-amino acid hybrid macrocycle starting from 2,6-anhydro heptitol 383a, which was synthesized from *C*-glycopyranosyl aldehyde 4a. Synthesis of 2,6-anhydro heptitol 383a-c was achieved by Khatri

*et al.*<sup>52</sup> from the reduction of aldehyde 4a-c using  $\text{NaBH}_4$  in methanol afforded 382a-c in 90-95% yield, followed by treatment with trifluoro acetic acid, acetic anhydride, and sodium methoxide in methanol (Scheme 58a). 2,6-Anhydroheptitol 383a was condensed with *N*-boc-glycinate using EDC·HCl, DMAP in dichloromethane produced 2,6-anhydro heptitol bis-glycinate 384 in 99% yield. Treatment with trifluoro acetic acid afforded deprotection of the Boc-group to produce 385 in 99% yield, which was reacted with succinic/pyridine dicarboxylic acid to obtain sugar-amino acid hybrid macrocycle 386 and 388 in 40% yield (Scheme 58b). The deprotection of the benzyl group using Pd/C in methanol was achieved on macrocycle 386 to produce macrocycle 387 in 95% yield. Further host-guest anion interaction studies were carried out on macrocycles 386 and 388 with TBA salt of Boc-glycinate. Based on <sup>1</sup>H NMR titration experiments, it was found that the carboxylate anion of Boc-glycinate salt exhibits interaction with the host macrocycle through hydrogen bonding. The macrocyclic compounds 386 and 388 have binding constants ( $K_a$ ) of  $9.201 \times 10^3 \text{ M}^{-1}$  and  $1.437 \times 10^4 \text{ M}^{-1}$ , respectively.

Leclerc *et al.*<sup>46</sup> reported a highly selective synthesis of *C*-AFGP analogue 125 (Scheme 59). Julia-Kocienski-Lythgoe (JKL) olefination reaction was carried out between *C*-glycopyranosyl aldehyde 90 and sulfone 389 to obtain glycopyranosyl alkene 390 in 65% yield. The sulfone 389 used here could be synthesized from orthogonally protected L-serine methyl ester 394 (Scheme 59b). Thus, the Mitsunobu reaction of 389 with 5-phenyl tetrazolyl thiol furnished 395 in 82% yield. Subsequently, reduction with lithium borohydride followed by *N*,*O*-isopropylidene formation and oxidation using sharpless conditions furnished 396 in 65% yield.

The glycopyranosyl alkene 390 was reduced with concomitant deprotection of the Cbz group afforded amino alcohol 391



Scheme 57 Synthesis of benzylated cyclic tetramer 381.

in 95% yield using  $\text{H}_2$ ,  $\text{Pd}(\text{OH})_2$  in ethanol. Protection with Fmoc carbamate furnished 392 in 75% yield, which was oxidised to carboxylic acid 393 with 80% yield using TEMPO,  $\text{PhI}(\text{OAc})_2$ , and  $\text{NaClO}_2$ . Finally, synthesis of glycoconjugate 125 was achieved using standard Fmoc-based solid phase synthesis with Wang resin in 20% yield. Glycoconjugate 125 is a potent inhibitor of ice recrystallization and could protect embryonic liver cells from cryo-injury at millimolar concentration. Thus *C*-AFGP analogue 125 is an effective cryoprotectant for human embryonic liver cells and inhibition of ice recrystallization in the course of cryopreservation is an important function for a cryoprotectant.

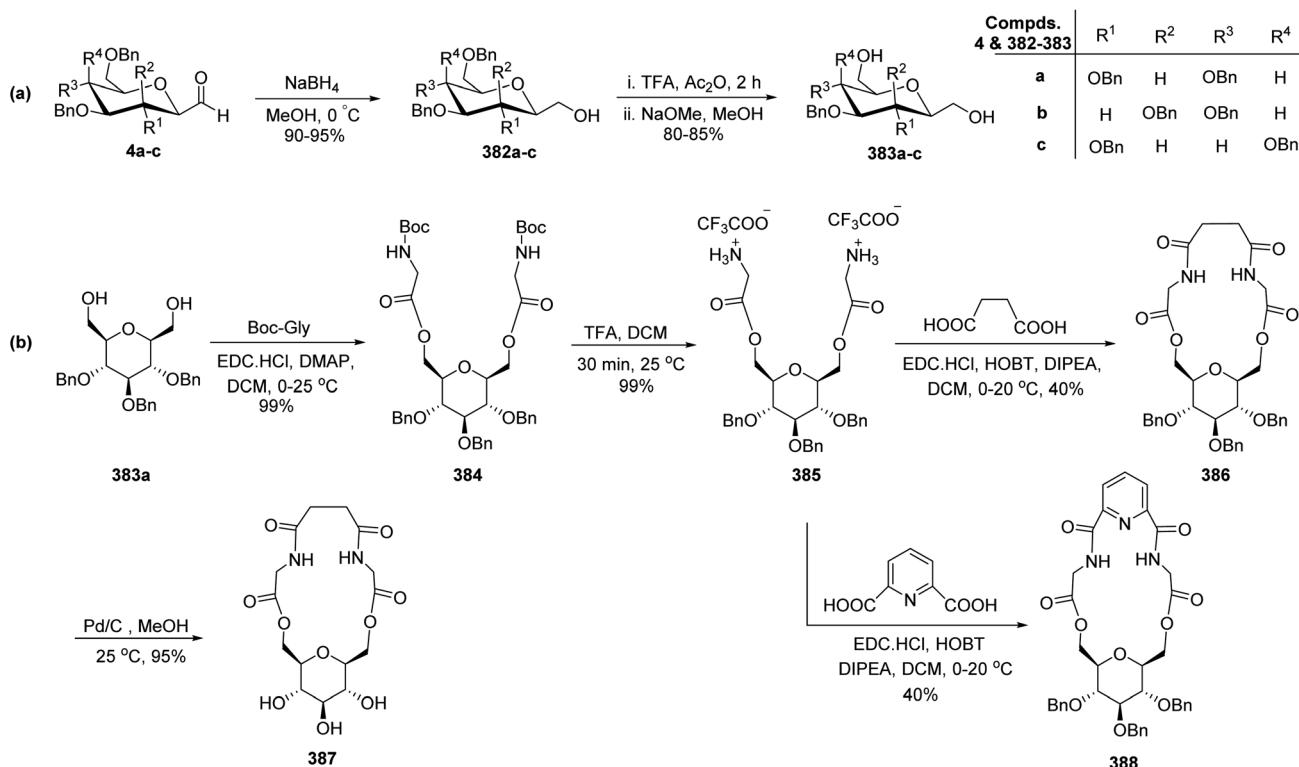
### 3.5 C-Glycopyranosyl phenyl methane and its derivatives

Kolympadi *et al.*<sup>26</sup> synthesized ( $\alpha$ -D-galactosyl)phenylmethane (402) and  $\alpha$ - and  $\beta$ -D-galactosyl-(difluoro)phenylmethane, *i.e.*

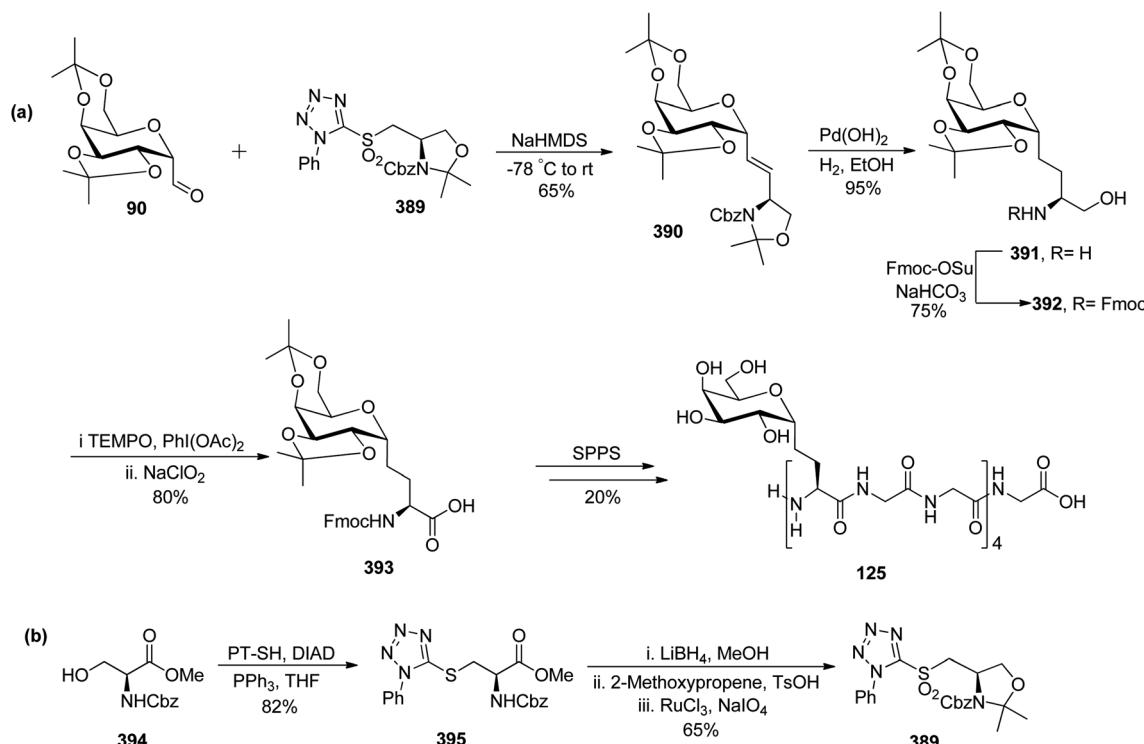
anomers 401 and 398, respectively.  $\alpha$ - and  $\beta$ -Glycopyranosyl aldehydes 4c and 3c on the addition of phenylmagnesium bromide followed by oxidation with PCC in DCM afforded corresponding ketones 396 and 399 in 50% and 45% yields, respectively. Ketones 396 and 399 upon difluorination with Deoxo-Fluor reagent in the presence of catalytic HF in pyridine afforded  $\beta$ - and  $\alpha$ -CF<sub>2</sub> protected sugar analogues 397 and 400 in 23% and 77% yields, respectively. Finally, benzyl protection of compounds 397 and 400 was deprotected by hydrogenolysis to give ( $\beta$ - and  $\alpha$ -D-lactosyl)-(difluoro)phenylmethane 398 and 401 in 67% and 70% yield, respectively. ( $\alpha$ -D-Galactosyl)phenylmethane 402 was obtained from glycopyranosyl ketone 399 by reduction with catalytic hydrogenolysis followed by deprotection of benzyl ether (Scheme 60).

McGrane *et al.*<sup>93</sup> worked on designing a synthetic route for *C*-mannosides analogues, which specifically block uropathogenic





Scheme 58 Synthesis of 2,6-anhydro heptitol 383a-c and sugar-amino acid hybrid macrocycles 386–388.

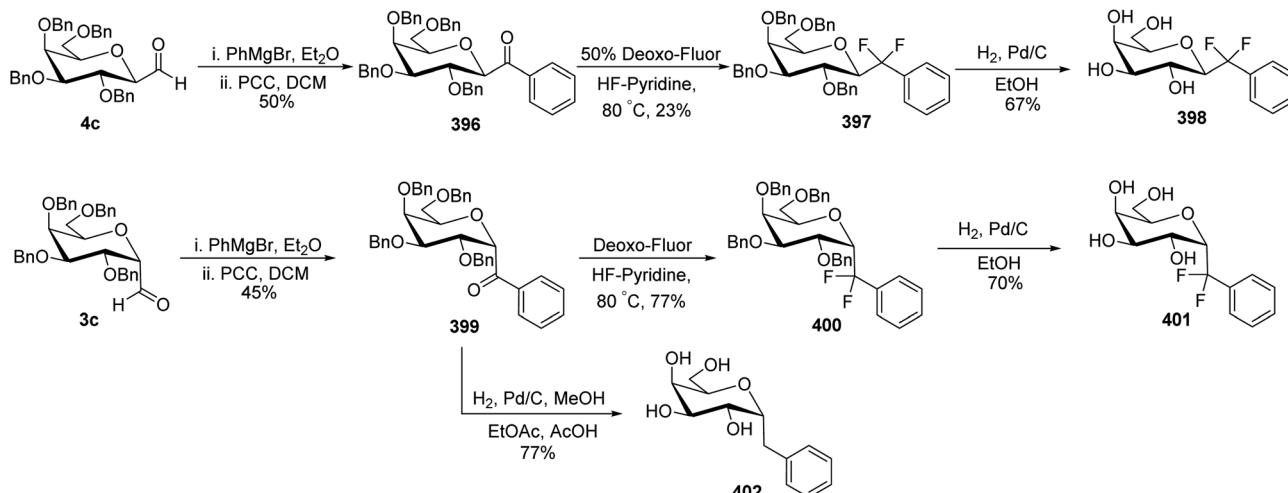


Scheme 59 Synthesis of C-AFGP analogue 125.

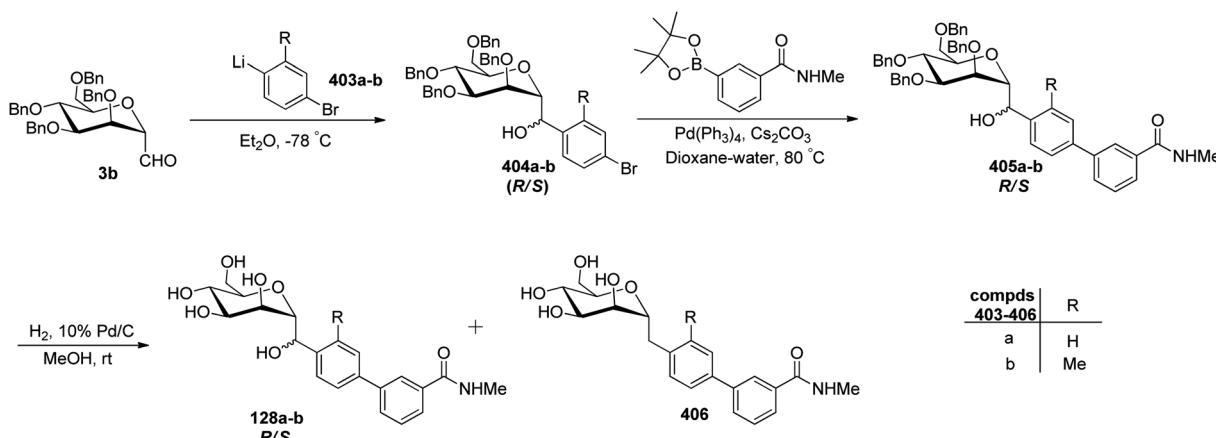
*Escherichia coli* from colonizing the lower urinary tract. *C*-Mannosides were synthesised *via* a new pathway starting from *C*-linked glycopyranosyl aldehyde **3b**, which on reaction with

organolithium reagent **403a–b** formed *in situ* by lithiation of 1,4-dibromobenzene with butyl lithium afforded *R/S* mixture of alcohol **404a–b**. The palladium-mediated reaction of alcohol





Scheme 60 Synthesis of compounds 398, 401, and 402.



Scheme 61 Synthesis of C-mannosides analogues 128a-b and 406.

**404a-b** with 3-(*N*-methylaminocarbonyl)phenylboronate furnished the cross-coupled carboxamide **405a-b**, which on further hydrogenation with  $\text{H}_2$ ,  $\text{Pd/C}$  afforded mannosides **128a-b** and **406** (Scheme 61). Methylene *C*-mannoside can be synthesised only by differing the organolithium reagent (4-bromo-2-methyliodobenzene).

Dietrich *et al.*<sup>42</sup> utilised the  $\alpha$ -*C*-glycopyranosyl aldehyde for the synthesis of benzyl- $\alpha$ -*C*-glucosides and anilinomethyl- $\alpha$ -*C*-glucosides **412a-d**, which act as  $\alpha$ -glucosidase inhibitors.  $\alpha$ -*C*-glucopyranosyl aldehyde **3a** was treated with Grignard reagent phenylmagnesium bromide to afford diastereoselectively one isomer of compound **407** in 80% yield. Phenylcarbinol derivative **407** was converted into mesylated product **409**, which on treatment with tetramethylguanidine azide in DMF afforded **410** together with elimination product **408**. Azido compound **410** was reduced with  $\text{LiAlH}_4$  to furnish **411** in 56% yield, which was converted into one of the desired compounds **412a** via a sequence of reactions (Scheme 62).

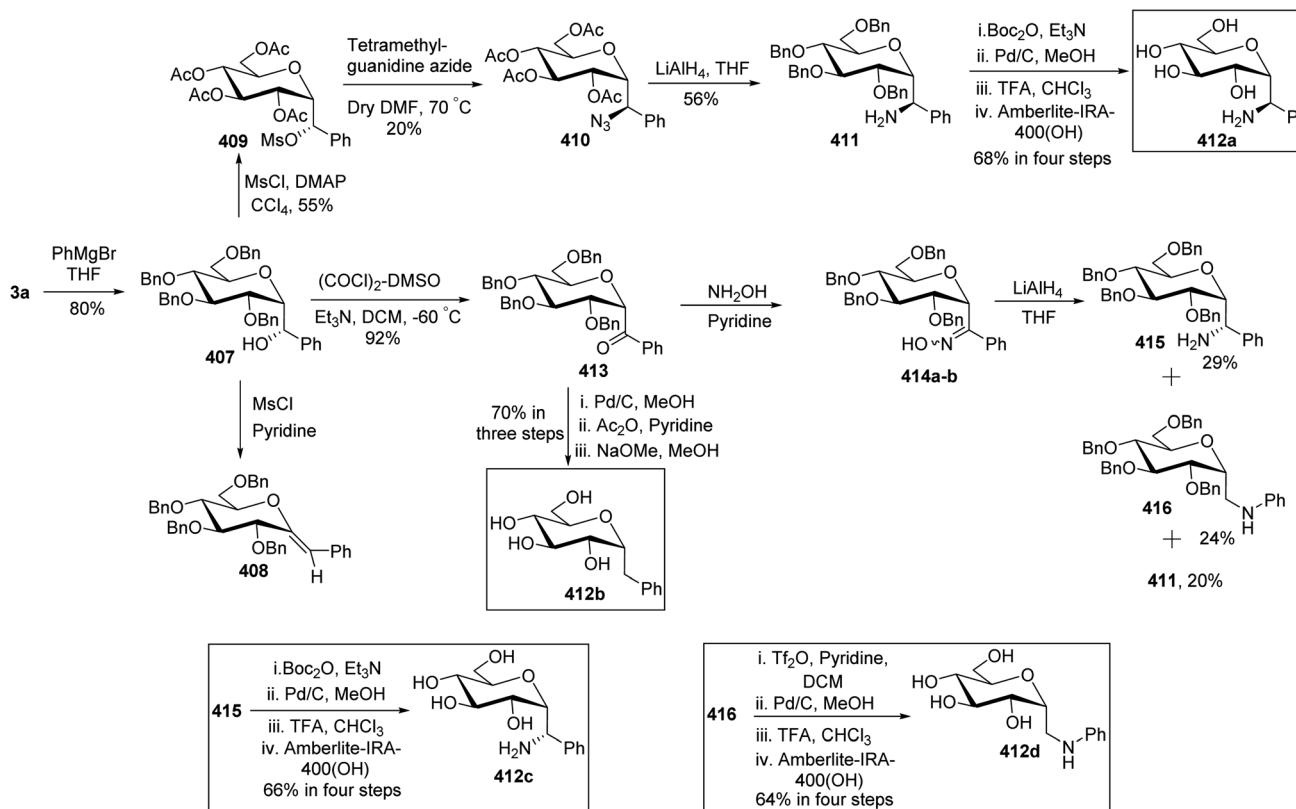
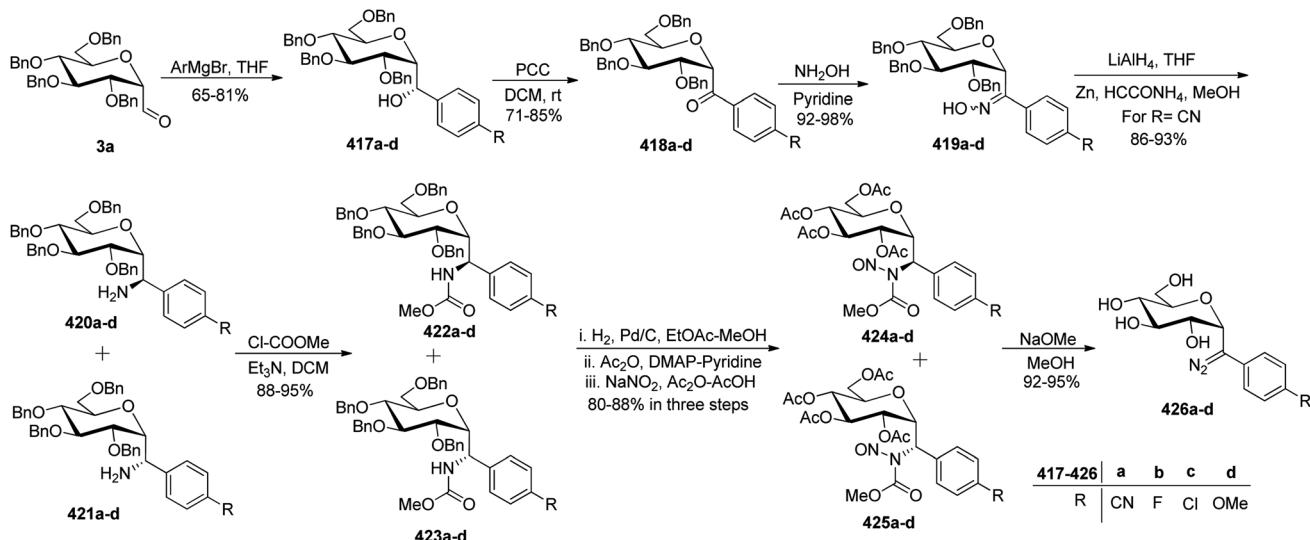
Due to the low yield of the product, another route for the synthesis of **412a** was investigated. Swern oxidation of **407**

afforded compound **413** in 92% yield, which on treatment with hydroxylammonium chloride produced diastereomeric oximes **414a-b** in a 1:1 ratio. Reduction of an isomeric mixture of **414a-b** with  $\text{LiAlH}_4$  furnished diastereomeric amines **411**, **415** and **416** in a ratio of 1:1:1 with 20%, 29%, and 24% yield, respectively. Finally, desired **412a**, **412c**, and **412d** were obtained in 64–68% yield in four steps from **411**, **415**, and **416** following the reaction sequence as shown in Scheme 62.

Direct hydrogenolysis of compound **413** with palladium on charcoal following *O*-acetylation of crude product and treatment with sodium methoxide was carried out to obtain desired **412b** in 70% yield.

Geng *et al.*<sup>94</sup> synthesized *C*-( $\alpha$ -*D*-glucopyranosyl)-phenyldiazomethane using  $\alpha$ -*C*-glucopyranosyl aldehyde **3a** as the starting precursor (Scheme 63). A library of compounds with different substituent groups at the para position of the phenyl ring was prepared and further investigated for their stability. *C*-Glucopyranosyl aldehyde **3a** was reacted with different substituted arylmagnesium bromide in THF to afford  $\alpha$ -*C*-glucopyranosyl benzylic alcohols **417a-d** in 65–81% yield with



Scheme 62 Synthesis of benzyl- $\alpha$ -C-glucosides and anilinomethyl- $\alpha$ -C-glucosides 412a-d.Scheme 63 Synthesis of C-( $\alpha$ -D-glucopyranosyl)-phenyldiazomethanes 426a-d.

different substituents at the para position of the phenyl ring. Further oxidation with PCC in DCM led to the formation of 418a-d with 71–85% yield, which on reaction with hydroxylammonium chloride furnished compounds 419a-d with 92–98% yield. Reduction of oximes 419a-d was carried out to furnish a diastereomeric mixture of amines 420a-d and 421a-d in 86–93% yield. Reaction with methylchloroformate and

triethylamine with each of these diastereomers 420a-d and 421a-d afforded 422a-d and 423a-d, respectively in 88–95% yield. Hydrogenolytic debenzylation with H<sub>2</sub>-Pd/C followed by acetylation with acetic anhydride, further treatment with NaNO<sub>2</sub> in Ac<sub>2</sub>O-AcOH mixture afforded 424a-d and 425a-d, respectively in 80–88% yield in three steps. Both diastereomers on treatment with sodium methoxide in methanol furnished C-

( $\alpha$ -D-glucopyranosyl)-phenyldiazomethanes **426a–d** in 92–95% yield.

Investigation of the stability of these diazo compounds showed that substituent groups on the phenyl ring had a strong influence. The presence of an electron-withdrawing cyano group at the phenyl ring as in the case of compound **426a** was found to be stable enough to resist the solvolysis. Compound **426a** was further tested for inhibiting activity and type of inhibition towards  $\alpha$ -glucosidase from *Saccharomyces cerevisiae* and found that compound was an irreversible inhibitor of  $\alpha$ -glucosidase.

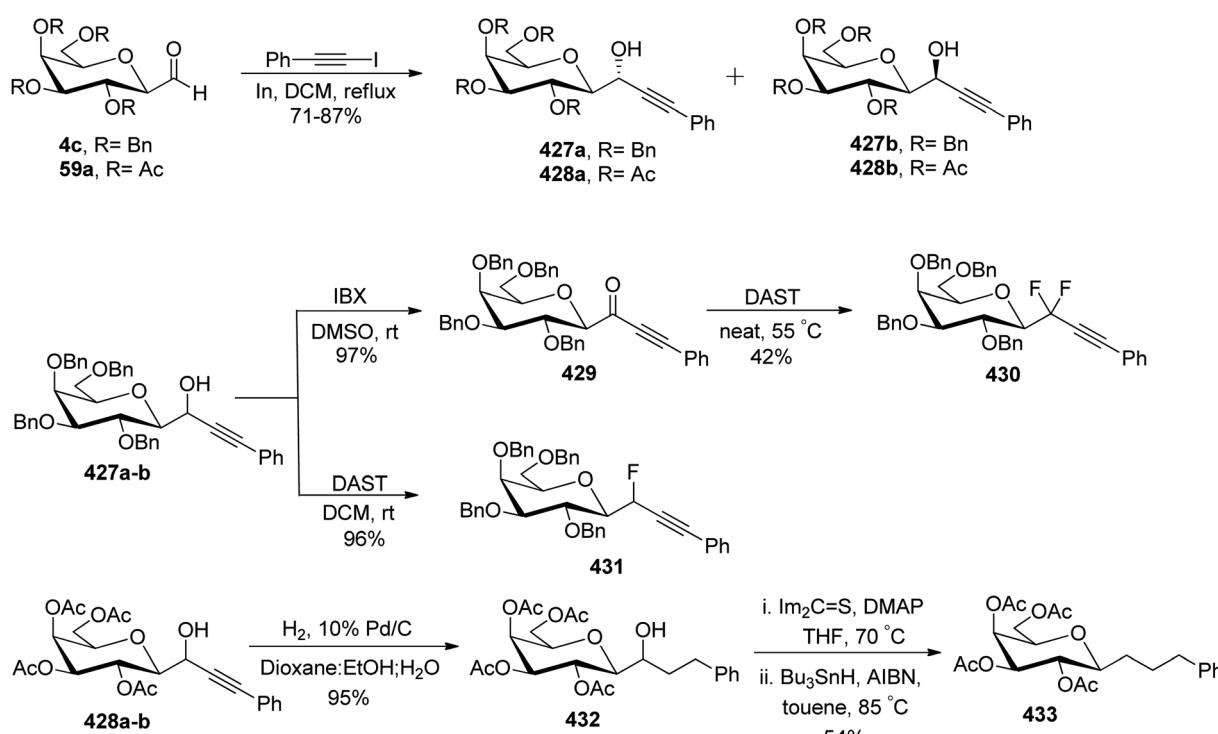
Picard *et al.*<sup>95</sup> introduced the indium-mediated alkynylation of  $\beta$ -C-galactopyranosyl aldehydes in order to synthesize various  $\beta$ -C-glycosides. Galactopyranosyl aldehydes **4c** and **59a** were reacted with phenylacetylene iodide in the presence of indium in DCM, which resulted in the formation of corresponding propargylic alcohols **427a–b** and **428a–b**, respectively in 71–87% yield, as a diastereomeric mixture (65 : 35). Propargylic alcohols **427a–b** upon oxidation with 2-iodoxybenzoic acid (IBX) in DMSO led to the formation of propargylic ketone **429** with 97% yield. Ketone **429** gave difluorinated product **430** on treatment with neat diethylaminosulfur trifluoride DAST (Scheme 64).

Also, propargylic alcohols **427a–b** were mono-fluorinated by treatment with DAST, forming corresponding fluorinated compound **431** in 96% yield (Scheme 64). The propargylic alcohol **428a–b** underwent palladium-catalysed hydrogenation leading to the formation of alcohol **432** in 95% yield, which upon treatment with thiocarbonyldiimidazole and tributyltin hydride afforded dehydroxylated compound **433** in 54% yield (Scheme 64).

Reddy *et al.*<sup>58</sup> developed a scalable synthetic approach to synthesise acyl- $C$ - $\beta$ -D-glucosides and benzyl- $C$ - $\beta$ -D-glucosides, which proved to promote glucose-uptake activity in C2C12 myotubes. The synthesis of these acyls and benzyl- $C$ - $\beta$ -D-glucosides was executed from  $\beta$ -C-glucopyranosyl aldehyde **4a**, which was oxidised under Pinnick oxidation reaction conditions using  $\text{NaClO}_4$  and  $\text{H}_2\text{O}_2$  affording carboxylic acid **434** in 97% yield. Carboxylic acid **434** on reaction with pivolyl chloride in  $\text{Et}_3\text{N}$  followed by  $\text{HCl}\cdot\text{NH}(\text{Me})(\text{Ome})$  in DCM afforded amide **435** in 93% yield. The amide **435** was easily converted to a range of ketone derivatives **436a–p** in 60–94% yields with differently substituted aryl groups by Grignard reagent  $\text{ArMgX}$  in dry THF. The ketone derivatives **436a–p** were converted to corresponding acyl- $C$ - $\beta$ -D-glucoside derivatives by first reacting with TMSOTf in acetic anhydride yielding peracetylated compounds **437a–p** in 46–97% yield, followed by its deprotection using  $\text{NaOMe}$  in methanol afforded acyl- $C$ - $\beta$ -D-glucosides **126a–p** in 60–85% yield (Scheme 65a).

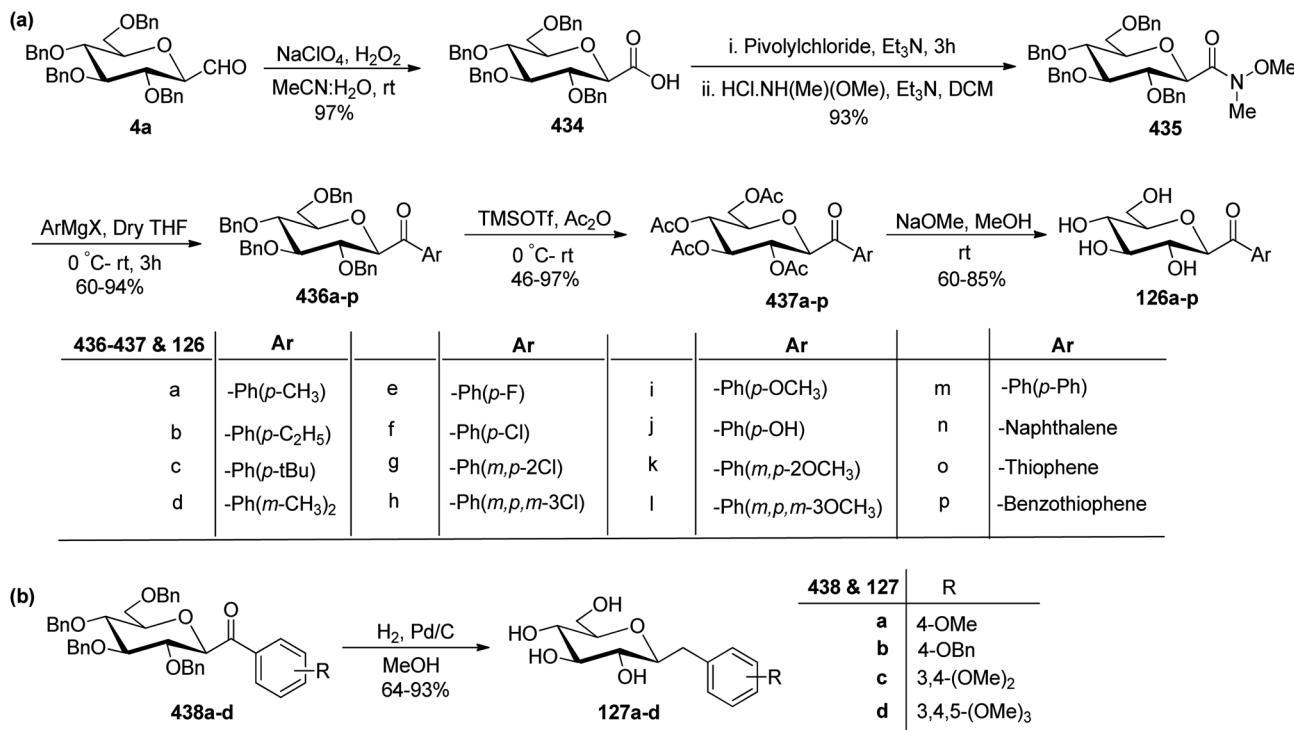
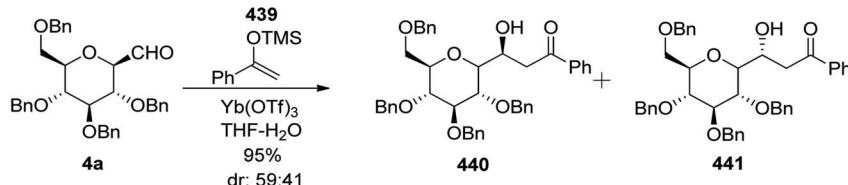
The  $C$ - $\beta$ -D-glucosides **438a–d** were also synthesised by one-pot reduction of the carbonyl group and benzyl ether deprotection from the corresponding perbenzylated- $C$ - $\beta$ -D-glucosides **127a–d** using  $\text{H}_2$ ,  $\text{Pd/C}$  in methanol in 64–93% yield (Scheme 65b).

Zeitouni *et al.*<sup>70</sup> reported a new strategy for the formation of C-glycosides by using the Mukaiyama aldol reaction. C-Glucopyranosyl aldehyde **4a** was reacted with trimethylsilyl enol ether **439** using Mukaiyama aldol reaction in the presence of  $\text{Yb}(\text{Otf})_3$  to furnish **440** and **441** as a diastereomeric mixture in ratio 59 : 41 with 95% yield (Scheme 66).



Scheme 64 Synthesis of  $\beta$ -C-glycosides **430–433**.



Scheme 65 Synthesis of C- $\beta$ -D-glucosides 126a-p and 127a-d.

Scheme 66 Synthesis of C-glycosides 440 and 441.

### 3.6 C-Glycopyranosyl heterocycles

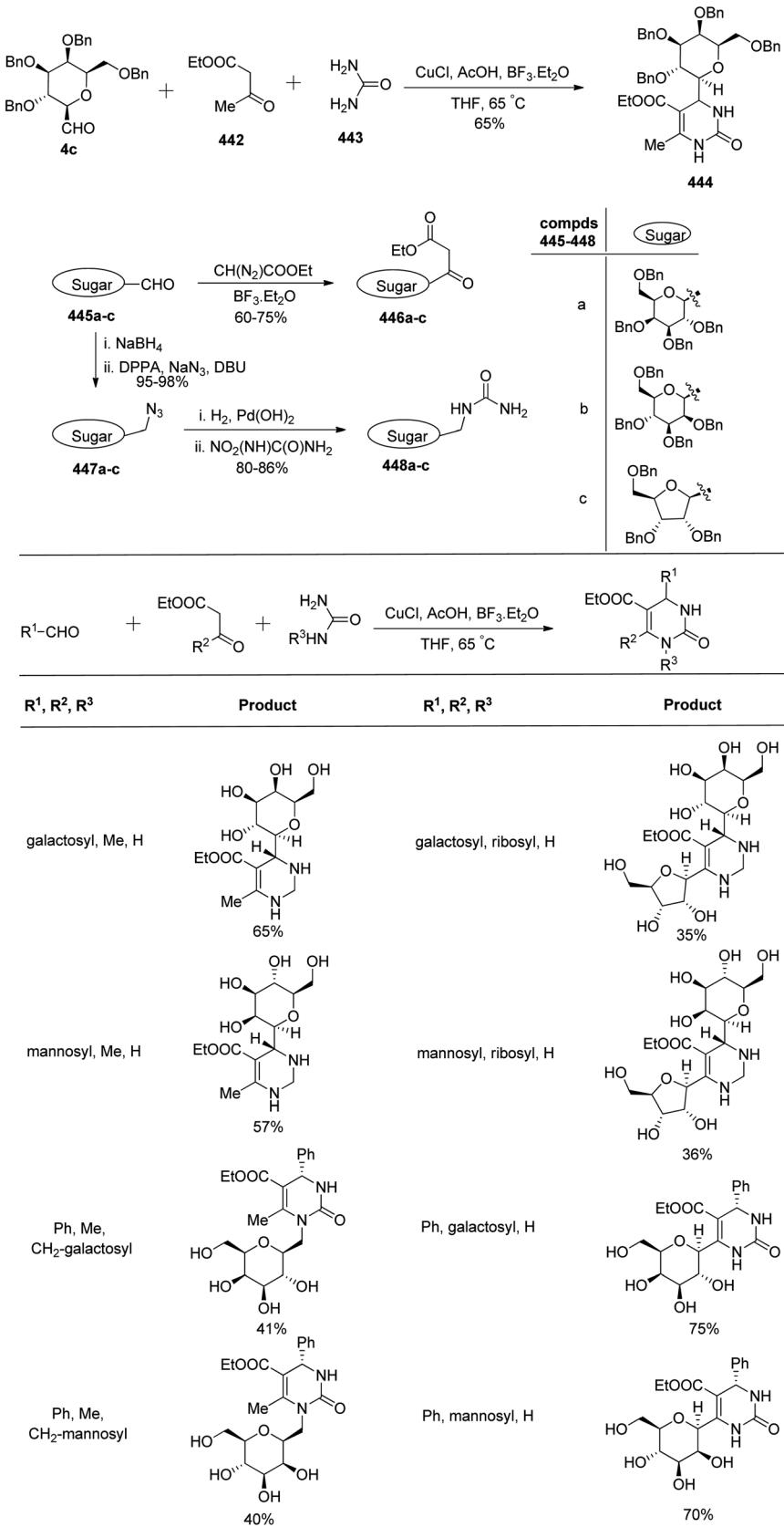
The three-component Biginelli cyclo condensation reaction involving aldehyde-ketoester-urea was explored by Dondoni *et al.*<sup>96</sup> using C-glycopyranosyl aldehyde to design a potential library of dihydropyrimidinone glycoconjugates. Under suitable acid additive and optimal reaction conditions, perbenzylated formyl C-galactopyranosyl aldehyde **4c**, ethyl acetoacetate **442**, and urea **443** were combined to form the cyclocondensed product **444** in 65% yield (Scheme 67).

Aiming to prepare a collection of mono-glycosylated and multiple-glycosylated DHPM derivatives, various substituted sugar residues were employed as substrates, which were in turn prepared from sugar aldehydes (Scheme 67). The C-glycosyl- $\beta$ -ketooesters **446a-c** were synthesised in 60–75% yield starting from sugar aldehydes **445a-c** *via* coupling with ethyl diazoacetate in the presence of  $\text{BF}_3 \cdot \text{Et}_2\text{O}$ . Similarly, the sugar aldehydes **445a-c** were reduced in the presence of  $\text{NaBH}_4$  followed by DPPA (diphenylphosphorylazide), DBU, and sodium azide to synthesize glycosylmethylazides **447a-c** in 95–98% yield *via* the formation of corresponding alcohol molecules as intermediate.

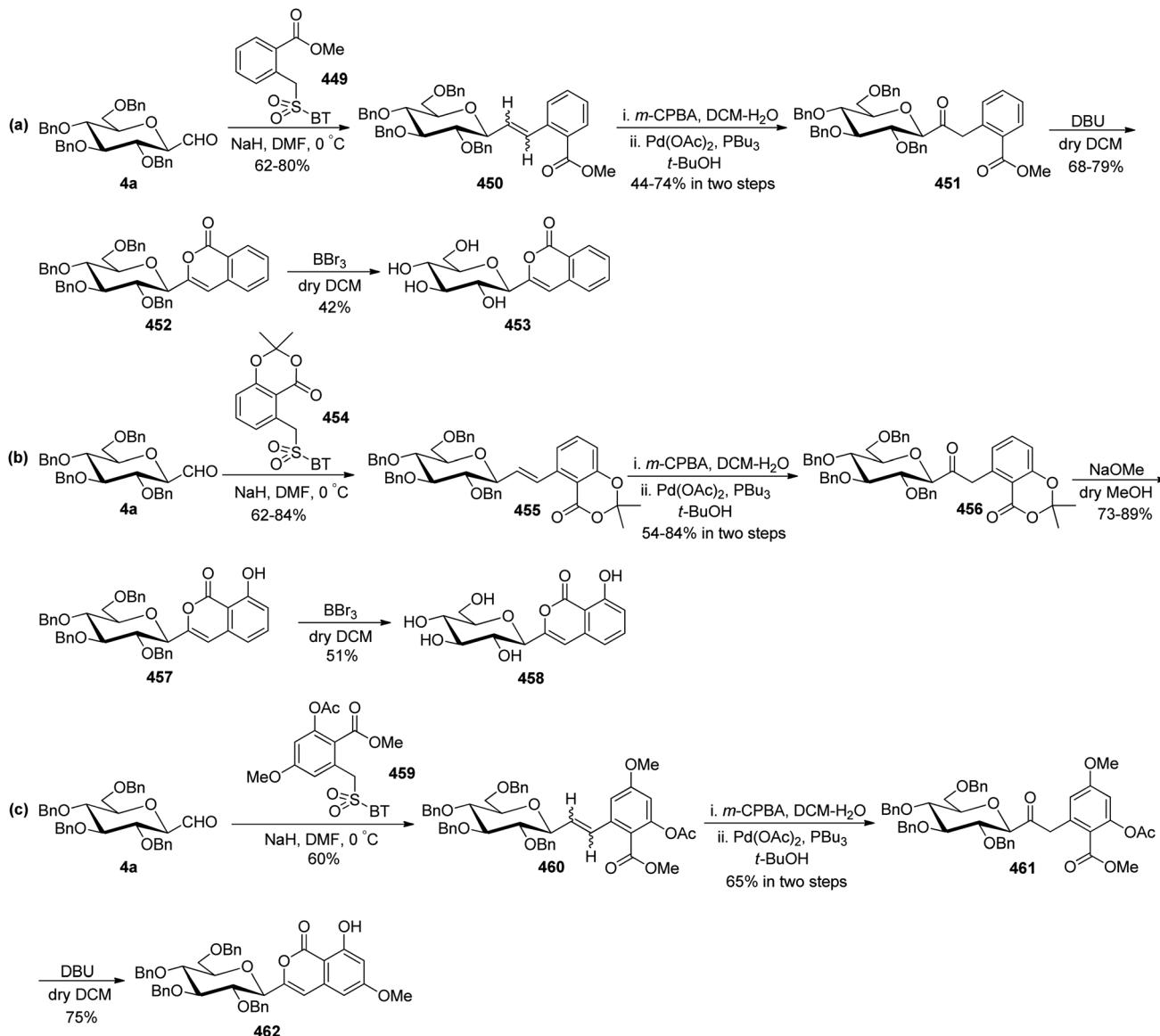
Azides **447a-c** upon catalytic hydrogenation formed the corresponding amine, which on condensation with nitrourea afforded ureido sugars **448a-c** with good overall yields (80–86%). Thus, various cyclocondensations were studied taking differently substituted substrates *via* the Biginelli reaction and the results were found to adhere to the standard method, giving a collection of glycosylated DHPM derivatives (Scheme 67).

Sudarshan *et al.*<sup>97</sup> developed a route for the synthesis of 3-glycosylated isocoumarins by using modified Julia-olefination for initial C-C bond formation between C-glycopyranosyl aldehyde and benzylic-sulfones (Scheme 68). C-Glucopyranosyl aldehyde **4a** and benzyl-sulfones **449**, **454**, and **459** were subjected to Julia-olefination reaction to afford alkenes **450**, **455**, and **460** in 62–80%, 62–84%, and 60% yields, respectively, with *E*-isomer as the major product (Scheme 67a-c). These olefins further oxidised to ketone intermediates **451**, **456**, and **461** in 44–74%, 54–84%, and 65% yields, respectively, using palladium-catalysed Meinwald rearrangement *i.e.* *m*-CPBA in DCM-H<sub>2</sub>O followed by  $\text{Pd}(\text{OAc})_2$ ,  $\text{PBU}_3$  in *tert*-butanol with good yields. The ketone intermediates **451**, **456**, and **461** were





Scheme 67 Synthesis of various sugar-based dihydropyrimidinones.

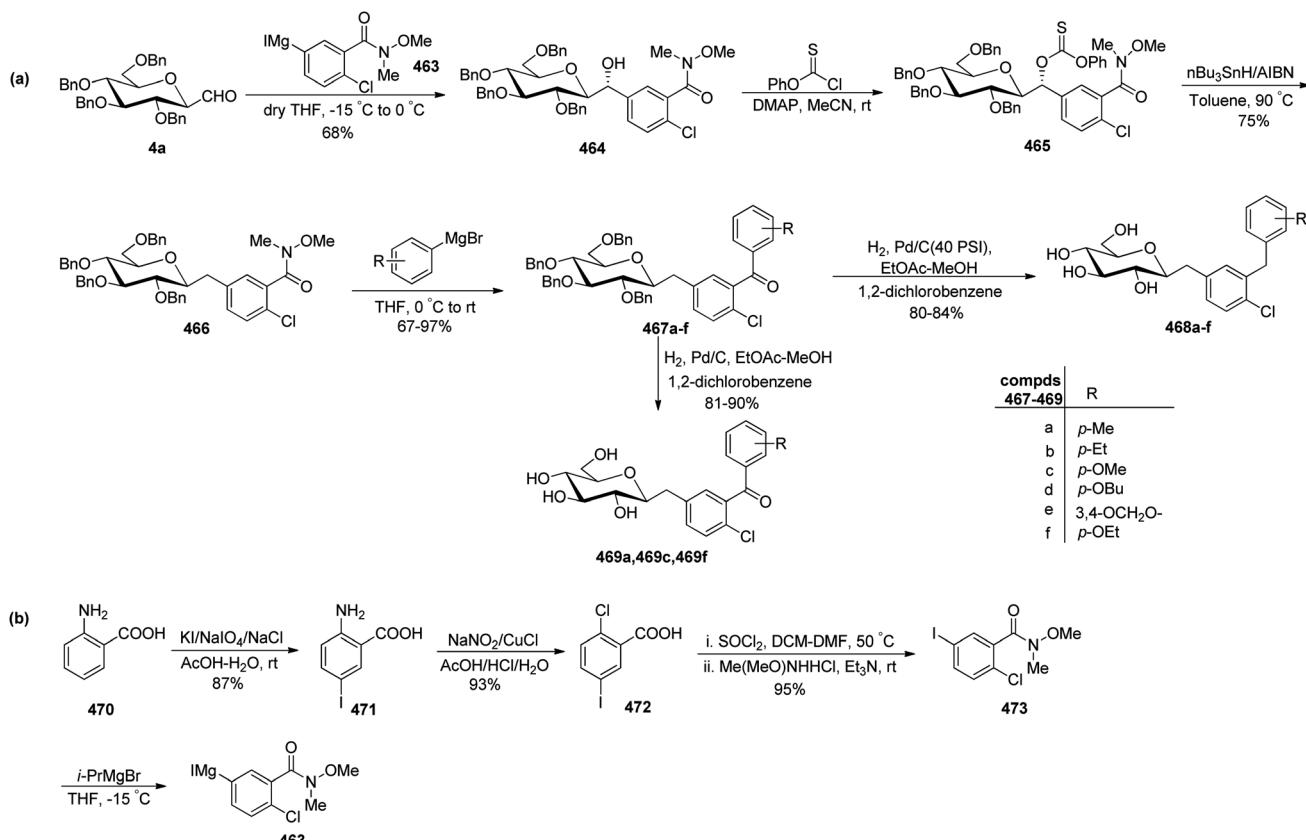


Scheme 68 Synthesis of 3-glycosylated isocoumarins 453, 458, and 462.

transformed into isocoumarins 452, 457, and 462 by base-promoted intramolecular cyclisation using DBU in dry DCM. Finally, 3-glycosylated isocoumarin 453 and 458 were obtained in 42% and 51% yield by debenzylation of 452 and 457 using boron tribromide in dry DCM.

Mukkamala *et al.*<sup>98</sup> discovered a pathway to synthesise C-aryl glucoside analogues of Dapagliflozin, which act as SGLT inhibitors for the treatment of type-2 diabetes. Key products benzyl C-glucosyl aryl ketone 464 was synthesised from glucopyranosyl aldehyde 4a and functionalized Grignard reagent 463 generated *in situ* from anthranilic acid 470. Iodinated anthranilic acid 471 was obtained with 87% yield by the reaction of 470 with KI/NaIO<sub>4</sub>/NaCl in acetic acid. Acid 471 on diazotisation reaction followed by the replacement of the diazonium group by chloro-group afforded carboxylic acid 472 in 93% yield, which afforded Weinreb-amide 473 in 95% yield on the reaction with SOCl<sub>2</sub>

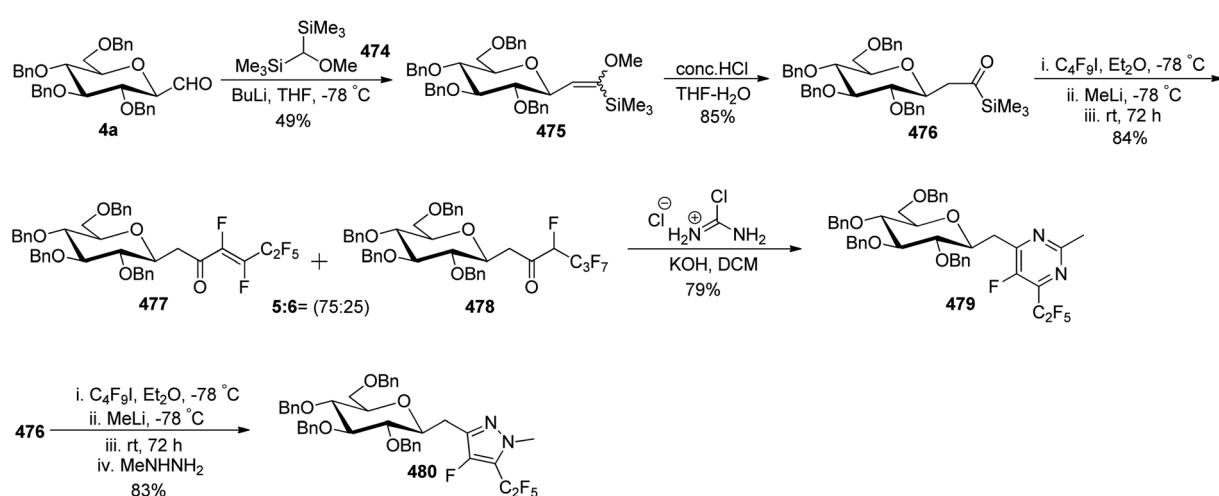
in DCM-DMF followed by Me(MeO)NHHCl. Functionalized arylmagnesium bromide 463 was obtained by reacting acid 473 with *i*PrMgBr under Paul Knochel's condition (Scheme 69b). Synthesised Grignard reagent 463 was reacted directly with aldehyde 4a to afford addition product 464 in 68% yield, which undergoes subsequent deoxygenation on reaction with phenyl chlorothionocarbonate in 4-dimethylaminopyridine (DMAP) and acetonitrile yielding thionocarbonate derivative 465. Compound 465 on radical de-oxygenation in tri-*n*-butyl tin hydride and AIBN in toluene afforded functionalized benzyl C-glucoside 466 in 75% yield, which upon addition of arylmagnesium bromides afforded benzyl C-glucosyl diaryl ketones 467a-f in 67–97% yield. Ketone 467a-f when subjected to simple hydrogenation with H<sub>2</sub>, Pd/C in dichlorobenzene afforded de-protected C-benzylglucosyl ketones 469a, 469c, and 469f in 81–90% yield while for other derivatives the hydrogenation was performed with 40 psi

Scheme 69 Synthesis of *C*-aryl glucoside 467–469.

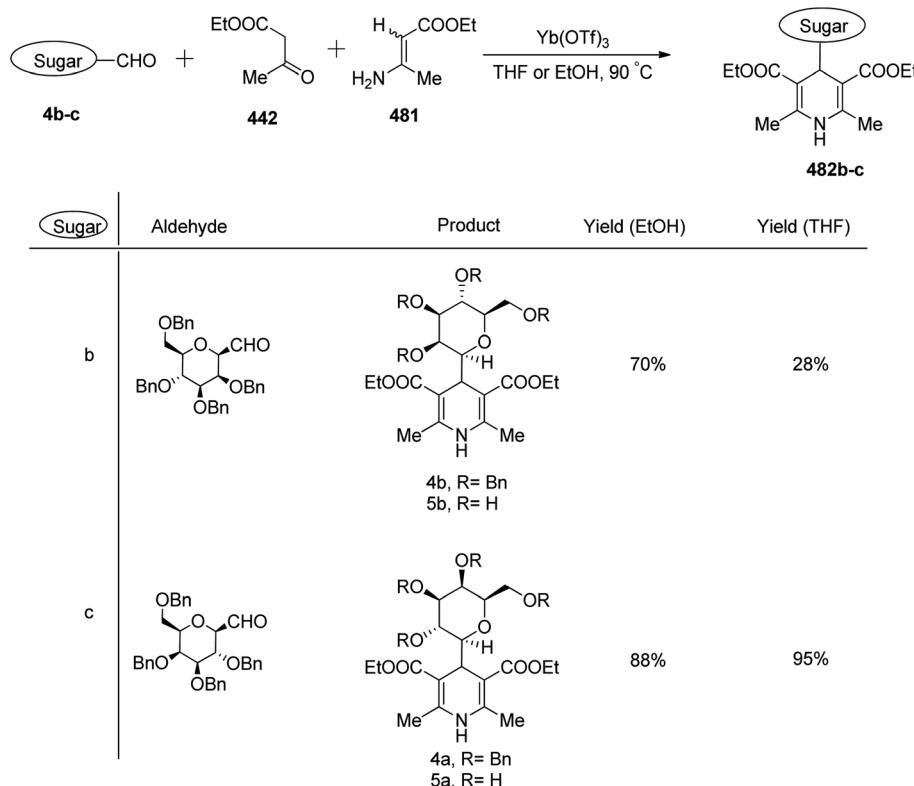
pressure affording *C*-benzyl analogues of dapagliflozin 468a–f in 80–84% yield (Scheme 69a).

Chanteau *et al.*<sup>99</sup> designed a stereo-controlled synthetic pathway for the synthesis of carbohydrate-derived acylsilanes starting from *C*-glucopyranosyl aldehyde 4a. The aldehyde 4a undergoes nucleophilic addition on reaction with bis(trimethylsilyl)methoxymethane (474) in *n*-butyl lithium-THF *via* Peterson reaction to furnish enol ether 475 in 49% yield.

Acidic hydrolysis of ether 475 with HCl in THF-H<sub>2</sub>O afforded acylsilane 476 in 85% yield, which on treatment with perfluorobutyl iodide with methylolithium furnished the corresponding hemifluorinatedenone 477 and  $\alpha$ -hydroperfluorobutyl ketone 478 in a ratio of 75 : 25 in 84% yield. The mixture of 477 and 478 when reacted with acetamide leads to cyclisation affording the pyridine derivative 479 with a 79% yield. Also, acylsilane 476 when reacted with perfluorobutyl



Scheme 70 Synthesis of glycopyranosyl pyridine and pyrazole derivatives 479 and 480.



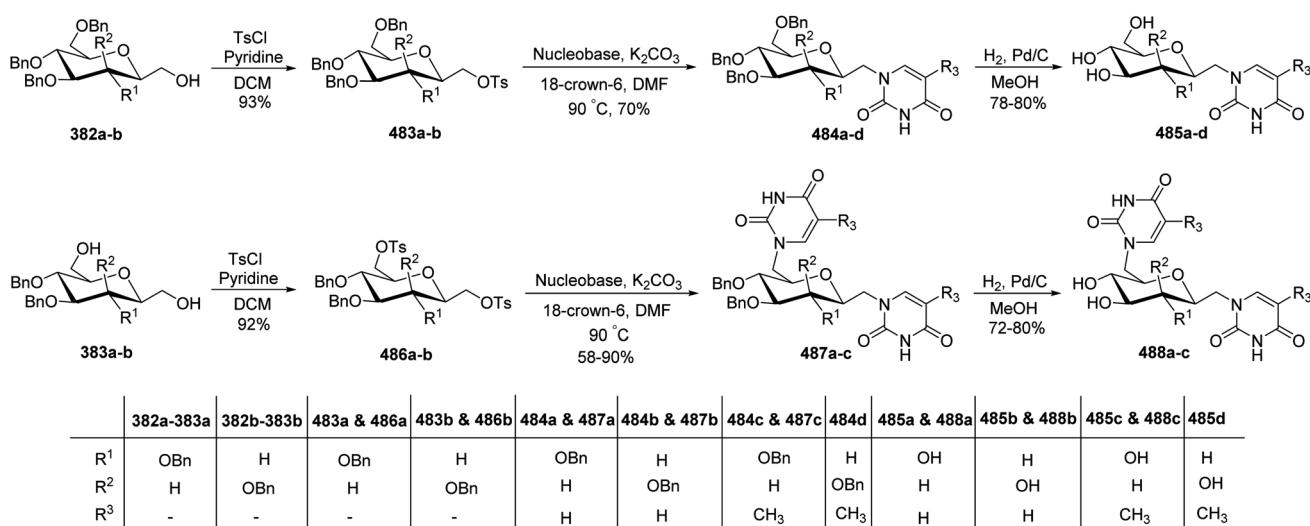
Scheme 71 Synthesis of C-glycosylated dihydropyridine 482b-c.

iodide with methylolithium followed by methylhydrazine at room temperature afforded pyrazole derivative **480** with 83% yield (Scheme 70).

Dondoni *et al.*<sup>100,101</sup> synthesized *C*-glycosylated dihydropyridine by Hantzsch condensation reaction using *C*-glycopyranosyl aldehyde (Scheme 71). One pot three-component reaction was performed by taking *C*-glycopyranosyl aldehyde **4b-c**, ethyl acetoacetate **442**, and ethyl 3-aminobut-2-enoate **481**

in the presence of  $\text{Yb}(\text{OTf})_3$  in THF or EtOH to furnish *C*(4)-glycosylated dihydropyridine **482b-c**. The overall yield with respect to the solvent taken is given in Scheme 71.

Verma *et al.*<sup>102</sup> reported a very simple methodology for the synthesis of hexopyranosyl pyrimidine homonucleosides and hexopyranosyl double-headed pyrimidine homonucleosides using *C*-glycopyranosyl aldehyde as a precursor. 2,6-anhydro heptitols **382a-b** and **383a-b** were converted into their tosylated



Scheme 72 Synthesis of homonucleosides 485a-d and 488a-c.

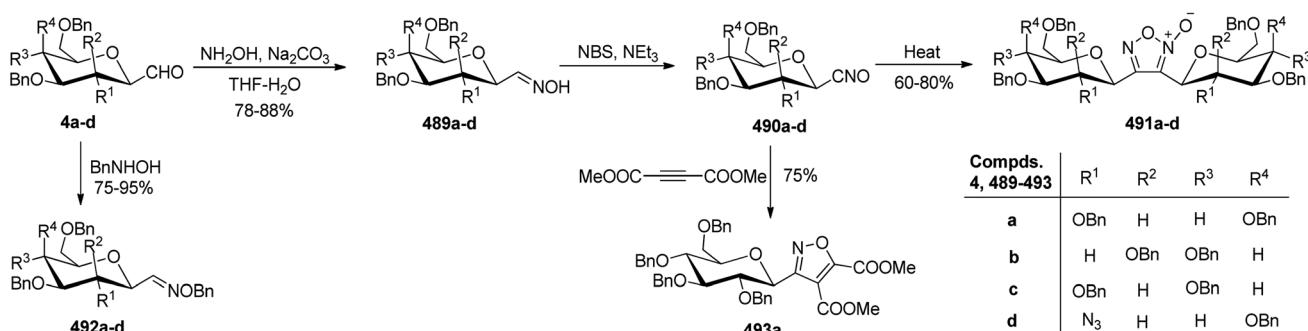


form using tosyl chloride in pyridine-DCM to afford **483a–b** and **486a–b** in 92–93% yield, respectively. Further nucleophilic substitution reactions on **483a–b** and **486a–b** were carried out using thymine/uracil as nucleobase,  $K_2CO_3$ , 18-crown-6 in DMF to obtain hexopyranosyl homonucleosides **484a–d**, and **487a–c**, respectively. Treatment with  $H_2$ , Pd/C in methanol afforded debenzylated form of homonucleosides **485a–d** and **488a–c** in 78–80% and 72–80% yield, respectively (Scheme 72).

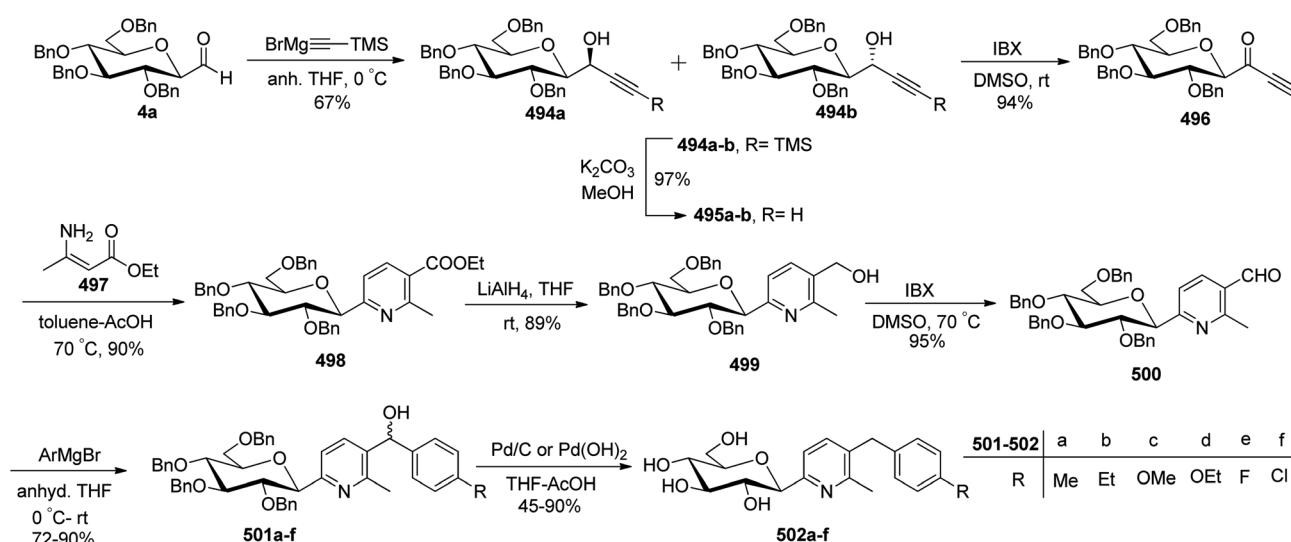
Dondoni *et al.*<sup>103</sup> used  $\beta$ -C-glycopyranosyl aldehydes for the synthesis of glycosyl nitrile oxides and nitrones, which in turn could be used for the synthesis of more complex C-glycoconjugates. C-Glycopyranosyl aldehydes **4a–d** on treatment with hydroxylamine and sodium carbonate in THF-H<sub>2</sub>O at room temperature afforded corresponding oximes **489a–d** in 78–88% yield. Oximes **489a–d** on treatment with *N*-bromo-succinimide (NBS) followed by triethylamine, led to the formation of nitrile oxide **490a–d**. Upon heating, these nitrile oxides dimerised to give furoxans **491a–d** in 60–80% yield. Compound **490a** reacted with dimethyl acetylenedicarboxylate, which underwent the cycloaddition reaction and afforded corresponding C-glycosylated isoxazole **493a** with 75% yield. Also, compounds **4a–d** afforded the corresponding *N*-

benzyl nitrones **492a–d** in 75–95% yield on treatment with *N*-benzylhydroxyl-amine (Scheme 73).

Reddy *et al.*<sup>104</sup> reported the synthesis of 2- $\beta$ -D-glucopyranosyl pyridines by using Bohlmann–Rahtz hetero-annulation starting from  $\beta$ -C-glucopyranosyl aldehyde (Scheme 74). Nucleophilic addition of TMS-ethynyl magnesium bromide was carried out on C-glucopyranosyl aldehyde **4a** to afford a diastereomeric mixture of **494a** and **494b** in 67% yield, which on further treatment with  $K_2CO_3$  in methanol removed the TMS group and furnished **495a** and **495b**, respectively, in 97% yield. Oxidation of the diastereomeric mixture of **495a–b** with IBX in DMSO produced **496** in 94% yield, which was followed by Bohlmann–Rahtz hetero-annulation reaction conditions with  $\beta$ -amino-crotonate **497** in toluene–AcOH at 70 °C to afford trisubstituted pyridine **498** in 90% yield. Further, reduction of glycoside **498** with LiAlH<sub>4</sub> produced **499** in 89% yield, which on oxidation with IBX in DMSO afforded **500** in 95% yield. Compound **500** was treated with substituted arylmagnesium bromide to afford a diastereomeric mixture of compounds **501a–f** in 72–90% yield, which on direct hydrogenation with palladium on charcoal afforded targeted compounds **502a–f** in 45–90% yield. These compounds were

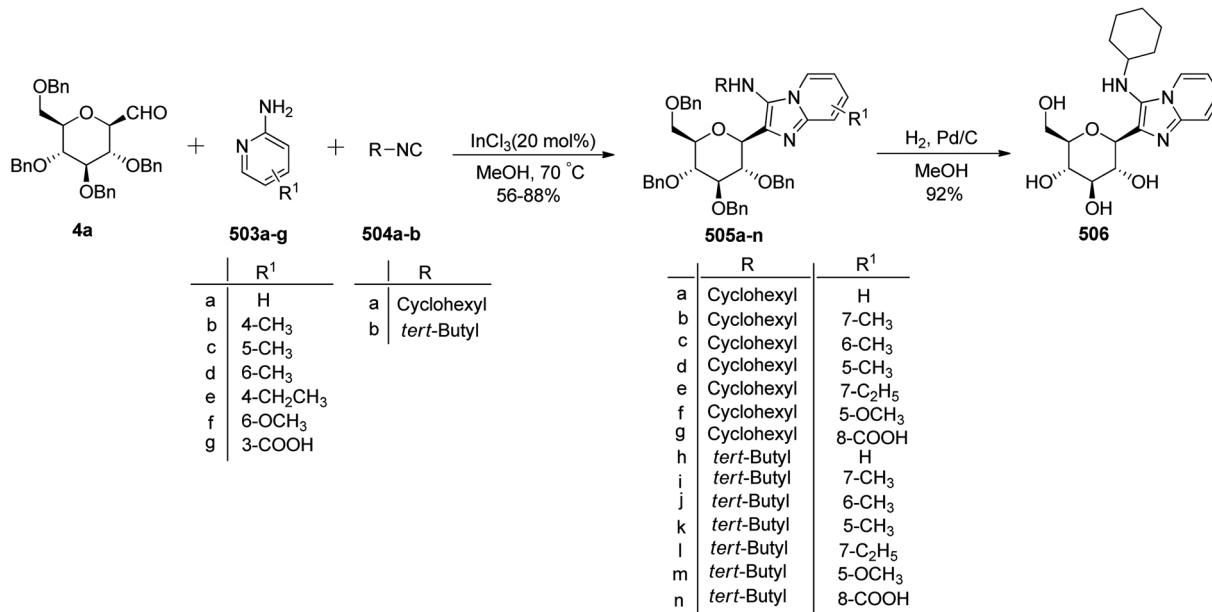


Scheme 73 Synthesis of glycosyl nitrile oxide **490a** and glycosyl nitrones **492a–d**.



Scheme 74 Synthesis of 2- $\beta$ -D-glucopyranosyl pyridines **502a–f**.





Scheme 75 Synthesis of C-glucosides of 1-azaindolizines 505a-n and 506.

found to be the potential analogue of Dapagliflozin, an approved drug that lowers blood glucose levels by inhibiting the sodium-glucose transport in the kidney.

Very recently our research group has synthesized a library of C-glucosides of 1-azaindolizines from C-glycopyranosyl aldehyde using the Groebke–Blackburn–Bienayame<sup>105–107</sup> (GBB) reaction protocol (Scheme 75).<sup>108</sup> The multicomponent reaction of C-glycopyranosyl aldehyde (4a) with 2-aminopyridine derivatives 503a-g and isocyanides 504a-b was carried out in the presence of the catalytic amount of InCl<sub>3</sub> in MeOH at 70 °C to afford C-glucosides of 1-azaindolizines 505a-n in 56–88% yield. Deprotection was carried out for 505h using H<sub>2</sub>, Pd/C in methanol to obtain 506 in 92% yield.

### 3.7 C-Glycopyranosyl based natural product fragments

A new approach to the synthesis of ambruticin fragment by employing  $\beta$ -C-glycoside aldehyde as starting material was generated by Michelet *et al.*<sup>109</sup> The key phenomena introduced was stereoselective chain-elongating hydroxy alkylation of  $\beta$ -C-glycopyranosyl aldehyde 4a by using various alkynyl derivatives 507a-d in the presence of methyl lithium and magnesium dibromide leading to formation of diastereomeric alcohols 508a-d and 510a-d with a diastereomeric ratio of 75 : 25 in 75% yield. The major alcohol derivative 508b on treatment with a series of reagents led to the formation of alcohol 510 in 66% yield, which was hydrogenated in the presence of Pd/C followed by alkylation with NaCH(COOMe)<sub>2</sub>, palladium acetate, and DPPE in THF forming compound 511 as a single isomer in just 30% yield. Alcohol 511 on activation with 2,4-dichlorobenzoyl chloride followed by cyclization afforded tetra-O-benzylated cyclopropane 512 in 48% yield (Scheme 76a), which in turn is the western part of ambruticin.

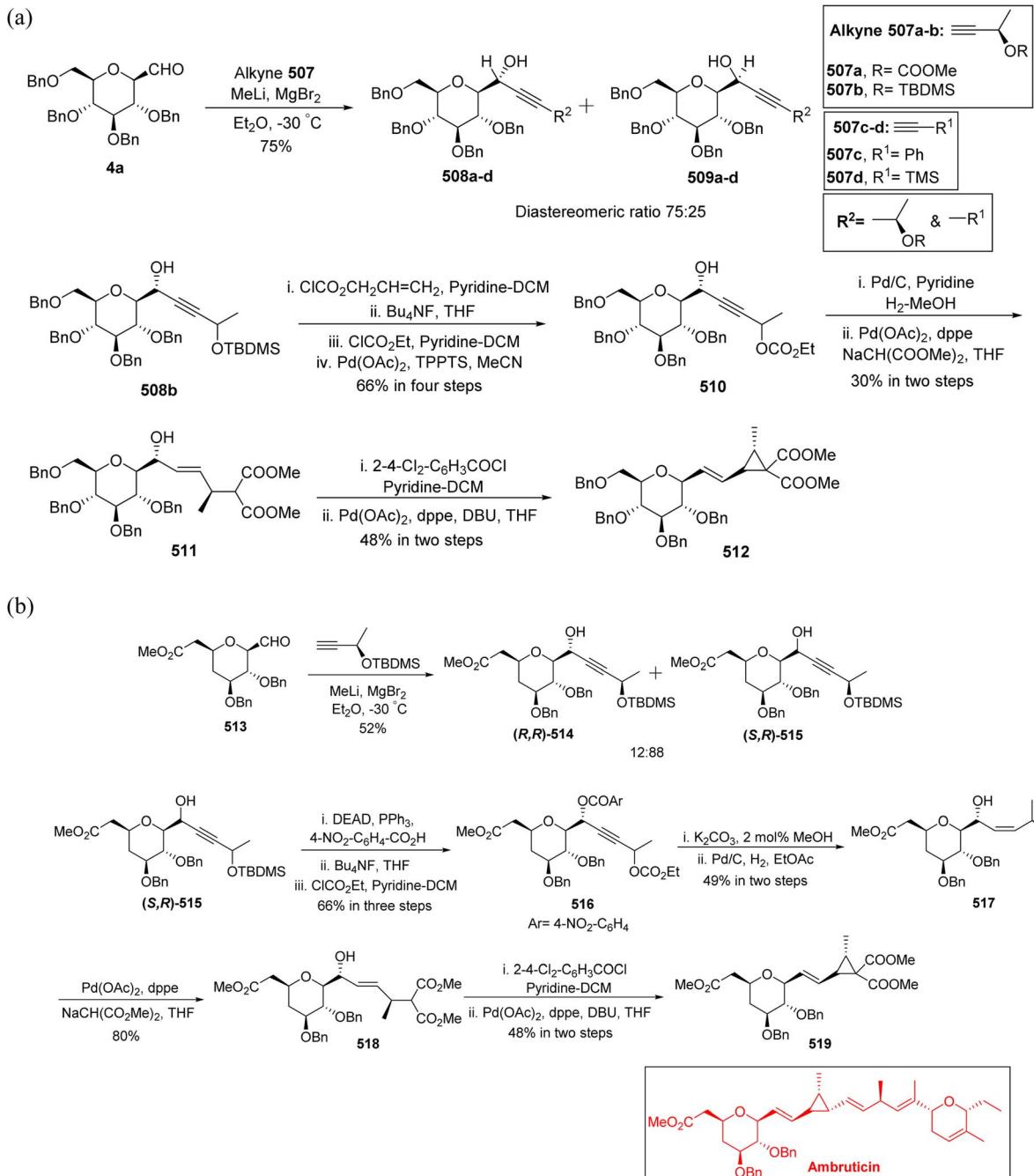
Synthesis of the western part of ambruticin was achieved from C-glycosyl aldehyde 513 (Scheme 76b). C-Glycosyl aldehyde 513 was reacted with alkyne 507b in the presence of MeLi–MgBr<sub>2</sub> to afford alcohol mixtures in 12 : 88 diastereomeric ratio (*R,R*)-513 and (*S,R*)-514 in 52% yield. Mitsunobu reaction was applied on (*S,R*)-514 to invert the stereochemistry of alcohol, which produced 516 in 66% yield. Further treatment of potassium carbonate in 2 mol% methanol followed by H<sub>2</sub>, Pd/C in ethyl acetate produced 517 in 49% yield. Compound 518 was achieved using Pd(OAc)<sub>2</sub>, dimethyl malonate sodium salt in THF. Finally, the western part of Ambruticin 519 was obtained in 48% yield using Pd-catalysed cyclization.

### 3.8 Miscellaneous

The Ugi reaction is a multicomponent reaction where aldehyde, amine, carboxylic acid, and isocyanide components are combined to form bis-amide (Scheme 77a). Lockhoff *et al.*<sup>110</sup> used this reaction to synthesise glycoconjugates libraries by using carbohydrate building blocks for the Ugi condensation. C-Glycosyl aldehyde 4a which also serves as an aldehyde building block could be easily oxidised into carboxylic acid 520 in 81% yield by using KMnO<sub>4</sub>–NaH<sub>2</sub>PO<sub>4</sub>. Similarly, amine and isocyanide building blocks were synthesised starting from C-glycosyl aldehyde (Scheme 77b). Compound 4a was reduced with LiBH<sub>4</sub> to afford glycosylmethyl alcohol 521 in 95% yield, which was converted into amine 522 in 71% yield by following the reaction sequence, *i.e.* tosylation, azide substitution followed by reduction. Further, N-formylation of 522 and dehydration afforded isocyanide 523 in 52% yield. All these C-glycosides are the desired building blocks for Ugi condensation and were used to synthesise glycoconjugates (Table 4).

Dondoni *et al.*<sup>111</sup> synthesized [60]fulleropyrrolidine glycoconjugates by using C-glycosyl aldehyde 4c and 524 (Scheme





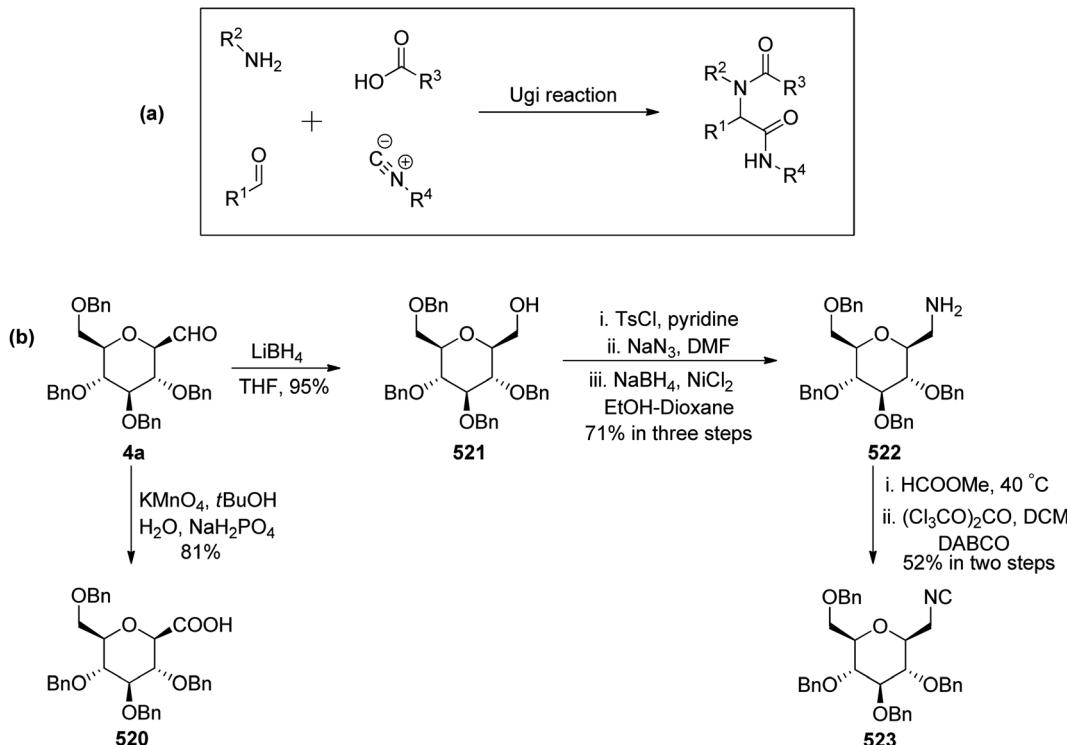
Scheme 76 (a) Synthesis of tetra-O-benzylated cyclopropane 512. (b) Synthesis of the western part of Ambruticin 519.

78). In this protocol, *C*-glycosyl aldehydes **4c** and **524**, [60]fullerene, and *N*-methylglycine (sarcosine) **525** were refluxed in toluene to afford a diastereomeric mixture of [60]fulleropyrrolidine glycoconjugates **527a-b** in 10–14% yield. The reaction proceeds through the formation of sugar azomethine ylide intermediate **526**. It was found that an attack of azomethine ylide **526** occurred on a 6,6-ring junction of  $\text{C}_{60}$  through 1,3-dipolar cycloaddition reaction. Deprotection of the benzoyl group was carried out to obtain **528b** using sodium methoxide in methanol-toluene.

Auge *et al.*<sup>112</sup> while studying vinyl halides realised that these are the building blocks of olefin synthesis and hence, they designed various vinyl halide synthesis. One of them involved the *C*-glycopyranosyl aldehydes as the starting product **4a**, which upon treatment with  $\text{CHI}_3$  and  $\text{CrCl}_3$  in the presence of zinc in sodium iodide yielded the corresponding vinyl iodide **529** in an isomeric mixture in 63% yield (Scheme 79).

Janes *et al.*<sup>113</sup> and team explored the scope of organometallic *C*-glycosides containing chromium carbene and used  $\beta$ -*C*-glucopyranosyl aldehyde **4a** for the synthesis. Glucopyranosyl aldehyde **4a** on reaction with pentacarbonyl[(methoxy)-



Scheme 77 Synthesis of sugar-based building blocks for the Ugi reaction, *i.e.* acid 520, amine 522, and isocyanide 523.Table 4 Various sugar-based bis-amides synthesized<sup>a</sup>

Ugi building blocks				Ugi product			
Aldehyde	Amine	Acid	Isocyanide	R <sup>1</sup>	R <sup>2</sup>	R <sup>3</sup>	R <sup>4</sup>
<b>4a</b>	PMB	Acetic acid	Cyclohexyl isocyanide	A	PMB	CH <sub>3</sub>	C <sub>6</sub> H <sub>11</sub>
Benzaldehyde	522	Acetic acid	Cyclohexyl isocyanide	C <sub>6</sub> H <sub>5</sub>	A-CH <sub>2</sub>	CH <sub>3</sub>	C <sub>6</sub> H <sub>11</sub>
Benzaldehyde	PMB	520	Cyclohexyl isocyanide	C <sub>6</sub> H <sub>5</sub>	PMB	A	C <sub>6</sub> H <sub>11</sub>
Benzaldehyde	PMB	Acetic acid	523	C <sub>6</sub> H <sub>5</sub>	PMB	CH <sub>3</sub>	A-CH <sub>2</sub>
<b>4a</b>	522	Acetic acid	Cyclohexyl isocyanide	A	A-CH <sub>2</sub>	CH <sub>3</sub>	C <sub>6</sub> H <sub>11</sub>
<b>4a</b>	PMB	520	Cyclohexyl isocyanide	A	PMB	A	C <sub>6</sub> H <sub>11</sub>
<b>4a</b>	PMB	Acetic acid	523	A	PMB	CH <sub>3</sub>	A-CH <sub>2</sub>
Benzaldehyde	522	520	Cyclohexyl isocyanide	C <sub>6</sub> H <sub>5</sub>	A-CH <sub>2</sub>	A	C <sub>6</sub> H <sub>11</sub>
Benzaldehyde	522	Acetic acid	523	C <sub>6</sub> H <sub>5</sub>	A-CH <sub>2</sub>	CH <sub>3</sub>	A-CH <sub>2</sub>
Benzaldehyde	PMB	520	523	C <sub>6</sub> H <sub>5</sub>	PMB	A	A-CH <sub>2</sub>
<b>4a</b>	522	520	Cyclohexyl isocyanide	A	A-CH <sub>2</sub>	A	C <sub>6</sub> H <sub>11</sub>
<b>4a</b>	522	Acetic acid	523	A	A-CH <sub>2</sub>	CH <sub>3</sub>	A-CH <sub>2</sub>
<b>4a</b>	PMB	520	523	A	PMB	A	A-CH <sub>2</sub>
Benzaldehyde	522	520	523	C <sub>6</sub> H <sub>5</sub>	A-CH <sub>2</sub>	A	A-CH <sub>2</sub>
<b>4a</b>	522	520	523	A	A-CH <sub>2</sub>	A	A-CH <sub>2</sub>

<sup>a</sup> For R<sup>1</sup>, R<sup>2</sup>, R<sup>3</sup>, R<sup>4</sup> see Scheme 77a, PMB = 4-methoxybenzyl, A = 2,3,4,6-tetra-O-benzyl- $\beta$ -D-glucopyranosyl.

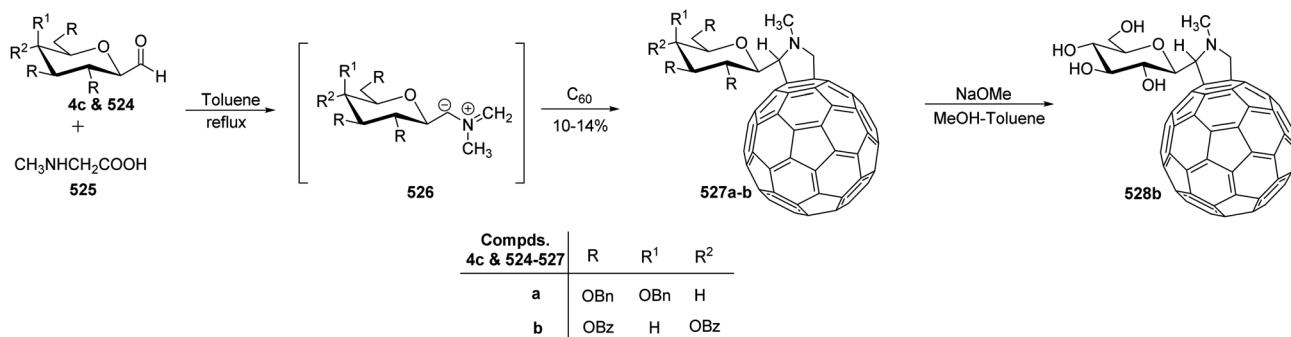
methylcarbene] chromium **530** underwent aldol condensation in the presence of TiCl<sub>4</sub> in *i*Pr<sub>2</sub>NEt to afford the novel *C*-glycoside compound, 1-deoxy-2,3,4,6-tetra-O-benzyl- $\beta$ -D-glucopyranose **531** in 54% yield (Scheme 80).

*C*-glycosylenol aldehydes **78a–b** synthesized from D-glucose and D-mannose by Xia *et al.*<sup>41</sup> were utilised for the synthesis of L-sugar derivatives also. Reduction of **78a–b** with sodium triacetoxyborohydride (NaBH(OAc)<sub>3</sub>) afforded **532a–b**, which on further acetylation produced **533a–b**. The hydroxyl

group at C5 was deprotected using TMSCl, NaI in acetonitrile to produce **534a–b** in 36–54% yield, which was oxidised to carboxylic acid **535a–b** in 70–85% yield using TEMPO, iodosobenzene diacetate (DIB) in MeCN–H<sub>2</sub>O. Oxidative decarboxylation mediated by lead(IV)tetraacetate in THF–AcOH afforded L-sugar derivatives **536a–b** in 76–80% yield (Scheme 81).

*C*-Glycosylenol aldehydes synthesised by Petrusova *et al.*<sup>57</sup> via the nitromethane route were further utilised for the synthesis of 2-( $\beta$ -D-glycosylenol)nitroethenes and





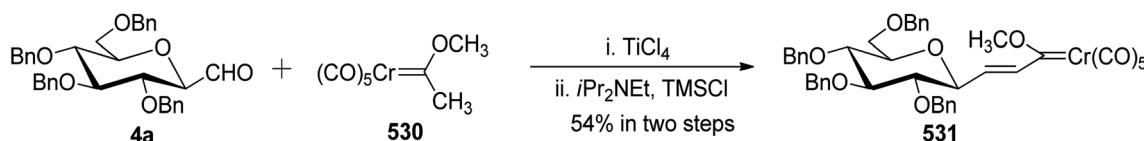
Scheme 78 Synthesis of [60]fulleropyrrolidine glycoconjugates 527a-b and 528b.



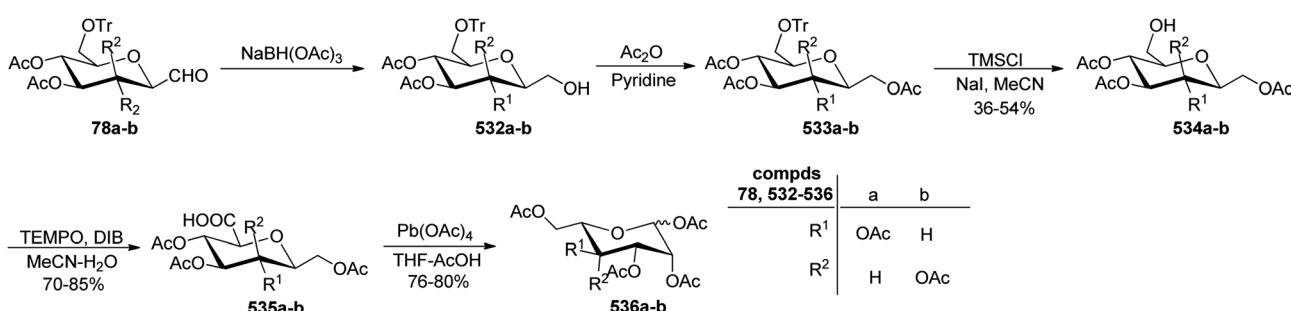
Scheme 79 Synthesis of C-glucopyranosyl vinyl iodide 529.

-nitroethanes (Scheme 82). The addition of nitromethane in the presence of NaOMe afforded epimeric nitroethanes 537a-d with 57% yield, which on further acetylation using acetic anhydride in the presence of sulfuric acid produced epimeric mixtures of 538a-c in 85% yield. The treatment of compounds 538a-c with sodium bicarbonate in benzene at 80 °C afforded 2-( $\beta$ -D-glycopyranosyl)nitroethenes 539a-d in 90–94% yield. Hydrogenolysis was carried out using H<sub>2</sub>, Pd/C in ethyl acetate to give 2-( $\beta$ -D-glycopyranosyl)nitroethanes 540a-d in 80–86% yield. Finally, deacetylation was achieved using sodium methoxide in methanol to afford 541a-d in 85–94% yield.

Lehmann *et al.*<sup>114</sup> explored the synthetic route for the synthesis of 4,8-anhydro-2,3-dideoxy-D-galacto- and -D-glucopyranose dimethyl acetals which can be used for the determination of the steric course of glycoside hydrolases-initiated protonation. C-Linked galacto- and glucopyranosyl aldehyde 59a-b were treated with formylmethylenetriphenylphosphorane 542 in benzene to furnish  $\beta$ -D-galacto- and glucopyranose 543a-b in 75% yield, respectively, which on addition of HBr followed by acetylation afforded diastereomeric 3-bromides 544a-b in 42% yield. Elimination of HBr from 544a-b in the presence of AgF in pyridine furnished dimethyl acetal 545a-b with 80% yield, which upon treatment with sodium methoxide in methanol afforded acetylated product 546a-b in 89% yield. Enzymatic deuteriohydration of 546b was performed in the presence of  $\alpha$ -D-galactosidase in the sodium/potassium phosphate-D<sub>2</sub>O buffer to give 2,3-dideoxy- $\alpha$ -D-galacto-(3-<sup>2</sup>H) nonos-4-ulose dimethyl acetal 547b in 94% yield. The reduction was carried out using sodium borohydride in water to afford epimers 548 and 549 in 44% yield, which could be separated by HPLC technique and were treated separately with 0.5 M CF<sub>3</sub>COOH in methanol to afford 1,6-anhydro-2,3-dideoxy-3(S)-D-

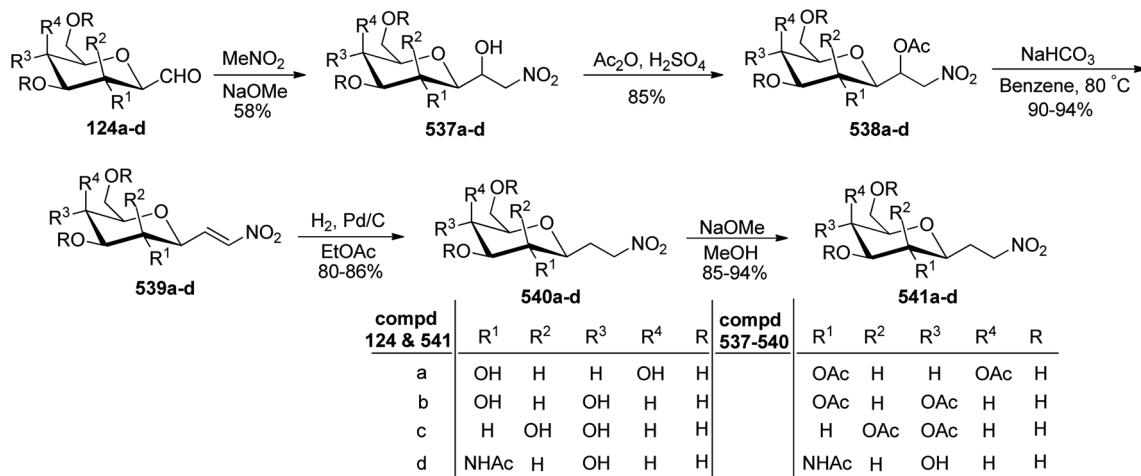


Scheme 80 Synthesis of organometallic C-glycosides 531.

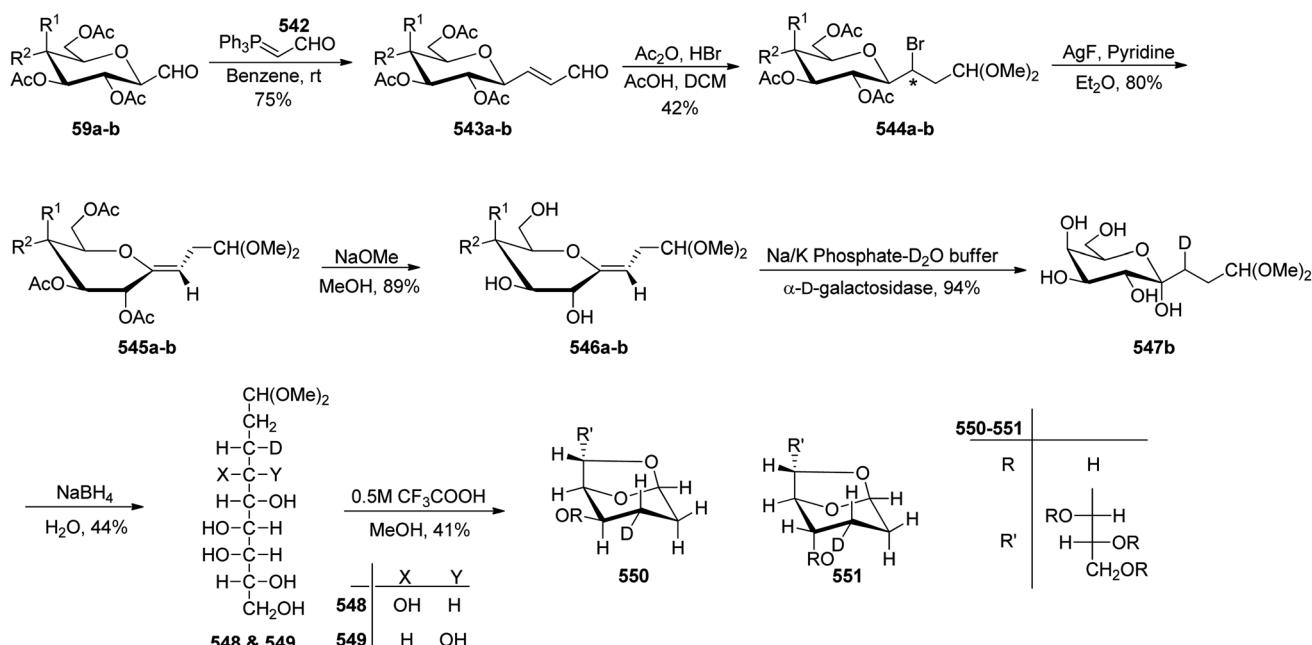
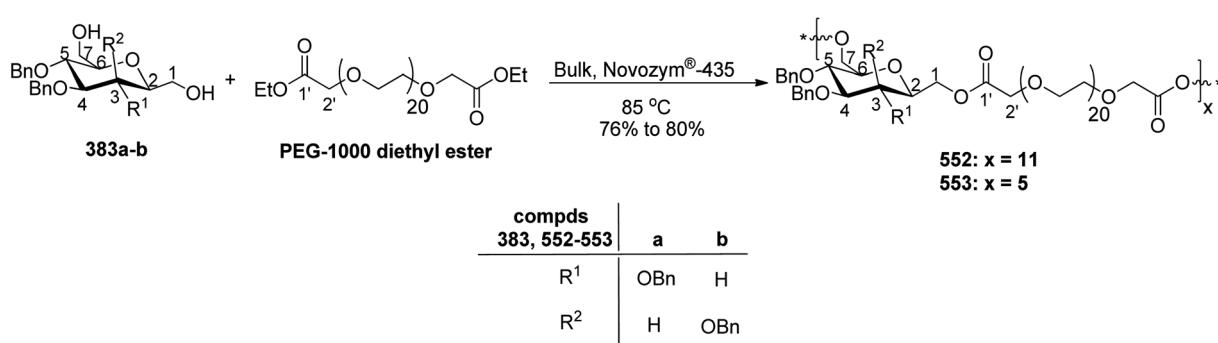


Scheme 81 Synthesis of L-sugar derivatives 536a-b.



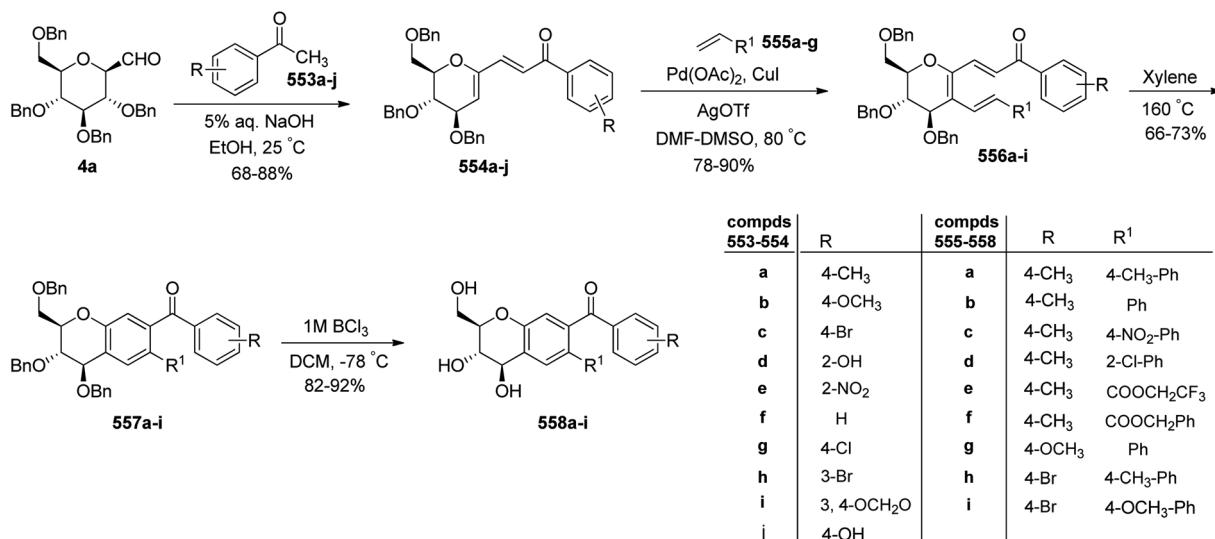


Scheme 82 Synthesis of 2-(β-D-glycopyranosyl)nitroethenes and -nitroethanes 539a-d &amp; 541a-d.

Scheme 83 Synthesis of 1,6-anhydro-2,3-dideoxy-3(S)-D-glycero-L-gluco-(3-<sup>2</sup>H)nonopyranose 550 and 551.

Scheme 84 Synthesis of gluco- and manno-heptitol-PEG copolymers 552 and 553.





Scheme 85 Synthesis of (2R,3S,4R)-chromanes 558a-i.

glycero-L-gluco-(3-<sup>2</sup>H)nonopyranose 550 and 551 in 41% yield, respectively (Scheme 83).

Khatri *et al.*<sup>115</sup> recently synthesized a sugar-PEG copolymer starting from 2,6-anhydro heptitol 383a-b, which was obtained from *β*-C-glycopyranosyl aldehydes 4a-b by reduction with NaBH<sub>4</sub> followed by selective debenzylation of primary benzyl protection. The synthesized two diastereomeric sugar alcohol derived from D-glucose and D-mannose were employed for the synthesis of sugar PEG-based copolymers using PEG-1000 diethyl ester 552 and 553 in 80% and 76% yields, respectively (Scheme 84). This synthesis of copolymers was achieved by Novozym®-435 catalyzed transesterification reaction. The configurational change at one of the carbons of diastereomeric 2,6-anhydro-heptitols has a significant effect on the degree of polymerization of the synthesized polymers. The aqueous solution of these copolymers forms small spherical micelles, which have the capability to encapsulate Nile red dye.

Very recently our group developed an efficient methodology for the synthesis of (2R,3S,4R)-chromanes 558a-i from C-glycopyranosyl aldehyde 4a (Scheme 85).<sup>116</sup> Thus, C-glycopyranosyl aldehyde 4a was submitted to Claisen-Schmidt condensation using various acetophenones 553a-j in the presence of 5% aq. sodium hydroxide in ethanol to obtain 1-(E-1-arylpropenon-3-yl)-3,4,6-tri-O-benzyl-D-glucals 554a-j in 68-88% yields. Further, a cross dehydrogenative reaction was carried out on these C-1 substituted glucalpropenones using alkenes 555a-g in the presence of Pd(OAc)<sub>2</sub>, CuI, AgOTf in DMF-DMSO solvent system at 80 °C to afford 1,2-disubstituted glucals 556a-i in 78-90% yields. The CDC reaction afforded products with (E) stereoselectivity in good to excellent yield. Thus, E,Z,E-triene 556a-i heated at 160 °C in xylene, which on 6π-electrocyclization followed by *in situ* dehydrogenative aromatization produced chromanes 557a-i in 66-73% yields. The cyclization of trienes 557e and 557f was not achieved under optimised conditions. The benzyl protection was removed using 1 M BCl<sub>3</sub> in DCM at -78 °C to furnish desired (2R,3S,4R)-chromanes derivatives 558a-i in 82-92% yields.

## 4. Conclusion

In this review, we have described various approaches for the synthesis of C-glycopyranosyl aldehydes and their applications in the synthesis of diverse biologically relevant C-glycoconjugates. A total of seven approaches have been designed based on the key intermediates involved in the synthesis of C-glycopyranosyl aldehydes, which refer to facile and efficient methods developed including multistep synthetic protocols. In addition, the purpose of this review is to scrutinize the importance of C-glycopyranosyl aldehydes to the vast field of organic synthesis. This review will serve as a collection of literature reports, where researchers will find both the synthetic methodologies to access C-glycopyranosyl aldehydes as well as their applications to synthesize various complex C-glycoconjugates as key precursor molecules.

## 5. Future prospects

This review describes a wide scope of syntheses of C-glycopyranosyl aldehydes *via* different key intermediates along with a vast library of C-glycoconjugates derived from them. Although many synthetic routes are found to be very interesting even though some methods are economically unfavourable due to very expensive reagents used in the synthetic routes, also in some procedures harsh conditions make the syntheses cumbersome. Therefore, there is a need to develop more synthetic protocols that must be simple, economical, and environment friendly. We believe that the upcoming decades will bring us many exciting reports on the syntheses of C-glycopyranosyl aldehydes and glycoconjugates. The synthesis of glycoconjugates must be explored in the desire of many biologically important sugar-based natural products and the total synthesis of target molecules. Since the last decade, we have had our own interest in these C-glycopyranosyl aldehydes and to further utilise these compounds for the syntheses of

glycoconjugates. At present, we are working on the cost-effective, greener, and easy synthetic routes for the synthesis of *C*-glycopyranosyl aldehydes and glycoconjugates and will discuss them in the coming years.

## Abbreviations

AIBN	Azobisisobutyronitrile
BtOH	Butanol
BAIB	Bis(acetoxy)iodobenzene
BCl <sub>3</sub>	Boron trichloride
BF <sub>3</sub> ·Et <sub>2</sub> O	Boron trifluoride diethyl etherate
Bu <sub>3</sub> SnH	Tributyltin hydride
CH <sub>3</sub> COSH	Thioacetic acid
DBU	1,8-Diazabicyclo[5.4.0]undec-7-ene
DCC	<i>N,N</i> -Dicyclohexylcarbodiimide
DIPEA	<i>N,N</i> -Diisopropylethylamine
DMAP	4-Dimethylaminopyridine
DIBAL-H	Diisobutylaluminiumhydride
DAST	Diethylaminosulfur trifluoride
DPPE	1,2-Bis(diphenylphosphino)ethane
DMDO	Dimethyldioxirane
EDC	1-Ethyl-3-(3-dimethylaminopropyl) carbodiimide
Et <sub>3</sub> SiH	Triethylsilane
HOEt	Hydroxybenzotriazole
2-LTT	2-Lithiothiazole
PTSA	<i>para</i> -Toluenesulfonic acid
P <sub>2</sub> O <sub>5</sub>	Phosphorous pentoxide
Pd/C	Palladium on charcoal
PMB	<i>para</i> -Methoxybenzyl
PEG	Polyethylene glycol
TMSOTf	Trimethylsilyl triflate
TMSCl	Trimethylsilyl chloride

## Author contributions

Sandeep Kumar and Vinod Khatri wrote the review. Priyanka Mangla and Rajni Johar checked the review thoroughly and made suitable changes. The review was written under the supervision of Virinder S. Parmar and Ashok K. Prasad.

## Conflicts of interest

The authors declare no conflict of interest.

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## References

- 1 D. E. Levy and C. Tang, *The Chemistry of C-glycosides*, Pergamon Publishers, 1995.

- 2 M. Brito-Arias, *Synthesis and Characterization of Glycosides*, Springer, Boston, MA, 2007.
- 3 K. Kitamura, Y. Maezawa, Y. Ando, T. Kusumi, T. Matsumoto and K. Suzuki, *Angew. Chem., Int. Ed.*, 2014, **53**, 1262–1265.
- 4 Z. Wu, G. Wei, G. Lian and B. Yu, *J. Org. Chem.*, 2010, **75**, 5725–5728.
- 5 Z. Han, M. Achilonu, P. S. Kendrekar, E. Joubert, D. Ferreira, S. L. Bonnet and J. H. van der Westhuizen, *J. Nat. Prod.*, 2014, **77**, 583–588.
- 6 J. Li and B. Yu, *Angew. Chem., Int. Ed.*, 2015, **54**, 6618–6621.
- 7 D. Hager, P. Mayer, C. Paulitz, J. Tiebes and D. Trauner, *Angew. Chem., Int. Ed.*, 2012, **51**, 6525–6528.
- 8 (a) P. G. Hultin, *Curr. Top. Med. Chem.*, 2005, **5**, 1299–1331; (b) K. Kitamura, Y. Ando, T. Matsumoto and K. Suzuki, *Chem. Rev.*, 2018, **118**, 1495–1598.
- 9 (a) A. Cavezza, C. Boulle, A. Guéguinat, P. Pichaud, S. Trouille, L. Ricard and M. Dalko-Csiba, *Bioorg. Med. Chem. Lett.*, 2009, **19**, 845–849; (b) L. Leseurre, C. Merea, S. Duprat de Paule and A. Pinchart, *Green Chem.*, 2014, **16**, 1139–1148.
- 10 X.-J. Wang, L. Zhang, D. Byrne, L. Nummy, D. Weber, D. Krishnamurthy, N. Yee and C. H. Senanayake, *Org. Lett.*, 2014, **16**, 4090–4093.
- 11 J. P. Henchke, C.-W. Lin, P.-Y. Wu, W.-S. Tsao, J.-H. Liao and P.-C. Chiang, *J. Org. Chem.*, 2015, **80**, 5189–5195.
- 12 C. Guo, M. Hu, R. J. DeOrazio, A. Usyatinsky, K. Fitzpatrick, Z. Zhang, J.-H. Maeng, D. B. Kitchen, S. Tom, M. Luche, Y. Khmelnitsky, A. J. Mhyre, P. R. Guzzo and S. Liu, *Bioorg. Med. Chem.*, 2014, **22**, 3414–3422.
- 13 G. Yang, J. Schmieg, M. Tsuji and R. W. Franck, *Angew. Chem., Int. Ed.*, 2004, **43**, 3818–3822.
- 14 A. Shcherbakova, M. Preller, M. H. Taft, J. Pujols, S. Ventura, B. Tiemann, F. F. Buettner and H. Bakker, *Elife*, 2019, **8**, e52978.
- 15 C. Taillefumier and Y. Chapleur, *Chem. Rev.*, 2004, **104**, 263–292.
- 16 M. Choumane, A. Banchet, N. Probst, S. Gerard, K. Ple and A. C. R. Haudrechy, *Chimie*, 2011, **14**, 235–273.
- 17 J. Stambasky, M. Hocek and P. Kocovsky, *Chem. Rev.*, 2009, **109**, 6729–6764.
- 18 E. Von Moos and R. N. Ben, *Curr. Top. Med. Chem.*, 2005, **5**, 1351–1361.
- 19 D. Y. W. Lee and M. He, *Curr. Top. Med. Chem.*, 2005, **5**, 1333–1350.
- 20 E. Bokor, S. Kun, D. Goyard, M. Toth, J. P. Praly, S. Vidal and L. Somsak, *Chem. Rev.*, 2017, **117**, 1687–1764.
- 21 K. Lalitha, K. Muthusamy, Y. S. Prasad, P. K. Vemula and S. Nagarajan, *Carbohydr. Res.*, 2015, **402**, 158–171.
- 22 Y. Yang and B. Yu, *Chem. Rev.*, 2017, **117**, 12281–12356.
- 23 A. Dondoni, *Pure Appl. Chem.*, 2000, **72**, 1577–1588.
- 24 W. R. Kobertz, C. R. Bertozzi and M. D. Bednarski, *Tetrahedron Lett.*, 1992, **33**, 737–740.
- 25 L. Kroger, D. Henkensmeier, A. Schafer and J. Thiem, *Bioorg. Med. Chem. Lett.*, 2004, **14**, 73–75.



- 26 M. Kolypadi, M. Fontanella, C. Venturi, S. Andre, H. J. Gabius, J. J. Barbero and P. Vogel, *Chem. - Eur. J.*, 2009, **15**, 2861–2873.
- 27 J. Guillaume, T. Seki, T. Decruy, K. Venken, D. Elewaut, M. Tsuji and S. V. Calenbergh, *Org. Biomol. Chem.*, 2017, **15**, 2217–2225.
- 28 A. Dondoni and M. C. Scherrmann, *Tetrahedron Lett.*, 1993, **34**, 7319–7322.
- 29 A. Dondoni and M. C. Scherrmann, *J. Org. Chem.*, 1994, **59**, 6404–6412.
- 30 A. Dondoni and A. Marra, *Tetrahedron Lett.*, 2003, **44**, 13–16.
- 31 M. E. L. Sanchez, V. Michelet, I. Besnier and J. P. Genet, *Synlett*, 1994, 705–708.
- 32 F. Labeguere, J. P. Lavergne and J. Martinez, *Tetrahedron Lett.*, 2002, **43**, 7271–7272.
- 33 P. Gerber and P. Vogel, *Tetrahedron Lett.*, 1999, **40**, 3165–3168.
- 34 S. Sipos and I. Jablonkai, *Carbohydr. Res.*, 2011, **346**, 1503–1510.
- 35 M. T. G. Lopez, F. G. D. Las Heras and A. S. Felix, *Carbohydr. Chem.*, 1987, **6**, 273–279.
- 36 H. M. Dettinger, G. Kurz and J. Lehmann, *Carbohydr. Res.*, 1979, **74**, 301–307.
- 37 K. Fujiwara, Y. Koyama, E. Doi, K. Shimawaki, Y. Ohtaniuchi, A. Takemura, S. I. Souma and A. Murai, *Synlett*, 2002, **9**, 1496–1499.
- 38 M. Toth, K. E. Kover, A. Benyei and L. Somsak, *Org. Biomol. Chem.*, 2003, **1**, 4039–4046.
- 39 J. Zeitouni, S. Norsikian and A. Lubineau, *Tetrahedron Lett.*, 2004, **45**, 7761–7763.
- 40 S. Norsikian, J. Zeitouni, S. Rat, S. Gerard and A. Lubineau, *Carbohydr. Res.*, 2007, **342**, 2716–2728.
- 41 T. Y. Xia, Y. B. Li, Z. J. Yin, X. B. Meng, S. C. Li and Z. J. Li, *Chin. Chem. Lett.*, 2014, **25**, 1220–1224.
- 42 H. Dietrich and R. R. Schmidt, *Carbohydr. Res.*, 1993, **250**, 161–176.
- 43 (a) J. R. Pougny, M. A. M. Nassr and P. Sinaj, *J. Chem. Soc., Chem. Commun.*, 1981, 375–376; (b) J. M. Lancelin, J. R. Pougny and P. Sinaj, *Carbohydr. Res.*, 1985, **136**, 369–374.
- 44 F. Nicotra, R. Perego, F. Ronchetti, G. Russo and L. Toma, *Carbohydr. Res.*, 1984, **131**, 180–184.
- 45 T. V. RajanBabu and G. S. Reddy, *J. Org. Chem.*, 1986, **51**, 5458–5461.
- 46 M. Leclerc, B. K. Kwok, L. K. Wu, D. S. Allan and R. N. Ben, *Bioconjugate Chem.*, 2011, **22**, 1804–1810.
- 47 R. Patnam, J. M. Juarez-Ruiz and R. Roy, *Org. Lett.*, 2006, **8**, 2961–2964.
- 48 G. Chen, M. Chien, M. Tsuji and R. W. Franck, *ChemBioChem*, 2006, **7**, 1017–1022.
- 49 J. Desire and A. Veyrieres, *Carbohydr. Res.*, 1995, **268**, 177–186.
- 50 (a) R. Gigg, A. A. E. Penglis and R. Conant, *J. Chem. Soc., Perkin Trans. 1*, 1977, **1**, 2014–2017; (b) T. Iversen and D. R. Bundle, *Carbohydr. Res.*, 1982, **103**, 29–40.
- 51 G. J. McGarvey, F. W. Schmidtmann, T. E. Benedum and D. E. Kizer, *Tetrahedron Lett.*, 2003, **44**, 3775–3779.
- 52 V. Khatri, A. Kumar, B. Singh, S. Malhotra and A. K. Prasad, *J. Org. Chem.*, 2015, **80**, 11169–11174.
- 53 W. Feng, Z. Fang, J. Yang, B. Zheng and Y. Jiang, *Carbohydr. Res.*, 2011, **346**, 352–356.
- 54 O. R. Martin, F. E. Khamis and S. P. Rao, *Tetrahedron Lett.*, 1989, **30**, 6143–6146.
- 55 (a) L. Petrus, S. Bystricky, T. Sticzay and V. Bilik, *Chem. Zvesti*, 1982, **36**, 103; (b) A. Fortsch, H. Kogelberg and P. Koll, *Carbohydr. Res.*, 1987, **164**, 391.
- 56 O. Simo, K. Michael, W. Yoshida, V. A. Chertkov and P. H. Gross, *Synth. Commun.*, 2005, **35**, 1589–1599.
- 57 M. Petrusova, J. N. BeMiller, A. Krihova and L. Petrus, *Carbohydr. Res.*, 1996, **295**, 57–67.
- 58 M. R. Reddy, S. Hemaiswarya, H. Kommidi, I. S. Aidhen and M. Doble, *Eur. J. Org. Chem.*, 2019, 6053–6070.
- 59 L. M. McGrane, Z. Cusumano, Z. Han, J. Binkley, M. Kostakioti, T. Hannan, J. S. Pinkner, R. Klein, V. Kalas, J. Crowley, N. P. Rath, S. J. Hultgren and J. W. Janetka, *J. Med. Chem.*, 2016, **59**, 9390–9408.
- 60 C. R. Bertozzi, D. G. Cook, W. R. Kobertz, F. G. Scarano and M. D. Bednarski, *J. Am. Chem. Soc.*, 1992, **114**, 10639–10641.
- 61 L. Awad, R. Madani, A. Gillig, M. Kolypadi, M. Philgren, A. Muhs, C. Gerand and P. Vogel, *Chem. - Eur. J.*, 2012, **18**, 8578–8582.
- 62 R. Demange, L. Awad and P. Vogel, *Tetrahedron: Asymmetry*, 2004, **15**, 3573–3585.
- 63 A. Dondoni, D. Perrone and E. Turturici, *J. Org. Chem.*, 1999, **64**, 5557–5564.
- 64 A. Dondoni, A. Marra and A. Massi, *Tetrahedron*, 1998, **54**, 2827–2832.
- 65 W. R. Kobertz, C. R. Bertozzi and M. D. Bednarski, *Org. Chem.*, 1996, **61**, 1894–1897.
- 66 R. Demange, C. Buhlmann and P. Vogel, *Helv. Chim. Acta*, 2003, **86**, 361–376.
- 67 Y. H. Zhu and P. Vogel, *Synlett*, 2001, 79–81.
- 68 L. Awad, J. Riedner and P. Vogel, *Chem. - Eur. J.*, 2005, **11**, 3565–3573.
- 69 (a) A. Itoh, S. Ozawa, K. Oshima and H. Nozaki, *Tetrahedron Lett.*, 1980, **21**, 361–364; (b) A. Itoh, S. Ozawa, K. Oshima and H. Nozaki, *Bull. Chem. Soc. Jpn.*, 1981, **54**, 274–278.
- 70 J. Zeitouni, S. Norsikian, D. Merlet and A. Lubineau, *Adv. Synth. Catal.*, 2006, **348**, 1662–1670.
- 71 T. Mukaiyama, K. Narasaka and K. Banno, *Chem. Lett.*, 1973, **2**, 1011–1014.
- 72 E. Levoirier, Y. Canac, S. Norsikian and A. Lubineau, *Carbohydr. Res.*, 2004, **339**, 2737–2747.
- 73 Y. Canac, E. Levoirier and A. Lubineau, *J. Org. Chem.*, 2001, **66**, 3206–3210.
- 74 A. Dondoni, H. M. Zuurmond and A. Boscarato, *J. Org. Chem.*, 1997, **62**, 8114–8124.
- 75 A. Dondoni, M. Kleban, H. Zuurmond and A. Marra, *Tetrahedron Lett.*, 1998, **39**, 7991–7994.
- 76 A. Dondoni, M. Mizuno and A. Marra, *Tetrahedron Lett.*, 2000, **41**, 6657–6660.
- 77 A. Dondoni, A. Marra, M. Mizuno and P. P. Giovannini, *J. Org. Chem.*, 2002, **67**, 4186–4199.



- 78 S. Sipos, I. Jablonkai, O. Egyed and M. Czugler, *Carbohydr. Res.*, 2011, **346**, 2862–2871.
- 79 A. Charfedinne, P. Julien, L. G. Nadege, U. Jacques and A. Jacques, *Sci. China: Chem.*, 2010, **53**, 1921–1926.
- 80 A. Dondoni and D. Perrone, *Org. Synth.*, 2000, **77**, 64–77.
- 81 A. Dondoni, A. Massi, S. Sabbatini and V. Bertolasi, *Tetrahedron Lett.*, 2004, **45**, 2381–2384.
- 82 A. Dondoni, A. Massi and S. Sabbatini, *Chem. - Eur. J.*, 2005, **11**, 7110–7125.
- 83 A. Dondoni, A. Massi and A. Marra, *Tetrahedron Lett.*, 1998, **39**, 6601–6604.
- 84 A. Dondoni and A. M. A. Massi, *J. Org. Chem.*, 1999, **64**, 933–944.
- 85 M. D. P. Risseeuw, J. Mazurek, A. V. Langenvelde, G. A. V. D. Marel, H. S. Overkleef and M. Overhand, *Org. Biomol. Chem.*, 2007, **5**, 2311–2314.
- 86 A. Dondoni, A. Massi, S. Sabbatini and V. Bertolasi, *Adv. Synth. Catal.*, 2004, **346**, 1355–1360.
- 87 N. Boutard, F. Labeguere, Y. Vidal, J. P. Lavergne and J. Martinez, *Synth. Commun.*, 2012, **42**, 1461–1471.
- 88 A. Guerrini, G. Varchi and A. Battaglia, *J. Org. Chem.*, 2006, **71**, 6785–6795.
- 89 B. Kumar, J. Maity, B. Shankar, S. Kumar, Kavita and A. K. Prasad, *Carbohydr. Res.*, 2021, **500**, 108236.
- 90 (a) M. Passerini and L. Simone, *Gazz. Chim. Ital.*, 1921, **51**, 126; (b) M. Passerini, *Gazz. Chim. Ital.*, 1921, **51**, 181.
- 91 M. Raunkjaer, F. E. Oualid, G. A. Van der Marel, H. S. Overkleef and M. Overhand, *Org. Lett.*, 2004, **6**, 3167–3170.
- 92 A. Singh, V. K. Maikhuri, V. Verma, R. J. Chhatwal, D. Sharma and A. K. Prasad, *Synth. Commun.*, 2020, **50**, 2787–2795.
- 93 L. M. McGrane, Z. Cusumano, Z. Han, J. Binkley, M. Kostakioti, T. Hannan, J. S. Pinkner, R. Klein, V. Kalas, J. Crowley, N. P. Rath, S. J. Hultgren and J. W. Janetka, *J. Med. Chem.*, 2016, **59**, 9390–9408.
- 94 Y. Geng, A. Kumar, H. M. Faidallah, H. A. Albar, I. A. Mhkalid and R. R. Schmidt, *Bioorg. Med. Chem.*, 2013, **21**, 4793–4802.
- 95 J. Picard, N. L. Germain, J. Uziel and J. Auge, *Synthesis*, 2006, **6**, 979–982.
- 96 A. Dandoni, A. Massi, S. Sabbatini and V. Bertolasi, *J. Org. Chem.*, 2002, **67**, 6979–6994.
- 97 K. Sudarshan and I. S. Aidhen, *Eur. J. Org. Chem.*, 2017, **2017**, 34–38.
- 98 R. Mukkamala, R. Kumar, S. K. Banerjee and I. S. Aidhen, *Eur. J. Org. Chem.*, 2020, **2020**, 1828–1839.
- 99 F. Chanteau, R. P. Royon and C. Portella, *Synlett*, 2004, **3**, 512–516.
- 100 A. Dondoni, A. Massi and E. Minghini, *Synlett*, 2002, **1**, 89–92.
- 101 A. Dondoni, A. Massi and E. Minghini, *Helv. Chim. Acta*, 2002, **85**, 3331–3348.
- 102 V. Verma, V. K. Maikhuri, V. Khatri, A. Singh and A. K. Prasad, *Synth. Commun.*, 2021, **51**, 446–452.
- 103 A. Dondoni and P. P. Giovannini, *Synthesis*, 2002, **12**, 1701–1706.
- 104 M. R. Reddy and I. S. Aidhen, *Eur. J. Org. Chem.*, 2018, 5744–5753.
- 105 K. Groebke, L. Weber and F. Mehlin, *Synlett*, 1998, 661–663.
- 106 C. Blackburn, B. Guan, P. Fleming, K. Shiosaki and S. Tsai, *Tetrahedron Lett.*, 1998, **39**, 3635–3638.
- 107 H. Bienayme and K. Bouzid, *Angew. Chem. Int. Ed.*, 1998, **37**, 2234–2237; *Angew. Chem. Int. Ed.*, 1998, **110**, 2349.
- 108 B. Kumar, B. Shankar, S. Kumar, J. Maity and A. K. Prasad, *Synth. Commun.*, 2020, **50**, 2853–2859.
- 109 V. Michelet, K. Adiey, S. Tanier, G. Dujardin and J. P. Genet, *Eur. J. Org. Chem.*, 2003, 2947–2958.
- 110 O. Lockhoff, *Angew. Chem. Int. Ed.*, 1998, **37**, 3436–3439.
- 111 A. Dondoni and A. Marra, *Tetrahedron Lett.*, 2002, **43**, 1649–1652.
- 112 J. Auge, V. Boucard, R. Gil, N. L. Germain, J. Picard and J. Uziel, *Synth. Commun.*, 2003, **33**, 3733–3739.
- 113 E. Janes and K. H. Dotz, *J. Organomet. Chem.*, 2003, **669**, 1–5.
- 114 H. F. J. Lehmann, M. S. Schuchardt and W. Weiser, *Carbohydr. Res.*, 1991, **218**, 129–141.
- 115 V. Khatri, S. Bhatia, S. Deep, E. Kohli, R. Haag, N. N. Senapati and A. K. Prasad, *New J. Chem.*, 2020, **44**, 15369–15375.
- 116 B. Shankar, V. Khatri, B. Kumar, V. K. Maikhuri, A. Kumar, R. Tomar and A. K. Prasad, *ACS Omega*, 2021, **6**, 11248–11259.

