



Rim-differentiation vs. mixture of constitutional isomers: A binding study between pillar[5]arene-based glycoclusters and lectins from pathogenic bacteria

Zhiping Liu, Fanny Demontrond, Anne Imbert, Andrew C.-H. Sue, Sébastien Vidal, Hongxia Zhao

► To cite this version:

Zhiping Liu, Fanny Demontrond, Anne Imbert, Andrew C.-H. Sue, Sébastien Vidal, et al.. Rim-differentiation vs. mixture of constitutional isomers: A binding study between pillar[5]arene-based glycoclusters and lectins from pathogenic bacteria. Chinese Chemical Letters, 2023, 34 (2), pp.107872. 10.1016/j.cclet.2022.107872 . hal-03989896

HAL Id: hal-03989896

<https://hal.science/hal-03989896>

Submitted on 15 Feb 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Rim-differentiation vs. mixture of constitutional isomers: A binding study between pillar[5]arene-based glycoclusters and lectins from pathogenic bacteria[☆]

Zhiping Liu^{a,#}, Fanny Demontrond^{b,#}, Anne Imberty^c, Andrew C.-H. Sue^{d,*}, Sébastien Vidal^{b,e,*}, Hongxia Zhao^{a,*}

^a Tianjin Key Lab for Modern Drug Delivery & High-Efficiency, School of Pharmaceutical Science and Technology, Tianjin University, Tianjin 300072, China

^b Institut de Chimie et Biochimie Moléculaires et Supramoléculaires, Laboratoire de Chimie Organique 2-Glycochimie, UMR 5246, CNRS, Université Claude Bernard Lyon 1, Université de Lyon, Villeurbanne 69622, France

^c Univ. Grenoble Alpes, CNRS-CERMAV, Grenoble 38000, France

^d College of Chemistry and Chemical Engineering, Xiamen University, Xiamen 361005, China

^e Université Paris-Saclay, CNRS, Institut de Chimie des Substances Naturelles, UPR 2301, Gif-sur-Yvette 91198, France

Abstract - Macrocyclic glycoclusters, on account of their promising anti-adhesive properties against bacteria, are potential therapeutic alternatives to classic antibiotics through the much less explored anti-adhesive strategy. In this study, a series of constitutionally-pure pentavalent glycoclusters was prepared by conjugating assorted azido-carbohydrates onto a penta-propargyl rim-differentiated pillar[5]arene (RD-P[5]) scaffold through Cu(I)-catalyzed azide-alkyne cycloaddition “click” reactions. Their binding towards therapeutically relevant bacterial lectins, such as LecA and LecB from *Pseudomonas aeruginosa* and concanavalin A (ConA), were evaluated subsequently by isothermal titration calorimetric studies. Most of these isomer-free RD-P[5] pentavalent glycoclusters, except the fucosylated ones, display good affinities to lectins. Nonetheless, the dissociation constants observed are similar to those displayed by an analogous pentavalent glycocluster consisting of four P[5] constitutional isomers, in which the RD-P[5] component merely accounts for 7% in the mixture. Our results revealed that high constitutional purity is not essential for achieving effective multivalent interactions between P[5]-based glycoclusters and lectins, presumably as a result of the conformationally labile nature of the P[5] scaffold. This information provides valuable design principles for low-cost and facile syntheses of glycosylated P[5]s for biomedical applications.

Carbohydrate-protein interactions are involved in a large panel of biological events including, but not limited to, cell-cell communication [1], inflammation [2], viral or bacterial infection [3], immune responses [4], and tumor cell metastasis [5]. Current advances in glycobiology have shown that individual interactions between carbohydrates and proteins are weak in energy, generally showing dissociation constants in the millimolar range. Oligosaccharide ligands, on the other hand, possess much higher binding affinities towards lectin receptors on account of the “glycoside cluster effect” [6]. Inspired by the multivalency concept, a vast array of polysaccharides [7], glycopolymers [8], glycodendrimers [9] and supramolecular glycopolymers [10] have been successfully exploited, offering opportunities to design anti-adhesins [11], drug delivery systems [12,13], and vaccines [14] on account of their abilities to recognize and bind specific biological targets.

Recently, multivalent glycoconjugates have been developed as anti-adhesive molecules against pathogen infections. *Pseudomonas aeruginosa*, an opportunistic Gram-negative bacterial pathogen, is of special interest because of its morbidity and mortality risks for immuno-compromised and cystic fibrosis patients [15]. This bacterium expresses two soluble lectins (LecA

and LecB), involved in host recognition, adhesion to tissue and formation of biofilms [15,16].

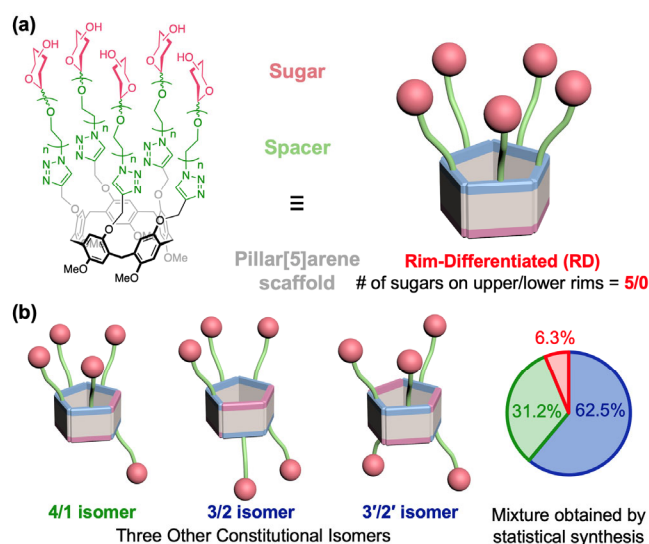


Fig. 1. Schematic illustration of the molecular design of pentavalent glycoclusters based on (a) rim-differentiated P[5] and (b) mixture of four penta-substituted P[5] constitutional isomers.

Their tetrameric structures allow for the cross-linking between the bacterial biofilm polysaccharides and the host cells [17]. Among strategies that have been developed to competitively interfere with the recognition processes between host cells and pathogens, multivalent glycoconjugates have the potential to prevent colonization or even reverse the formation of biofilms for fighting bacterial infection. Therefore, a large number of glycoclusters have been constructed based on various scaffolds

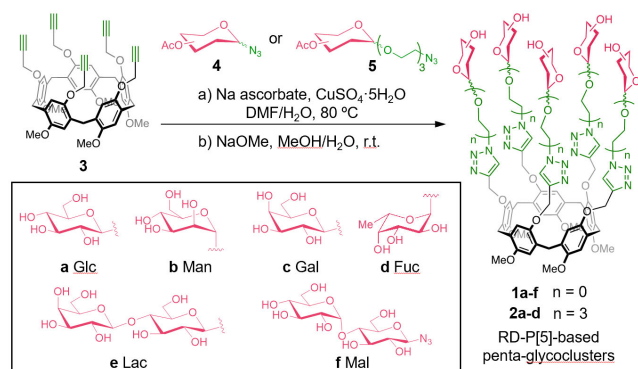
[☆] Dedicated to Sir Fraser Stoddart on the occasion of his 80th birthday.

* Corresponding authors.

E-mail addresses: andrewsue@xmu.edu.cn (A.C.-H. Sue), sebastien.vidal@cnrs.fr (S. Vidal), zhaohongxia@tju.edu.cn (H.X. Zhao).

These authors contributed equally to this work.

including proteins [18,19], polymers [20,21], dendrimers [22], calixarenes [23-31], resorcinarenes [32], cyclodextrins [33], porphyrins [34-37], fullerenes [38-47], and pillararenes [48-51], to prevent or treat diseases caused by bacteria.



Scheme 1. Synthesis of RD-P[5]-based glycoclusters using RD-(propargyl)₅-P[5] scaffold.

Pillar[*n*]arenes, as a novel family of macrocyclic host molecules [52-54], have been well-received by the supra(bio)molecular chemistry community since their first report in 2008 by Ogoshi [55]. Different from *meta*-bridged calixarenes, the highly symmetrical scaffolds of pillararenes consist of *para*-linked hydroquinone units [56]. In particular, *per*-functionalized pillar[5]arenes (P[5]) with ten identical substituents on both rims are especially easy to be synthesized and functionalized, allowing for the construction of a wide range of supramolecular architectures [57-60]. Intensive investigations on the lectin binding properties of deca-glycosylated P[5]s, as well as glyco[2]rotaxanes featuring *per*-glycosylated P[5] ring components, have been reported. The ability of these multivalent glycoclusters to compete with carbohydrate–lectin interactions could provide a promising anti-adhesive strategy for fighting pathogen infections [48-51].

In a previous study, one of us showed that penta-substituted P[5] macrocyclic platforms attached with five glycosides also provide excellent multivalent interactions with bacterial lectins [51]. Nonetheless, these P[5]-based pentavalent glycoclusters are not pure compounds but instead mixtures of four constitutional isomers, which arose as a result of the statistical cyclization of asymmetrically-alkylated hydroquinone monomers during the P[5] synthesis (Fig. 1). Although the overall binding affinities of these pentavalent glycoclusters are good for bacterial lectins, the influence of the constitutional integrity of the P[5] scaffolds on their lectin binding abilities could not be investigated as a result of the non-trivial separation of these isomers. Thanks to the recent improvements on the design and syntheses of penta-functionalizable rim-differentiated P[5]s (RD-P[5]s) [61-63], herein we describe the syntheses and characterizations of a series of carbohydrate functionalized RD-P[5]s (**1a-f** and **2a-d**). In each of them, one rim is *O*-methylated, and the other is decorated with glycosides. The binding affinities between these newly synthesized constitutionally-pure pentavalent glycoclusters and three types of lectins (ConA, LecA and LecB) were investigated successfully by isothermal titration microcalorimetry (ITC) methods. In addition, the influence of the TEG spacers between the RD-P[5] scaffolds and the carbohydrate epitopes on the water solubility and binding affinity were evaluated.

In order to obtain the desired RD-P[5]-based pentavalent glycoclusters (Scheme 1), Cu(I)-catalyzed azide–alkyne cycloaddition (CuAAC) “click” chemistry was exploited for the effective conjugations of assorted carbohydrate epitopes onto the P[5] scaffold under mild conditions [64]. Penta-propargyl RD-P[5] **3** was first obtained by following our previously reported protocol [61] as a single constitutional isomer. The azido-functionalized carbohydrate derivatives **4a-f**, e.g., glucosyl (Glc), galactosyl (Gal), mannosyl (Man) and fucosyl (Fuc) residues, as well as lactosyl (Lac) [65] and maltosyl (Mal) moieties, were readily prepared (Supporting information for detailed synthetic procedures). By executing CuAAC between **3** and **4a-f**, acetate protected intermediates **6a-f** were synthesized in good yields. The targeted RD-P[5]-based glycoclusters **1a-f** were then obtained after acetate deprotection under Zemplén conditions (MeOH/MeONa). The solubility of these glycoclusters **1a-f** in aqueous media varies depending on the nature of the glycosides. To obtain improved water solubility, azido-functionalized glycosides **5a-d** with triethyleneglycol (TEG) spacers, which provide flexibility to the designed glycoclusters, were prepared according to the literature procedures. Similarly, another series of acetate-protected intermediates **7a-d** and RD-P[5]-based glycoclusters **2a-d** with TEG linkers was synthesized (Scheme 1) to evaluate the influence of the spacer arms towards water solubility and lectin binding.

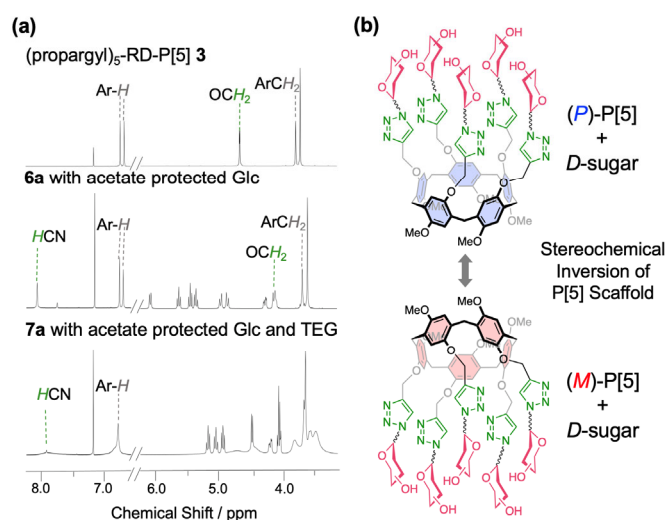
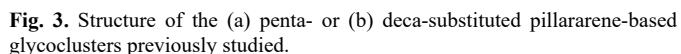


Fig. 2. (a) Partial ¹H NMR spectra (400 MHz, CDCl₃, 298 K) of compounds **3**, **6a** and **7a**. (b) The stereochemical inversion between conformers of RD-P[5]-based glycoclusters.

Subsequently, all RD-P[5]-based glycoclusters were fully characterized by NMR spectroscopy, high-resolution mass spectrometry, and analytical HPLC (Supporting information). The relatively simple and sharp ¹H NMR spectra of the penta-propargyl **3** and the glycocluster derivatives (Fig. 2), on account of their averaged five-fold structures, rendering the corresponding protons on the repeating hydroquinone units homotopic, confirm that these samples do not contain the other three types of P[5] constitutional isomers showing lower symmetries.

The anomeric stereochemistry of the carbohydrate moieties in these RD-P[5] glycoclusters were also determined by ¹H NMR analyses of the H1 anomeric protons. The Glc **1a** and **2a**, Gal **1c** and **2c**, Lac **1e** and Mal **1f** derivatives, with and without TEG spacer arms, respectively, are all β -anomers [66-70], whereas the Man glycoclusters **1b** and **2b** were assigned as α -anomers [67,71]. On the other hand, the Fuc glycocluster **1d** features pure

After the incorporation of glycoside moieties onto the inherently chiral and conformationally-labile P[5] macrocycle, these glycosylated RD-P[5]s exist as ensembles of diastereoisomeric conformers in solution. As the result of the “OMe-through-the-annulus” stereochemical inversion of the P[5] scaffold, all conformers are interchangeable to each other [74]. Most ^1H NMR signals of intermediates **6a-f** are coalesced and display single sets of sharp peaks on account of the rapid diastereoisomerization on the NMR time scale, *e.g.* the aromatic P[5], triazole and saccharide protons, while the diastereotopic $-\text{OCH}_2-$ methylene protons next to the triazole unit and the $-\text{CH}_2-$ methylenes on the P[5] units show more complicated splitting patterns. On the other hand, the removal of the acetate group, or rotations of the P[5] scaffold, resulting in more broadened ^1H NMR spectra.



In comparison to the monovalent reference, methyl α -D-mannopyranoside (α ManOMe), which shows a dissociation constant against ConA in the micromolar range, the penta-substituted glycoclusters **1b** and **2b**, both showing

enough solubility for the ITC measurements, display excellent affinities in the nanomolar range with potency β values of 67 and 38, respectively (Table 1 and Figs. S52 and S53 in

While ConA was used as a model lectin for these binding studies, the design of high affinity ligands for LecA was proven to be more useful toward potential antibacterial applications [12]. Glycoclusters **1c** and **2c** were then assayed (Table 2 and Figs. S54 and S55 in Supporting information) against LecA by ITC, both showing very strong affinities for the lectin with dissociation constants in the nanomolar range. The data collected is in line with the affinities reported for the previously studied penta-substituted glycocluster **A** and the deca-substituted analogue **B**.

The glycoside cluster effect is strong with binding potency β values in the range of 100, and the glycocluster **2c** with the TEG spacer ($\beta = 197$) is preferred over **1c** with short arm ($\beta = 63$). This preference is not due to steric hindrance since in both cases, the stoichiometries (n) of the ligand/lectin complex are very similar and close to 0.20, meaning that all five carbohydrate epitopes are bound to a LecA monomer. Increasing the valency to the decavalent glycocluster **B** did not trigger a sharp increase in binding potency since dissociation constant is in the same nanomolar range. Glycocluster **1a** was used as a negative control for binding to LecA (Fig. S57 in Supporting information) to demonstrate the absence of non-specific binding of the RD-P[5] scaffold to the lectin.

As for the effect of P[5] constitutional isomerism, the isomer-free glycoclusters **1c** and **2c** displayed very similar binding properties to corresponding glycocluster **A** consisting of all four constitutional isomers. The only difference between the RD-P[5] glycoclusters **1c** and **2c** and the corresponding mixture **A** only reside in the different thermodynamics parameters (ΔH° and $-T\Delta S^\circ$) while the overall change in free energy (ΔG°) remains virtually unchanged.

The fucosylated glycolusters **1d** and **2d** were designed and synthesized as potential ligands for LecB but also AFL, a multivalent lectin isolated from the fungi *Aspergillus fumigatus*. While the syntheses did not cause any trouble, we found that the water solubility of the short arm based glycolcluster **1d** was too low to proceed with binding studies. The hydroxyl group missing at the 6-position of fucose in comparison to Glc, Man and Gal glycolclusters was enough to produce an insoluble compound in water. Nevertheless, the TEG spacer arm incorporated in glycolcluster **2d** could provide enough solubility to perform the ITC binding measurements in aqueous media.

Surprisingly, the ITC data collected did not display any heat of interaction when titrating the glycocluster/lectin complex (Fig. S58 in Supporting information) with neither LecB nor AFL. Several attempts were performed with increased concentrations of lectin to ligand ratio to no avail. In parallel, a surface plasmon resonance (SPR) method was also investigated (data not shown) but again without success.

Table 1ITC data for the binding of mannosylated RD-P[5]-based glycoclusters **1b** (without spacer arm) and **2b** (with TEG spacer arm) towards ConA.

Ligand	n	ΔH° (kJ/mol) ^a	$-T\Delta S^\circ$ (kJ/mol) ^a	ΔG° (kJ/mol) ^a	K_d (nmol/L) ^a	β^b
α ManOMe ^c	1 ^d	−12	−14	−26	34 500	1
1b	0.25 ± 0.03	−17 ± 7	−19 ± 8	−36 ± 1	515 ± 149	67
2b	0.23 ± 0.01	−103 ± 5	68 ± 3	−35 ± 2	918 ± 679	38

^a Errors are the standard deviations of duplicate experiments.^b β is the binding potency calculated as the ratio of K_d values of the monovalent α ManOMe as a reference to the glycocluster.^c Single experiment measurement.^d Fixed parameter for the fitting procedure.**Table 2**ITC data for the binding of galactosylated RD-P[5]-based glycoclusters **1c** (without spacer arm) and **2c** (with TEG spacer arm) towards LecA.

Ligand	n	ΔH° (kJ/mol) ^a	$-T\Delta S^\circ$ (kJ/mol) ^a	ΔG° (kJ/mol) ^a	K_d (nmol/L) ^a	β^b
β GalOMe ^c	1 ^d	−20	−5	−25	32 260	1
1c	0.22 ± 0.02 ^c	−41 ± 10	5 ± 9	−36 ± 1	510 ± 64	63
2c	0.18 ± 0.03 ^c	−97 ± 4	58 ± 5	−39 ± 1	164 ± 89	197
Glycocluster A ^c	0.17 ± 0.01	−174 ± 9	138	−36	586 ± 38	55
Glycocluster B ^f	0.20 ± 0.01	−115 ± 2	78	−37	366 ± 129	88

^a Errors are the standard deviations of duplicate experiments.^b β is the binding potency calculated as the ratio of K_d values of the monovalent β GalOMe as a reference to the glycocluster.^c Single experiment measurement.^d Fixed parameter for the fitting procedure.^e Data from reference [51].^f Data from reference [49].

The ITC and SPR control experiments, on the other hand, could be successfully performed with the monovalent reference methyl α -L-fucopyranoside, demonstrating that the lack of binding observed for glycocluster **2d** was not due to experimental artifacts. As far as we are concerned, there is no clear explanation of why this pentavalent fucosylated glycocluster with good water solubility did not bind to the LecB and AFL fucose-binding lectins.

In addition, the desired water-soluble lactosylated glycocluster **1e** was evaluated as LecA ligand. A more detailed description of the thermodynamic parameter governing the binding mode was obtained by ITC (Fig. S59 in Supporting information). Nonetheless, while a titration curve could be observed with genuine heat measured, the curve was not sigmoidal and therefore could not provide any useful data.

In conclusion, pillar[5]arenes, as the ideal candidates, provide decaivalent scaffolds on a minimal molecular architecture to presentation of carbohydrate epitopes on their periphery. The developed multivalent glycosylated P[5] has been proved beneficial on targeting bacterial adhesion lectins. Calling for the design of P[5]-based glycocluster to understand the influence of the constitutional integrity of the P[5] scaffold, as well as the length and solubility of the spacer arms, on their binding to lectins, the syntheses of a series of RD-P[5] based glycoclusters were achieved by applying CuAAC conjugations from the azido-functionalized glycosides and alkyne-functionalized RD-P[5] precursors. The binding properties towards lectins of the glycosylated RD-P[5]-based multivalent ligands with and without TEG spacer arm were studied, respectively. The mannosylated RD-P[5]-based glycoclusters showed good binding properties toward ConA, and similarly the galactosylated RD-P[5]-based glycoclusters displayed high affinities to LecA. However, the fucosylated glycoclusters with TEG spacer arm did not bind to the LecB and AFL fucose-binding lectins at all. These results

show clearly that the pure RD-P[5]-based glycoclusters displayed similar lectin binding properties as the corresponding mixture of constitutional isomers. The only possible difference between them could reside in the different pattern of the thermodynamics parameters in terms of both enthalpy and entropy, while the overall free energy change remains virtually unaffected. In addition, glycosylated multivalent ligands with the spacer arm also displayed binding properties similar to those without spacer arm.

In the present study, we have employed a stereolabile system to demonstrate that the constitutional integrity of the pillar[5]arene scaffold influenced only marginally the binding properties toward lectin. In the future, stereostable P[5] glycoclusters of one handedness are, in principle, also of significant interest. As a matter of fact, when designing multivalent glycoclusters, the chirality of the core scaffold must be considered as a parameter potentially influencing, either positively or negatively, the binding properties to the lectins. All these studies, once accomplished, will jointly elucidate novel design principles for future developments of multivalent glycosylated P[5] derivatives in treating infections.

Acknowledgments

Financial supports from the National Natural Science Foundation of China (No. 21801184), the Tianjin Municipal Applied Basic and Key Research Scheme of China (No. 18JCQNJC06400), Xiamen University, Starry Night Science Fund of Zhejiang University Shanghai Institute for Advanced Study (grant no. SN-ZJU-SIAS-006), Université de Lyon, the French Agence Nationale de la Recherche (DynaSweet, ANR-08-BLAN-0305), Glyco@Alps (ANR-15-IDEX-02), and Labex Arcane/CBH-EUR-GS (ANR-17-EURE-0003) are gratefully acknowledged.

References

- [1] A. Varki, R. Cummings, J. Esko, H. Freeze, G.W. Hart, J. Marth, *Essentials of Glycobiology*, 2nd ed., Cold Spring Harbor Laboratory Press, New York, 1999.

- [2] P.C. Pang, P.C. Chiu, C.L. Lee, et al., *Science* 333 (2011) 1761-1764.
- [3] A. Varki, *Glycobiology* 3 (1993) 97-130.
- [4] Y.C. Lee, R.T. Lee, *Acc. Chem. Res.* 28 (1995) 321-327.
- [5] B. Ernst, G.W. Hart, P. Sinaÿ, *Carbohydrates in Chemistry and Biology*, Wiley-VCH, Weinheim, 2000.
- [6] S. Andre, F. Sansone, H. Kaltner, et al., *ChemBioChem* 9 (2008) 1649-1661.
- [7] A.S.A. Mohammed, M. Naveed, N. Jost, *J. Polym. Environ.* 29 (2021) 2359-2371.
- [8] I. Pramudya, H. Chung, *Biomater. Science* 7 (2019) 4848-4872.
- [9] Y. Kim, J.Y. Hyun, I. Shin, *Chem. Soc. Rev.* 50 (2021). 10567-10593.
- [10] A. Imberty, Y.M. Chabre, R. Roy, *Chem. Eur. J.* 14 (2008) 7490-7499.
- [11] F. Seidi, R. Jenjob, T. Phakkeeree, D. Crespy, *J. Controlled Release* 284 (2018) 188-212.
- [12] A. Bernardi, J. Jiménez-Barbero, A. Casnati, et al., *Chem. Soc. Rev.* 42 (2013) 4709-4727.
- [13] S. Cecioni, A. Imberty, S. Vidal, *Chem. Rev.* 115 (2015) 525-561.
- [14] V. Verez-Bencomo, V. Fernández-Santana, E. Hardy, et al., *Science* 305 (2004) 522-525.
- [15] A. Imberty, M. wimmerová, E.P. Mitchell, N. Gilboa-Garber, *Microbes Infect.* 6 (2004) 221-228.
- [16] N. Gilboa-Garber, *Methods Enzymol.* 83 (1982) 378-385.
- [17] G. Cioci, E.P. Mitchell, C. Gautier, et al., *FEBS Lett.* 555 (2003) 297-301.
- [18] T. Branson, T. McAllister, J. Garcia-Hartjes, et al., *Angew. Chem. Int. Ed.* 126 (2014)
- [19] S. Kuhaudomlarp, L. Cerofolini, S. Santarsia, et al., *Chem. Sci.* 11 (2020) 12662-12670.
- [20] D. Boffoli, F. Bellato, G. Avancini, et al., *Drug Deliv. Transl. Res.* 12 (2021) 1-23.
- [21] C. O'Reilly, S. Blasco, B. Parekh, et al., *RSC Adv.* 11 (2021) 16318-16325.
- [22] G. Paulíková, J. Houser, M. Kašáková, et al., *Sci. Rep.* 9 (2019) 1-12.
- [23] K. Chakroun, M. Taouai, V. Porkolab, et al., *J. Med. Chem.* 64 (2021) 14332-14343.
- [24] G.M.L. Consoli, G. Granata, V. Cafiso, S. Stefani, C. Geraci, *Tetrahedron Lett.* 52 (2011) 5831-5834.
- [25] S. Cecioni, R. Lalor, B. Blanchard, et al., *Chemistry* 15 (2009) 13232-13240.
- [26] S. Cecioni, S. Faure, U. Darbost, et al., *Chem. Eur. J.* 17 (2011) 2146-2159.
- [27] D. Sicard, S. Cecioni, M. Iazykov, et al., *Chem. Commun.* 47 (2011) 9483-9485.
- [28] S. Cecioni, S.E. Matthews, H. Blanchard, et al., *Carbohydr. Res.* 356 (2012) 132-141.
- [29] A.M. Boukerb, A. Rousset, N. Galanos, et al., *J. Med. Chem.* 57 (2014) 10275-10289.
- [30] S. Cecioni, J.P. Praly, S.E. Matthews, et al., *Chem. Eur. J.* 18 (2012) 6250-6263.
- [31] A. Dondoni, A. Marra, *Chem. Rev.* 110 (2010) 4949-4977.
- [32] Z.H. Soomro, S. Cecioni, H. Blanchard, et al., *Org. Biomol. Chem.* 9 (2011) 6587-6597.
- [33] T. Furuike, S. Aiba, S.I. Nishimura, *Tetrahedron* 56 (2000) 9909-9915.
- [34] Y.M. Chabre, R. Roy, *Chem. Soc. Rev.* 42 (2013) 4657-4708.
- [35] Y. Chen, H. Vedala, G.P. Kotchey, et al., *ACS Nano.* 6 (2012) 760-770.
- [36] H. Vedala, Y. Chen, S. Cecioni, et al., *Nano Lett.* 11 (2011) 170-175.
- [37] D. Sicard, Y. Chevolot, E. Souteyrand, et al., *J. Mol. Recognit.* 26 (2013) 694-699.
- [38] J.F. Nierengarten, J. Iehl, V. Oerthel, et al., *Chem. Commun.* 46 (2010) 3860-3862.
- [39] M. Durka, K. Buffet, J. Iehl, et al., *Chem. Commun.* 47 (2011) 1321-1323.
- [40] I. Nierengarten, J.F. Nierengarten, *Chem. Asian J.* 9 (2014) 1436-1444.
- [41] A. Muñoz, D. Sigwalt, B.M. Illescas, et al., *Nature Chem.* 8 (2016) 50-57.
- [42] J. Luczkowiak, A. Munoz, M. Sanchez-Navarro, et al., *Biomacromolecules* 14 (2013) 431-437.
- [43] M. Durka, K. Buffet, J. Iehl, et al., *Chem. Eur. J.* 18 (2012) 641-651.
- [44] M. Sánchez-Navarro, A. Muñoz, B.M. Illescas, J. Rojo, N. Martín, *Chem. Eur. J.* 17 (2011) 766-769.
- [45] P. Compain, C. Decroocq, J. Iehl, et al., *Angew. Chem. Int. Ed.* 122 (2010) 5889-5892.
- [46] R. Rísquez-Cuadro, J.M. Garcia Fernandez, J.F. Nierengarten, C. Ortiz Mellet, *Chem. Eur. J.* 19 (2013) 16791-16803.
- [47] S. Cecioni, V. Oerthel, J. Iehl, et al., *Chem. Eur. J.* 17 (2011) 3252-3261.
- [48] T. Mohy El Dine, R. Jimmidi, A. Diaconu, et al., *J. Med. Chem.* 64 (2021) 14728-14744.
- [49] K. Buffet, I. Nierengarten, N. Galanos, et al., *Chem. Eur. J.* 22 (2016) 2955-2963.
- [50] S.P. Vincent, K. Buffet, I. Nierengarten, A. Imberty, J.F. Nierengarten, *Chem. Eur. J.* 22 (2016) 88-92.
- [51] N. Galanos, E. Gillon, A. Imberty, S.E. Matthews, S. Vidal, *Org. Biomol. Chem.* 14 (2016) 3476-3481.
- [52] L.T. Wu, C. Han, X.B. Jing, Y. Yao, *Chin. Chem. Lett.* 32 (2021) 3322-3330.
- [53] G.P. Sun, L.T. Pu, S. Pangannaya, et al., *Front. Chem.* 7 (2019), 743.
- [54] K. Wang, X. Tian, J. H. Jordan, et al., *Chin. Chem. Lett.* 33 (2022) 89-96.
- [55] T. Ogoshi, S. Kanai, S. Fujinami, T.A. Yamagishi, Y. Nakamoto, *J. Am. Chem. Soc.* 130 (2008) 5022-5023.
- [56] M. Xue, Y. Yang, X.D. Chi, Z.B. Zhang, F.H. Huang, *Acc. Chem. Res.* 45 (2012) 1294-1308.
- [57] I. Nierengarten, M. Holler, M. Rémy, et al., *Molecules* 26 (2021) 2358.
- [58] K. Shang, Y. Wang, Y.C. Lu, *Isr. J. Chem.* 58 (2018) 1241-1245.
- [59] X.W. Wu, Y. Zhang, Y.C. Lu, et al., *J. Mater. Chem. B* 5 (2017) 3483-3487.
- [60] X. Liu, W. Shao, Y.J. Zheng, et al., *Chem. Commun.* 53 (2017) 8596-8599.
- [61] P. Demay-Drouhard, K. Du, K. Samanta, et al., *Org. Lett.* 21 (2019) 3976-3980.
- [62] K. Du, A.C.H. Sue, *Synlett* 30 (2019) 2209-2215.
- [63] M.J. Guo, X.M. Wang, C.H. Zhan, et al., *J. Am. Chem. Soc.* 140 (2018) 74-77.
- [64] J.Y. Zhao, W.W. Yang, C.Y. Liang, et al., *Chem. Commun.* 57 (2021) 11193-11196.
- [65] Y.C. Chang, Y.H. Lv, P. Wei, et al., *Adv. Funct. Mater.* 27 (2017) 1703083-1703095.
- [66] A. Bianchi, A. Bernardi, *J. Org. Chem.* 71 (2006) 4565-4577.
- [67] L. Mahal, A. Sanki, *Synlett* 2006 (2006) 0455-0459.
- [68] L.M. Artner, L. Merkel, N. Bohlke, et al., *Chem. Commun.* 48 (2012) 522-524.
- [69] K.S. Bücher, P.B. Konietzny, N.L. Snyder, L. Hartmann, *Chem. Eur. J.* 25 (2019) 3301-3309.
- [70] C. Pető, G. Batta, Z. Györgydeák, F. Sztaricskai, *Liebigs Ann. Chem.* 1991 (1991) 505-507.
- [71] L. Han, W. Sheng, X. Li, et al., *MedChemComm* 10 (2019) 598-605.
- [72] C. Palomo, J.M. Aizpurua, E. Balentová, et al., *Org. Lett.* 10 (2008) 2227-2230.
- [73] S. Wang, N. Galanos, A. Rousset, et al., *Carbohydr. Res.* 395 (2014) 15-18.
- [74] K. Du, P. Demay-Drouhard, K. Samanta, et al., *J. Org. Chem.* 85 (2020) 11368-11374.