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Selective functionalization of the 1,6-anhydro moiety and of the double bond of levoglucosenone

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Through a very efficient, step-economical (only 4 steps) and diastereoselective–chemoselective procedure, bio-based levoglucosenone has been converted into a versatile azide, which may be regarded as a synthetic equivalent of a 6-amino-6-deoxysugar. This procedure involves: (a) reduction of the ketone of LGO; (b) opening of the 1,6-anhydro moiety with acetic anhydride and a protic acid to give a triacetate; (c) biocatalytic deacetylation of the primary alcohol; (d) substitution of the alcohol with the azide. The overall yield from LGO is 59%. This azide has been employed in two diversity-generating protocols: Huisgen–Sharpless 1,3-dipolar cycloaddition with alkynes (also derived from bio-based phenols), and the Ugi multicomponent reaction. Furthermore, the double bond has been dihydroxylated with nearly complete diastereoselection both at the azide level or on the triazoles derived from Huisgen cycloadditions, furnishing compounds with the rare *D-althro* configuration. The chemistry described in this work may help in devising synthetic applications of levoglucosenone, a densely functionalised product of pyrolysis of lignocellulosic matter.

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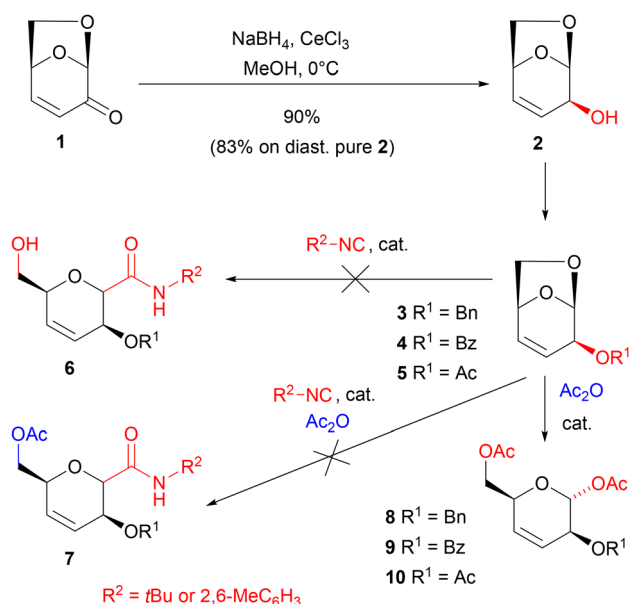
Introduction

Nowadays, oil is the main source of fine chemicals, but it is a non-renewable carbon source, destined to end by 50–100 years. Therefore, renewable biomass is entitled to become the oil of the future.¹ However, until now, it has been mainly used for the production of high volume, low value chemicals (polymers, solvents),² whereas its exploitation for the synthesis of more complex fine chemicals,³ also through a diversity-oriented approach,⁴ is still relatively underexplored. In this context, during the last years, our research group has studied the use of various bio-based derived components in multicomponent reactions such as the Passerini,^{5–7} the Ugi,^{8,9} the Ugi–Joullié,¹⁰ and the Hosomi–Sakurai¹¹ reactions.

Building blocks from biomass are often very challenging from the point of view of organic synthesis, being densely functionalized. On the other hand, they may offer the advantage to be chiral and enantiomerically pure. One such example is levoglucosenone **1** (LGO)¹² (Scheme 1). LGO is the main product of acid catalysed pyrolysis of cellulose containing products, including low value materials such as waste or lignocellulosic matters.^{13–16} If one considers that 180 billion tons of

non-food lignocellulosic biomass are produced annually, the potential of LGO as starting material is very high.

Several transformations (including total syntheses)¹⁷ have been accomplished starting from this building block,^{12,18} and



Scheme 1 Initial strategy.

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its derivatives have been often employed in the field of drug discovery.¹⁹ Anyway, we think that there is still ample room for further investigation. In particular, to our knowledge, only one example of multicomponent reaction has been reported so far on LGO (or better on its saturated derivative).²⁰ Thus, at the outset of this work, we wanted to study new possible applications of MCRs or other diversity generation processes, such as the azide-alkyne cycloaddition (“click” reaction),^{21,22} employing this bio-based building block.

Results and discussion

As shown in Scheme 1, our initial project involved ring-opening of the bicyclic acetal of **1** with isocyanides or other *C*- or *O*-nucleophiles, to give polyfunctionalised building-blocks **6** or **7**. Before opening the bicyclic acetal, we chose to convert LGO **1** into the corresponding alcohol **2**. Although this process, using Luche’s reduction,²³ was already described,^{24,25} in our hands the reported work-up conditions turned out to be not user-friendly. Because of the hydrophilicity of **2**, the standard aqueous work-up involved indeed many extractions, leading anyway to a significant loss of product. We eventually found out that the best procedure involves quenching with solid citric acid followed by filtration through Celite, evaporation, and direct chromatography.²⁶ In this way alcohol **2** could be obtained in 90% yield and 94 : 6 diastereomeric ratio. The minor diastereomer (slower running in TLC) is slightly separated and thus we were able to obtain **2** in up to 98 : 2 dr by chromatography. This alcohol was protected to give known compounds **3**,²⁷ **4**,²⁷ and **5**.²⁶

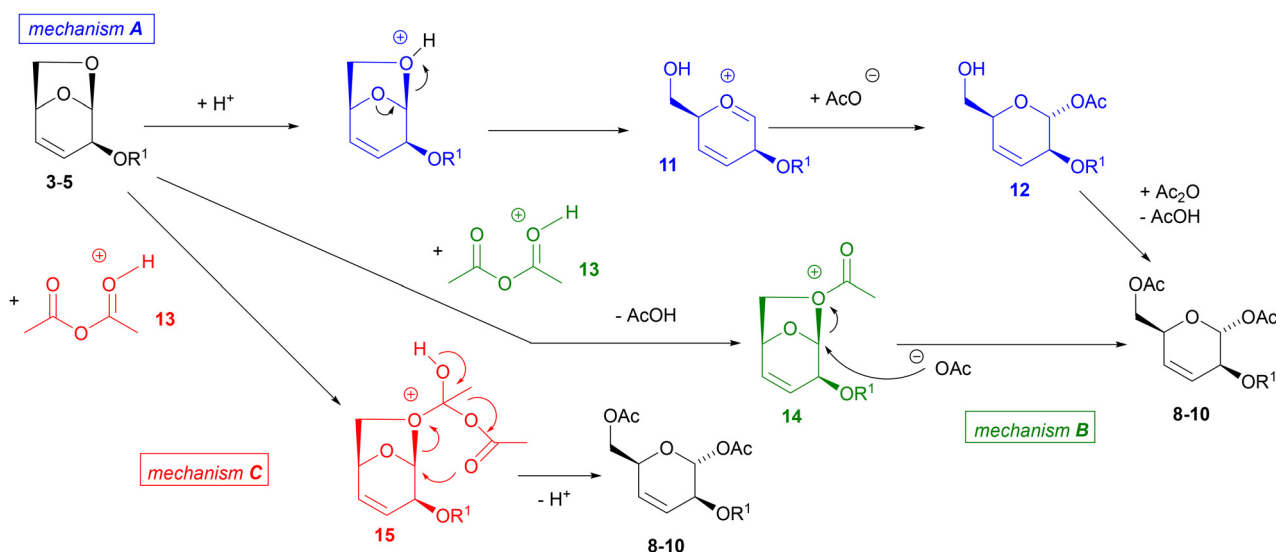
On these protected compounds, we investigated the possible reaction with isocyanides, under the catalysis of Lewis acids or TMS-OTf (trimethylsilyl trifluoromethanesulphonate).

Although very few examples of reactions of isocyanides with acetals are reported in the literature,^{28–30} we hoped to be able to open the bicyclic system introducing a new C–C bond in order to obtain interesting *C*-glycosides containing a secondary amide function. A search in the literature revealed very few examples regarding opening of **2** or its protected derivatives with *O*-nucleophiles,^{31–33} and none with *C*-nucleophiles.

However, as better described in the SI, despite several attempts, we never succeeded in introducing isocyanides as nucleophiles onto protected derivatives **3–5**. During these attempts, we reasoned that this failure might be due to reversible additions of the isocyanides and that trapping the liberated primary alcohol in **6** could be beneficial. Hoping to be able to obtain adducts **7**, we thus added Ac₂O to the reaction mixture. To our surprise, starting from **4**, and using TMS-OTf or Lewis acids as catalysts, we isolated, with excellent diastereoselectivity (>10 : 1), diacetate **9**. The same result was obtained with protic acids. This was somehow unexpected, because, in standard Passerini reactions, it is always the isocyanide to act as the nucleophile, and not the carboxylate anion.

Scheme 2 shows possible mechanisms of this opening reaction with Ac₂O. For the sake of clarity, protic catalysis is shown, but similar mechanisms can be envisaged using Lewis acids or TMSOTf. In mechanism A, the acid promotes opening of the ring to give oxocarbenium ion **11**, which may be attacked by a nucleophile. This mechanism does not seem very likely to us. First of all, we do not understand why **11** should not be attacked by the isocyanide, but by the carboxylate anion instead. Then, addition of acetate anion does not improve the process. Free alcohol **12** was never detected. Finally, according to this mechanism, the reaction should be poorly stereoselective or even give the other stereoisomer, as in other reported acid-catalysed opening of LGO with *O*-nucleophiles.³³

Other possible mechanisms are B or C, where acylation of the bridge oxygen precedes the opening of the ring. In mecha-



Scheme 2 Possible mechanisms for conversion of **3–5** into **8–10**. Similar mechanisms may be envisaged using a Lewis acid or TMSOTf.



nism B, an intermolecular substitution by the acetoxy anion either through a S_N1 (via oxocarbenium ion) or S_N2 process should then take place. Once again, it is not clear why other added nucleophiles, such as isocyanides, do not participate.

Thus, we think (although we do not have definitive proofs about that) that the reaction may proceed through the concerted mechanism C, with simultaneous entrance of both acetoxy groups starting from cation **15**. This mechanism, involving a 6-membered cyclic T.S., may also explain the high diastereoselectivity observed, and the preferred diastereomer. Reactions passing through an oxocarbenium ion should be less stereoselective (or even favour the other isomer),³³ and d.r.s should strongly depend on the nature of protecting group (because of anchimeric assistance), whereas in our case we did not observe significant differences.

Apart from the mechanistic rationalisations, we reasoned that diacetates **8–9** or triacetate **10** could be useful building blocks for diversity-oriented processes using glycomimetic fragments. This opening reaction was thus optimized (see SI). To make a long story short, we eventually found that: (a) protic acids, especially phosphoric acid, behave better than Lewis acids or TMSOTf, being also more sustainable; (b) previous protection of the allylic alcohol was not really necessary, and the reaction could be carried out directly on alcohol **2**, affording triacetate **10** in just 2 steps from LGO, with nearly complete stereocontrol for the stereocenter at position 1 (sugar numbering).

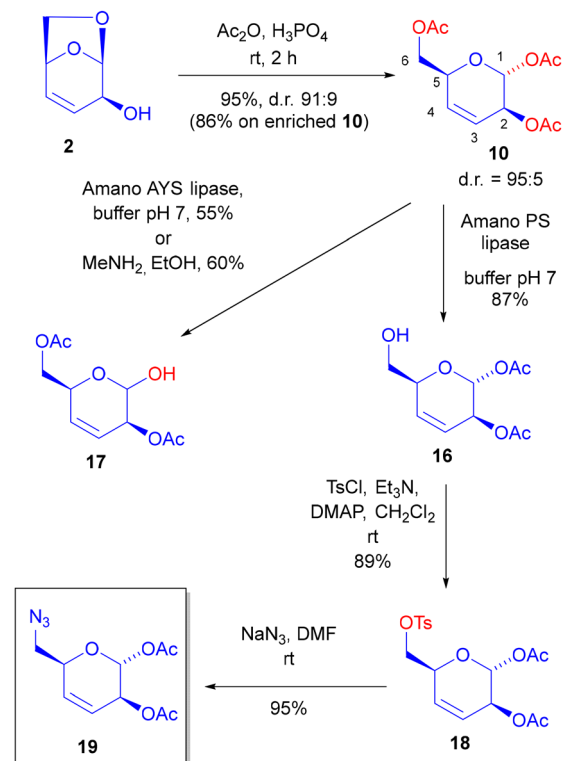
Although in this way we obtained a triacetate, we were confident to be able to differentiate the three groups by chemoenzymatic means. This was indeed the case. After screening various lipases, we found out that Amano P lipase was highly chemoselective, allowing hydrolysis of the primary acetate in **10** to give **16** (Scheme 3). Other enzymes (see SI) were less selective, whereas Amano AYS lipase preferred to hydrolyse the anomeric acetate to give **17**. Selective hydrolysis of the latter can be also achieved chemically, using MeNH_2 in EtOH.

Thus alcohol **16** could be obtained in just three steps from LGO **1**, in overall 62% yield, and with an operationally simple and “green” procedure.

In order to get a nitrogen containing building block, we then converted **16** into azide **19**, through the tosylate **18**, by a classical S_N2 substitution.

A comment on diastereomeric purity of alcohol **16**, tosylate **18** and azide **19** is worthy. We started from nearly pure (d.r. 98:2) alcohol **2** and performed diastereoselective opening to **10** (91:9) and finally chemoselective enzymatic hydrolysis to **16**. These two last steps are highly, but not completely, selective and thus small amounts of isomers were present. These could be eliminated by careful chromatographies at the level of **10**, **16** and **19**. However, tosylate **18** is a white solid, and we found out that, working on a larger scale, it is also possible to be less accurate in chromatography of intermediates, since a single trituration at the level of **18** can afford a very pure compound.

Azide **19** may be considered a synthetic equivalent of a 6-aminosugar, taking into account the possibility to convert



Scheme 3 Conversion of triacetate **10** into azide **19**.

the double bond into a diol, as described below. Although quite rare, 6-aminosugars are endowed with interesting biological activities.^{34–36}

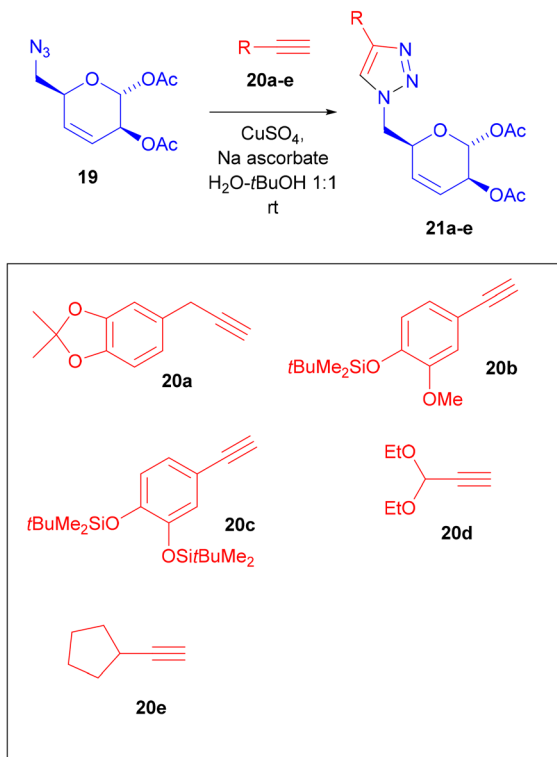
As a first application we employed azide **19** in a series of 1,3-dipolar cycloadditions with alkynes (“click” reactions).²¹ The alkynes used are shown in Scheme 4, whereas the results are listed in Table 1. As already previously observed by us in another work,³⁷ when using very small amounts of catalysts (0.01 equivalents of CuSO_4 and 0.1 equivalents of Na ascorbate) (see Table 1), these 1,3-dipolar cycloadditions tended to stop, probably because of inactivation of $\text{Cu}(i)$. Therefore, initially we used to add a second or even a third portion of both catalysts when the reaction appeared to stop.³⁷ In the last experiments, we preferred to add a higher catalyst quantity (especially ascorbate) from the beginning in order to have more complete reactions.

In these click reactions, we have also used some alkynes containing the catechol structure typical of natural polyphenols.

In order to gain access to hybrid peptidomimetics–glycomimetics, we also decided to employ azide **19** in Ugi multicomponent reactions.^{38,39} Our idea was to use azide **19** as a synthetic equivalent of a primary amine.

In the literature there are some examples^{40–42} of one-pot Staudinger-aza-Wittig-Ugi sequence, where an azidoaldehyde is first reduced by a phosphine (Staudinger reduction) to form a phosphazene, followed by an intramolecular aza-Wittig reaction affording a cyclic imine. Finally, the latter is the substrate of a 3-component Ugi-Joullié reaction.





Scheme 4 Click reactions starting from azide 19.

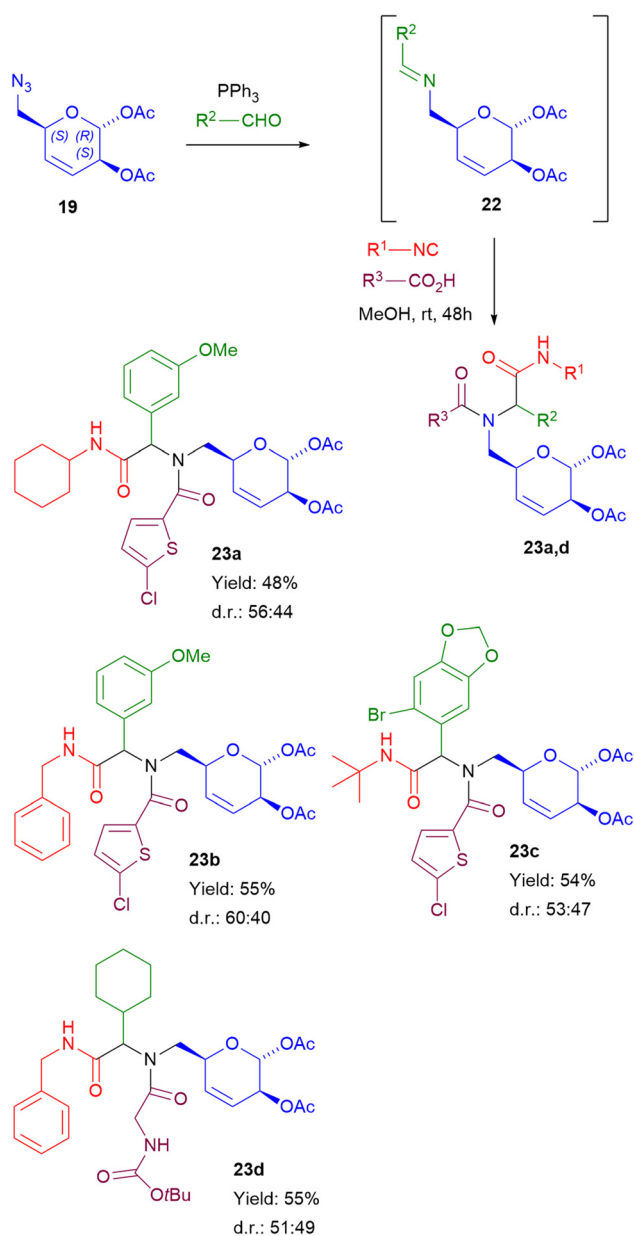
Table 1 Synthesis of triazoles 21^a

Alkyne	Triazole	Cat. amount (ascorbate/CuSO ₄)	Reaction time ^b	Yield ^c (%)
20a	21a	0.1/0.01 equiv. × 2	4 h + 1 h	65
20b	21b	0.1/0.01 equiv. × 2	3 h + 2 h	66
20c	21c	0.1/0.01 equiv. × 2	2 h + 1 h	90
20d	21d	0.1/0.01 equiv. × 3	2 h + 2 h + 1 h	84
20e	21e	0.5/0.2 equiv.	4 h	93

^a Conditions: azide **19** and alkyne **20** (1.2 equiv.) were treated, in *t*-BuOH/H₂O 1 : 1, at rt, with the indicated equiv. of Na ascorbate and of CuSO₄. The same amount of catalysts was added after the first time indicated in column 4. In some cases a third addition of catalysts was necessary. ^b For example (line 1), 4 h + 1 h means 4 h, followed by a second addition of catalyst and then further reaction for 1 h. ^c Isolated yields.

However, this protocol was always applied to azidoaldehydes, in an intramolecular way. We tried to transfer the same approach to an intermolecular process, thus applying a true 4-component Ugi reaction. We were pleased to find out that this was indeed possible, by treating azide **19** with PPh₃ in the presence of an aldehyde, followed by addition of an isocyanide and of a carboxylic acid. A series of Ugi products, shown in Scheme 5, were obtained. Unfortunately, diastereoselectivity was very low, as usual for this MCR, giving nearly 1 : 1 mixture of the possible diastereomers.

When using an aliphatic aldehyde (cyclohexanecarboxaldehyde to give **23d**) we surprisingly observed at the end of the process, the presence of starting azide **19**, notwithstanding

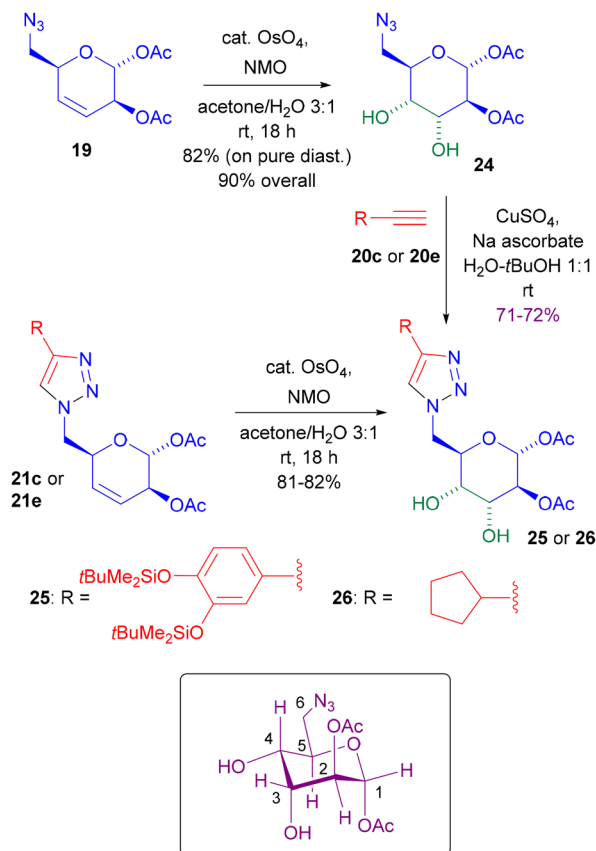


Scheme 5 Ugi reactions starting from azide 19.

the fact that PPh₃ was used in excess. We reasoned that the aldehyde could somehow inhibit the reduction of the azide. Therefore, in this case, we repeated the reaction treating the azide with PPh₃ before addition of the aldehyde and the yield was improved from 40% to 55%.

In all the products shown in Schemes 4 and 5, the double bond of starting levoglucosenone is still present. This double bond can be seen as a synthetic equivalent of a diol. In order to prove this synthetic equivalence, we studied dihydroxylation of azide **19** using catalytic OsO₄ (3%) in the presence of stoichiometric *N*-methylmorpholine-*N*-oxide (NMO) (Scheme 6). With our surprise, this dihydroxylation was found to be highly diastereoselective and we could isolate diol **24** as a single dia-





Scheme 6 Highly diastereoselective dihydroxylation of azide **19** and triazoles **21**.

stereomer after chromatography. Careful examination of the crude and of some head fractions of chromatography allowed to detect two possible isomers, in quantities around 5% and 3%, relative to the major isomer. Osmium catalysed hydroxylation is known to be stereospecific and thus we were a little surprised by the presence of two isomers. Due to the very low amount of them it was not possible to understand their structure.

Anyway, the relative stereoselection of the two *cis* diols is higher than 20 : 1, the yield is high and **24** can be easily isolated in pure form by chromatography. The relative configuration of this major product was easily assessed by examination of the coupling constants in ^1H NMR, which were compatible only with the $^4\text{C}_1$ conformation of the *altro* diastereomer, shown in Scheme 6 (sugar numbering). In particular, there is a J_{4-5} equal to 9.7 Hz, indicating that H-4 and H-5 are both axial and *trans* to each other. On the other hand, J_{3-4} and J_{2-3} , respectively 3.5 and 3.3 Hertz are in agreement with a *cis* (3-4) or a *trans* diequatorial (2-3) relationship. Neither conformation of the *talo* isomer fit with these coupling constants, because H-4 and H-5 would be *cis* and thus J_{4-5} would be around 3 Hz. The preference for the $^4\text{C}_1$ conformation may be ascribed to the α effect. Although highly diastereoselective dihydroxylation of levoglucosenone from the bottom face is known,^{24,43} in that case the bridge causes a much higher shield of the upper face

than in the case of **19** and thus this very high diastereoselectivity was unexpected to us.

Compound **24** has the relative and absolute configuration of α -D-*altro*pyranose, a very rare sugar. Therefore, this building block may be very useful for the “click” assembly of glycomimetics having this unusual relative configuration.

Hydroxylated azide **24** was used in 1,3-dipolar cycloaddition with alkynes **20c** and **20e** to give triazoles **25**, **26**, which were isolated as pure diastereomers. Alternatively, triazoles **21c** and **21e** may be dihydroxylated, again with high diastereoselection, to afford the same *altro* derivatives **25**, **26**. In the case of **21c**, we obtained a dr of 98 : 2, whereas, with **21e**, stereoselection was slightly lower (93 : 7). In these cases, a third isomer was again present, but in very little amount (<1%).

Conclusions

In conclusion, we have developed an efficient transformation of levoglucosenone into azide **19**, which may be considered an useful building block for diversity-oriented synthesis of complex molecule containing a fragment corresponding to a 6-aminosugar. Azide **19** was synthesized thanks to a highly diastereoselective opening of the bridge with acetic anhydride and protic acids, followed by an enzymatic differentiation of the hydroxy group at carbon 6.

The suitability of azide **19** in diversity-oriented synthesis was demonstrated by a series of click reactions or of Ugi reactions starting from it.

We also demonstrated the synthetic equivalence of the double bond of levoglucosenone with a diol, by an OsO_4 catalysed dihydroxylation.

The use of azide **19** in Ugi and click reactions demonstrates its synthetic equivalence with rare 6-deoxy-6-aminosugars.³⁴⁻³⁶ There are indeed very few examples of this kind of sugars in the literature, and none with the particular *D-altro* configuration that can be achieved by osmylation. While 1-aminosugars have been previously used as component in the Ugi reactions,⁴⁴ to our knowledge no example of use of 6-aminosugars in MCRs is known.

From the stereochemical point of view, it is worth noting that a series of 3 highly diastereoselective transformations has allowed to convert LGO (only 2 chirality centers) into stereopure compounds **24-26** (5 chirality centers).

Author contributions

Conceptualization: LB, RR. Funding acquisition: LB, RR. Resources: CL. Data analysis: CL, LB, RR. Investigation: MR, MJC, FR, DK. Supervision: CL, LB. Writing of draft: LB. Writing: editing and review: CL, RR, DK.

Conflicts of interest

There are no conflicts to declare.



Data availability

The data supporting this article have been included as part of the supplementary information (SI). Supplementary information: procedures, optimizations, characterization data, NMR spectra, and discussion on the assessment of relative configuration. See DOI: <https://doi.org/10.1039/d6ob00050a>.

Additional references were quoted within the SI.⁴⁵

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References

- N. Brun, P. Hesemann and D. Esposito, Expanding the biomass derived chemical space, *Chem. Sci.*, 2017, **8**, 4724–4738.
- F. H. Isikgor and C. R. Becer, Lignocellulosic biomass: a sustainable platform for the production of bio-based chemicals and polymers, *Polym. Chem.*, 2015, **6**, 4497–4559.
- T. Dekker, J. W. Hartevelde, G. Wagner, M. C. M. de Vries, H. Custers, A. C. van de Stolpe, I. J. P. de Esch and M. Wijtman, Green Drug Discovery: Novel Fragment Space from the Biomass-Derived Molecule Dihydrolevoglucosenone (Cyrene™), *Molecules*, 2023, **28**, 1777.
- L. Banfi, C. Lambruschini, L. Moni and R. Riva, in *RSC Green Chemistry*, ed. R. Ballini, Royal Society of Chemistry, 2019, vol. 2019-January, pp. 115–140.
- G. Vitali Forconesi, A. Basso, L. Banfi, D. Gugliotta, C. Lambruschini, M. Nola, R. Riva, V. Rocca and L. Moni, Total Synthesis of 4-epi-Bengamide E, *Molecules*, 2024, **29**, 1715.
- L. Moni, L. Banfi, D. Cartagenova, A. Cavalli, C. Lambruschini, E. Martino, R. V. A. Orru, E. Ruijter, J. M. Saya, J. Sgrignani and R. Riva, Zinc(II)-mediated diastereoselective Passerini reactions of biocatalytically desymmetrised renewable inputs, *Org. Chem. Front.*, 2020, **7**, 380–398.
- G. Vitali Forconesi, L. Banfi, A. Basso, C. Lambruschini, L. Moni and R. Riva, Synthesis of polyoxygenated heterocycles by diastereoselective functionalization of a bio-based chiral aldehyde exploiting the Passerini reaction, *Molecules*, 2020, **25**, 3227.
- D. Galante, L. Banfi, G. Baruzzo, A. Basso, C. D'Arrigo, D. Lunaccio, L. Moni, R. Riva and C. Lambruschini, Multicomponent synthesis of polyphenols and their in vitro evaluation as potential β -amyloid aggregation inhibitors, *Molecules*, 2019, **24**, 2636.
- C. Lambruschini, A. Basso, L. Moni, A. Pinna, R. Riva and L. Banfi, Bicyclic Heterocycles from Levulinic Acid through a Fast and Operationally Simple Diversity-Oriented Multicomponent Approach, *Eur. J. Org. Chem.*, 2018, 5445–5455.
- V. Cerulli, L. Banfi, A. Basso, V. Rocca and R. Riva, Diversity oriented and chemoenzymatic synthesis of densely functionalized pyrrolidines through a highly diastereoselective Ugi multicomponent reaction, *Org. Biomol. Chem.*, 2012, **10**, 1255–1274.
- C. Lambruschini, A. Barbero, A. Cherubin, L. Moni, L. Palio, R. Riva and L. Banfi, Multicomponent Hosomi-Sakurai reaction on chiral, bio-based, alcohols, *RSC Adv.*, 2025, **15**, 17897–17905.
- Z. J. Witezak, in *Levoglucosenone and Levoglucosans, Chemistry and Applications: Proceedings of the Symposium on Levoglucosenone and Levoglucosans, Sponsored by the Division of Carbohydrate Chemistry at the 204th National Meeting of the American Chemical Society*, Washington, D.C., 1992.
- S. Y. Feng, S. Li, W. Z. Huang, Q. Niu, D. Y. Chen, Z. M. Fang, L. J. Gao, K. Li and Q. Lu, Alkali pretreatment-assisted catalytic pyrolysis of waste cellulose acetate for selective preparation of levoglucosenone, *J. Environ. Chem. Eng.*, 2024, **12**, 113858.
- A. M. Gonzalez-Rosario, O. Oyola-Rivera and N. Cardona-Martinez, Production of Levoglucosan and Levoglucosenone from Cellulose Using Brønsted Acid Catalysts in Polar Aprotic Solvents, *Waste Biomass Valorization*, 2024, **16**, 787–803, DOI: [10.1007/s12649-024-02708-9](https://doi.org/10.1007/s12649-024-02708-9).
- H. Yang, S. Lei, K. Xu, Y. Fang, X. Chen, Y. Chen, X. Wang and H. Chen, Catalytic pyrolysis of cellulose with sulfonated carbon catalyst to produce levoglucosenone, *Fuel Process. Technol.*, 2022, **234**, 107323.
- J. Klepp, W. Dillon, Y. Lin, P. Feng and B. W. Greatrex, *Org. Synth.*, 2020, **97**, 38–53.
- M. B. Comba, Y. H. Tsai, A. M. Sarotti, M. I. Mangione, A. G. Suárez and R. A. Spanevello, Levoglucosenone and Its New Applications: Valorization of Cellulose Residues, *Eur. J. Org. Chem.*, 2018, 590–604, DOI: [10.1002/ejoc.201701227](https://doi.org/10.1002/ejoc.201701227).
- Z. J. Witezak and K. Tatsuta, *Carbohydrates Synthons in Natural Products Synthesis*, Oxford University Press, Washington, 2002.
- J. E. Camp and B. W. Greatrex, Levoglucosenone: Bio-Based Platform for Drug Discovery, *Front. Chem.*, 2022, **10**, 902239.
- L. A. Martinho, T. P. F. Rosalba, G. G. Sousa, C. C. Gatto, J. R. S. Politi and C. K. Z. Andrade, Cyrene: a very reactive bio-based chiral ketone in diastereoselective Passerini reactions, *Mol. Diversity*, 2024, **28**, 111–123.



- 21 P. Wu, A. K. Feldman, A. K. Nugent, C. J. Hawker, A. Scheel, B. Voit, J. Pyun, J. M. J. Fréchet, K. B. Sharpless and V. V. Fokin, Efficiency and Fidelity in a Click-Chemistry Route to Triazole Dendrimers by the Copper(I)-Catalyzed Ligation of Azides and Alkynes, *Angew. Chem., Int. Ed.*, 2004, **43**, 3928–3932.
- 22 Y. H. Tsai, C. M. B. Etichetti, C. Di Benedetto, J. E. Girardini, F. T. Martins, R. A. Spanevello, A. G. Suárez and A. M. Sarotti, Synthesis of Triazole Derivatives of Levoglucosenone As Promising Anticancer Agents: Effective Exploration of the Chemical Space through *retro-aza-Michael/aza-Michael* Isomerizations, *J. Org. Chem.*, 2018, **83**, 3516–3528.
- 23 J. L. Luche, Lanthanides in organic chemistry. 1. Selective 1,2 reductions of conjugated ketones, *J. Am. Chem. Soc.*, 1978, **100**, 2226–2227.
- 24 E. D. V. Giordano, A. Frinchaboy, A. G. Suárez and R. A. Spanevello, Synthesis of Tri-O-acetyl-D-allal from Levoglucosenone, *Org. Lett.*, 2012, **14**, 4602–4605.
- 25 B. T. Sharipov, A. N. Davidova, A. S. Ryabova, N. F. Galimzyanova and F. A. Valeev, Synthesis and fungicidal activity of methylsulfanylmethyl ether derivatives of levoglucosenone, *Chem. Heterocycl. Compd.*, 2019, **55**, 31–37.
- 26 X. H. Ma, X. Liu, P. Yates, W. Raverty, M. G. Banwell, C. X. Ma, A. C. Willis and P. D. Carr, Manipulating the enone moiety of levoglucosenone: 1,3-Transposition reactions including ones leading to isolevoglucosenone, *Tetrahedron*, 2018, **74**, 5000–5011.
- 27 K. Matsumoto, T. Ebata and H. Matsushita, Novel Synthesis of 3-Acetamido-3-Deoxy-D-Altrose and 4-Acetamido-4-Deoxy-D-Altrose from Levoglucosenone Using Regioselective Cis-Oxyamination, *Carbohydr. Res.*, 1995, **267**, 187–201.
- 28 M. Tobisu, A. Kitajima, S. Yoshioka, I. Hyodo, M. Oshita and N. Chatani, Brønsted Acid Catalyzed Formal Insertion of Isocyanides into a C–O Bond of Acetals, *J. Am. Chem. Soc.*, 2007, **129**, 11431–11437.
- 29 L. Y. Lyu, M. Y. Jin, Q. J. He, H. Xie, Z. X. Bian and J. Wang, Bi(OTf)₃-catalyzed addition of isocyanides to 2H-chromene acetals: an efficient pathway for accessing 2-carboxamide-2H-chromenes, *Org. Biomol. Chem.*, 2016, **14**, 8088–8091.
- 30 N. E. Golantsov, H. M. Nguyen, A. V. Varlamov, A. V. Aksenov and L. G. Voskressensky, Three-component reaction of ketals, isonitriles, and trimethylsilyl azide, *Chem. Heterocycl. Compd.*, 2017, **53**, 446–450.
- 31 M. E. Jung and M. Kiankarimi, Synthesis of methylene-expanded 2',3'-dideoxyribonucleosides, *J. Org. Chem.*, 1998, **63**, 8133–8144.
- 32 M. Ostermeier and R. Schobert, Total Synthesis of (+)-Chloriolide, *J. Org. Chem.*, 2014, **79**, 4038–4042.
- 33 F. A. Valeev, I. N. Gaisina, L. V. Spirikhin and M. S. Miftakhov, Reactions of 1,6-anhydro-3,4-dideoxy-2-O-methyl-beta-D-threo-hex-3-enopyranose with thiols and methanol, *Russ. Chem. Bull.*, 1997, **46**, 528–531.
- 34 D. Lafont, A. Wollny and P. Boullanger, Synthesis of 6-amino-1,6-anhydro-6-deoxysugar derivatives, *Carbohydr. Res.*, 1998, **310**, 9–16.
- 35 F. Kudo, Y. Kitayama, A. Miyanaga, M. Numakura and T. Eguchi, Stepwise Post-glycosylation Modification of Sugar Moieties in Kanamycin Biosynthesis, *ChemBioChem*, 2021, **22**, 1668–1675.
- 36 T. Li, X. Gao, L. Yang, Y. Shi and Q. Gao, Methyl 6-Amino-6-deoxy-d-pyranoside-Conjugated Platinum(II) Complexes for Glucose Transporter (GLUT)-Mediated Tumor Targeting: Synthesis, Cytotoxicity, and Cellular Uptake Mechanism, *ChemMedChem*, 2016, **11**, 1069–1077.
- 37 E. Tassano, A. Alama, A. Basso, G. Dondo, A. Galatini, R. Riva and L. Banfi, Conjugation of Hydroxytyrosol with Other Natural Phenolic Fragments: From Waste to Antioxidants and Antitumour Compounds, *Eur. J. Org. Chem.*, 2015, 6710–6726.
- 38 M. A. Fouad, H. Abdel-Hamid and M. S. Ayoup, Two decades of recent advances of Ugi reactions: synthetic and pharmaceutical applications, *RSC Adv.*, 2020, **10**, 42644–42681.
- 39 E. Fotopoulou, P. K. Anastasiou, C. Tomza and C. G. Neochoritis, The Ugi reaction as the green alternative towards active pharmaceutical ingredients, *Tetrahedron Green Chem*, 2024, **3**, 100044.
- 40 T. Wennekes, K. M. Bongers, K. Vogel, R. J. B. H. N. van den Berg, A. Strijland, W. E. Donker-Koopman, J. M. F. G. Aerts, G. A. van der Marel and H. S. Overkleeft, The Development of an Aza-C-Glycoside Library Based on a Tandem Staudinger/Aza-Wittig/Ugi Three-Component Reaction, *Eur. J. Org. Chem.*, 2012, 6420–6454, DOI: [10.1002/ejoc.201200923](https://doi.org/10.1002/ejoc.201200923).
- 41 L. Moni, L. Banfi, A. Basso, A. Galatini, M. Spallarossa and R. Riva, Enantio- and diastereoselective synthesis of highly substituted benzazepines by a multicomponent strategy coupled with organocatalytic and enzymatic procedures, *J. Org. Chem.*, 2014, **79**, 339–351.
- 42 L. Banfi, A. Basso, G. Guanti and R. Riva, Enantio- and diastereoselective synthesis of 2,5-disubstituted pyrrolidines through a multicomponent Ugi reaction and their transformation into bicyclic scaffolds, *Tetrahedron Lett.*, 2004, **45**, 6637–6640.
- 43 K. Matsumoto, T. Ebata, K. Koseki, H. Kawakami and H. Matsushita, Synthesis of D-altrose via D-altrosan from levoglucosenone, *Bull. Chem. Soc. Jpn.*, 1991, **64**, 2309–2310.
- 44 O. Lockhoff, An Access to Glycoconjugate Libraries through Multicomponent Reactions, *Angew. Chem., Int. Ed.*, 1998, **37**, 3436–3439.
- 45 F. A. Valeev, L. K. Kalimullina, S. M. Salikhov, O. V. Shitikova, I. P. Tsypysheva and M. G. Safarov, Synthesis of 2-amino derivatives of levoglucosenone, *Chem. Nat. Compd.*, 2004, **40**, 521–525.

