



HOKKAIDO UNIVERSITY

Title	Design of Sugar-Terpenoid Block Co-oligomers for Construction of Ultrasmall Microphase-Separated Structures
Author(s)	李, 采訓
Degree Grantor	北海道大学
Degree Name	博士(工学)
Dissertation Number	甲第16377号
Issue Date	2025-03-25
DOI	https://doi.org/10.14943/doctoral.k16377
Doc URL	https://hdl.handle.net/2115/97634
Type	doctoral thesis
File Information	CHAEHUN_LEE.pdf



**Design of Sugar–Terpenoid
Block Co-oligomers for Construction of
Ultrasmall Microphase-Separated Structures**

A Dissertation for the Degree of Doctor Philosophy

Chaehun Lee

Hokkaido University

March 2025

Acknowledgement

The author would like to express sincere gratitude to all those who contributed to the success of this dissertation.

First and foremost, the author is deeply indebted to Professor Toshifumi Satoh and Associate professor Takuya Isono, Division of Applied Chemistry, Faculty of Engineering, Hokkaido University, for their financial support and invaluable guidance throughout this work. Their encouragement and expertise were instrumental in the completion of this dissertation.

The author would like to extend appreciation to Associate professor Kenji Tajima, Associate professor Takuya Yamamoto, Assistant professor Li Feng, and specially Appointed assistant professor Tianle Gao for their insightful discussions and helpful suggestions, which greatly enhanced the quality and depth of this dissertation.

Working in the laboratory was a truly enriching experience due to its positive and dynamic environment. The author is especially grateful to all the members of the lab for fostering a collaborative atmosphere where everyone's opinions are respected and valued.

Lastly, the author wishes to extend gratitude to coworkers Minami Ebe, Ryota Suzuki, and Taiki Nishimura for their generous assistance. The author looks forward to collaborating with them in future endeavors.

This work was supported by Research Fellowship of Japan Society for the Promotion of Science (JSPS) for Young Scientists.

Contents

Chapter 1 General Introduction	1
1.1 Microphase Separation of Block Copolymer (BCP)	2
1.1.1 The Theory of Microphase Separation	2
1.1.2 Application of BCP Microphase-Separated Structure	6
1.2 Strategy for Obtaining Smaller Domain Spacing with High χ -low N BCP	9
1.3 The Impact of BCP Polydispersity on Microphase Separation Behavior	12
1.4 Objective and Outline of Dissertation	16
1.5 References.....	23
Chapter 2 Synthesis of Monodisperse High χ-low N Block Co-oligomers for Ultrasmall Microphase-Separated Structures	33
2.1 Introduction	34
2.2 Experimental Section	37
2.2.1 Materials	37
2.2.2 Instruments.....	38
2.2.3 Synthesis of Block Co-Oligomers.....	41
2.3 Result and Discussion.....	57
2.3.1 Synthesis of Block Co-oligomers (BCOs)	57
2.3.2 Nanostructural Formation of Solanesol-Based BCOs.....	59
2.3.3 Fine-Tuning Nanostructures by Varying Dispersity	65
2.3.4 Further Minimizing the Feature Size by Tocopherol- and Farnesol-Based BCOs	68
2.3.5 Microphase-Separation Behavior of Sugar-Terpenoid BCO Systems	70
2.4 Conclusion	72
2.5 References.....	73
2.6 Supporting Information	80
Chapter 3 Three-Dimensional Network Microphase-Separation Morphologies with Sugar-Terpenoid Block Co-oligomers.....	91
3.1 Introduction	92
3.2 Experimental Section	96
3.2.1 Materials	96
3.2.2 Instruments.....	97
3.2.3 Synthesis of Block Co-oligomers	100
3.3 Result and Discussion.....	108

3.3.1 Synthesis of Block Co-oligomers	108
3.3.2 Construction of Ultrasmall Microphase-Separated Structures.....	110
3.3.3 Construction of Three-Dimensional (3D) Structures	114
3.3.4 Microphase Separated Behavior with Different Linker Structure	123
3.4 Conclusion.....	129
3.5 References	130
3.6 Supporting Information	140
Chapter 4 Sugar-Rich Microphase-Separated Structures by Sugar–Terpenoid	
Block Co-oligomers	155
4.1 Introduction.....	156
4.2 Experimental Section	160
4.2.1 Materials.....	160
4.2.2 Instruments	161
4.2.3 Synthesis of Block Co-oligomers	164
4.3 Result and Discussion	173
4.3.1 Synthesis of Block Co-oligomers (BCOs).....	173
4.3.2 Construction of Sugar-Rich Microphase-Separated Structure	175
4.3.3 Microphase-Separated Structure in The Thin Film State.....	184
4.3.4 Self-Assembly Behavior of Sugar–Terpenoid BCO System.....	191
4.3.4.1 Flory-Huggins Interaction Parameter of The Sugar–Terpenoid BCO	
System	191
4.3.4.2 Understanding Microphase-Separation via Phase Diagram of	
Sugar–Terpenoid BCO	195
4.4 Conclusion.....	197
4.5 References	198
4.6 Supporting Information	206
Chapter 5 Conclusions	221

Chapter 1

General Introduction

1.1 Microphase Separation of Block Copolymer (BCP)

1.1.1 The Theory of Microphase Separation

Block copolymers (BCPs) are macromolecules in which two or more chemically distinct polymer blocks are covalently connected. Based on their architecture, BCPs can be categorized into various types, including diblock copolymer^{1,2}, triblock copolymer³⁻⁵, multiblock copolymer⁶⁻⁸, star-shaped copolymer^{9,10}, and bottle-brush copolymer¹¹⁻¹⁴. These BCPs exhibit diverse physicochemical properties and form microphase-separated structures through self-assembly, driven by interactions between the constituent blocks.¹⁵⁻¹⁸ This introductory section aims to discuss the theory of diblock copolymer self-assembly and to explain the fundamental principles and mechanisms involved in the formation of microphase-separated structures.

The free energy change (ΔG^M) of a system upon mixing two substances can be described by the following equation, incorporating the enthalpy change (ΔH^M), which represents intermolecular interactions, the entropy change (ΔS^M), which reflects the degree of disorder, and the temperature (T):¹⁹⁻²¹

$$\Delta G^M = \Delta H^M - T\Delta S^M$$

Negative ΔG^M signifies that mixing is thermodynamically favorable. In the case of mixing small molecules, the increase in disorder due to mixing results in a substantial entropy contribution, which often dominates over the enthalpic term and thus facilitates mixing (**Figure 1.1(a)**). In contrast, polymer chains exhibit restricted degree of freedom, particularly as the degree of polymerization (N) increases. This restriction not only reduces the entropic contribution to the free energy but also limits the number of possible configurational arrangements, further diminishing the entropy-driven tendency for mixing (**Figure 1.1(b)**). The diminished entropy effect in polymer systems amplifies the

relative importance of the enthalpic interactions, represented by the Flory-Huggins interaction parameter (χ). The χ parameter quantifies the strength of interactions between dissimilar blocks, with higher χ values indicating greater incompatibility and a stronger propensity for phase separation. Mathematically, χ is inversely proportional to temperature, following the relationship $\chi \propto \Delta H/RT$, where ΔH represents the enthalpic interaction and R is the gas constant.^{22–24} The interplay between enthalpy and entropy in BCPs is fundamentally captured by the product χN . As N increases, the reduced entropy contribution to the free energy enhances the influence of χ , making the χN a critical determinant of phase separation behavior. For BCPs with low χN value, the interface between the two blocks becomes diffuse, resulting in miscibility of the domain. In contrast, when χN surpasses a critical value (approximately 10.5 for symmetric diblock copolymers), microphase separation occurs, resulting in the formation of ordered morphologies (**Figure 1.2**). The type of morphologies formed is determined by the volume fraction (f_i) of each block, with changes in volume fraction altering the stability regions of phase-separated morphologies. Volume fraction plays a critical role in determining structure formation by balancing block interactions, enabling precise control over the resulting morphologies through its modulation. For instance, symmetric volume fraction favors the formation of lamellae (LAM) structure, while asymmetric volume fractions result in morphologies like double gyroid (GYR), hexagonally packed cylinders (HEX), and body-centered cubic spheres (BCC) structures.²⁵ This relationship highlights the thermodynamic stability of BCP systems and is visualized through phase diagrams that incorporate χ , N , and the f_A (**Figure 1.3**).

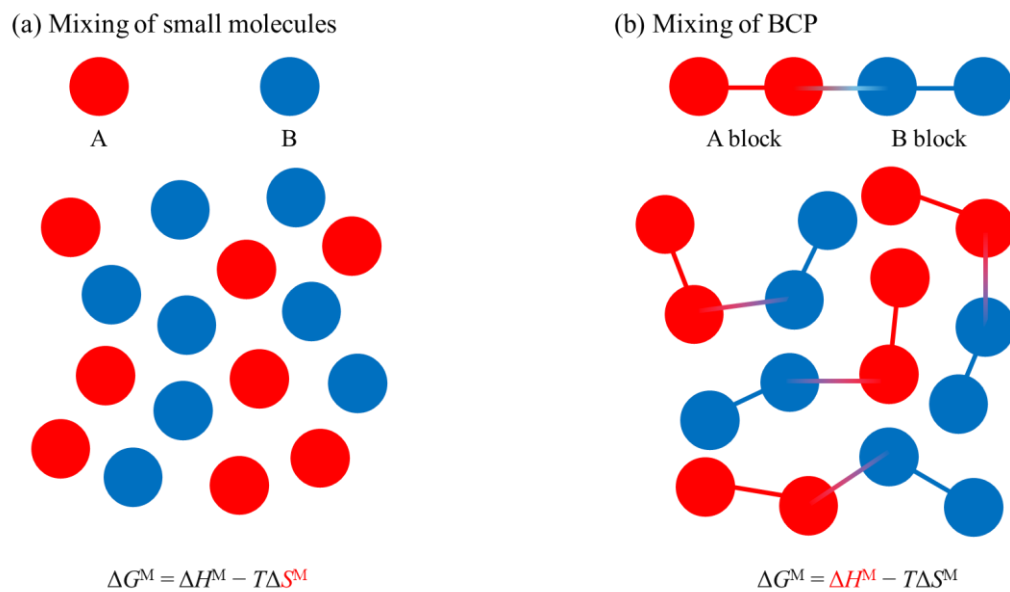


Figure 1.1. Schematic illustration of representing mixture of (a) small molecules and (b) BCP.

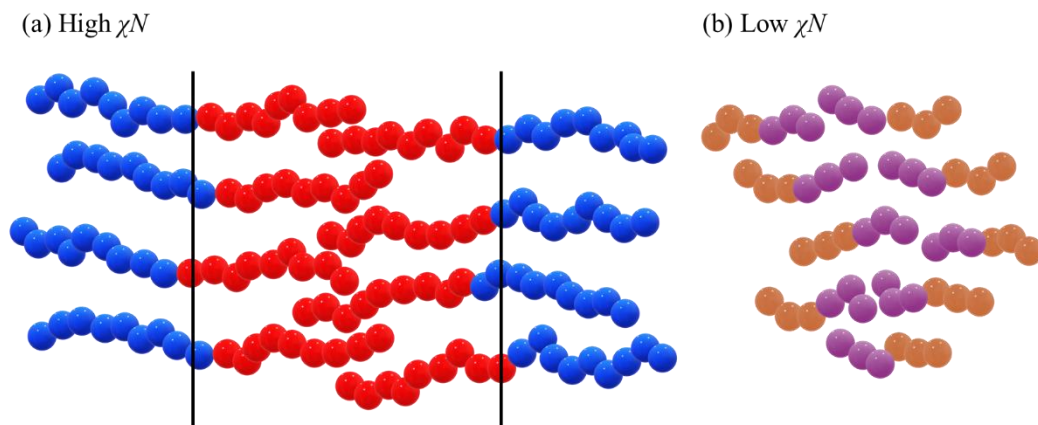


Figure 1.2. Schematic illustration of the self-assembly of BCP with (a) high χN and (b) low χN .

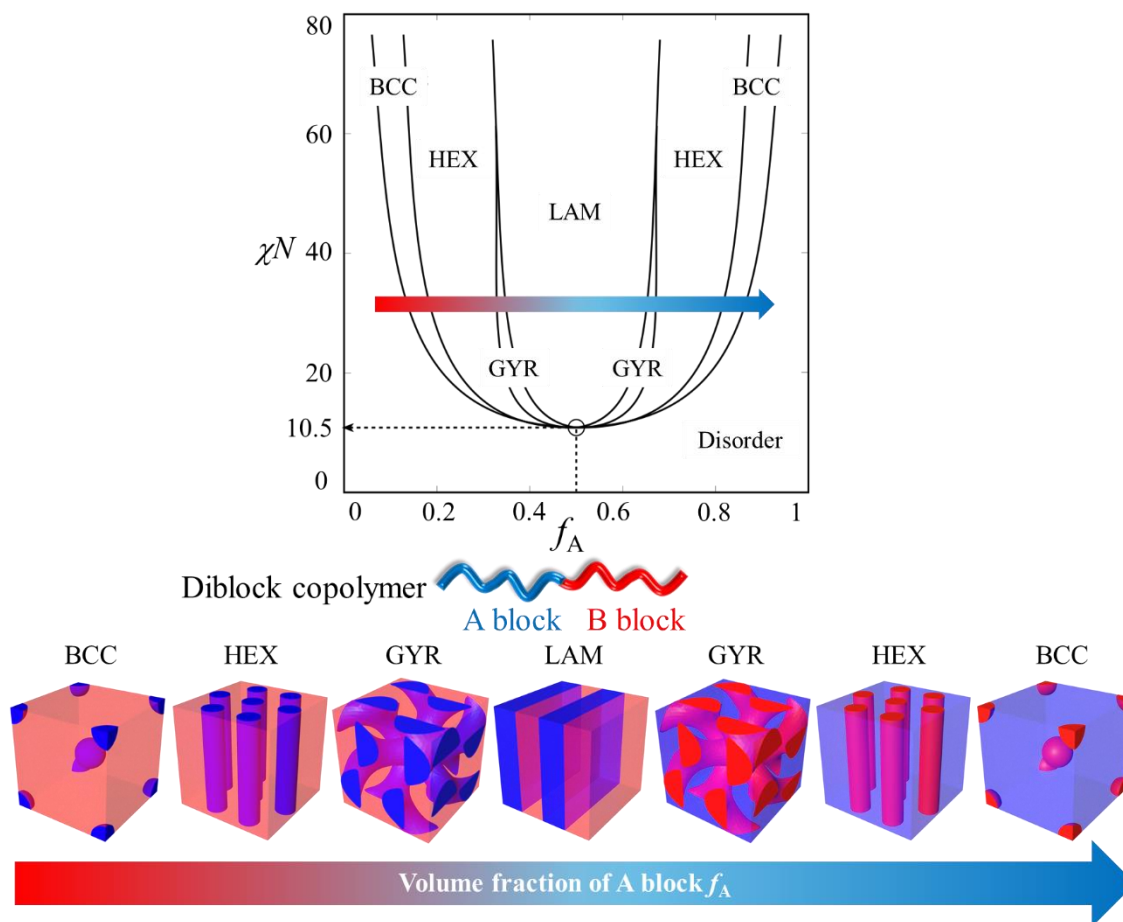


Figure 1.3. The theoretical phase diagram of diblock copolymers and schematic illustrations of lamellae (LAM), double gyroid (GYR), hexagonally packed cylinders (HEX), and body-centered cubic sphere (BCC) structure.²⁵

1.1.2 Application of BCP Microphase-Separated Structure

BCPs are renowned for their ability to self-assemble into well-ordered nanoscale microphase-separated structures, such as LAM, GYR, HEX, and BCC.²⁵ This versatility in morphology arises from their unique architecture and can be further tailored through the control of volume fraction in BCPs, molecular weight, and processing conditions, making them indispensable in various advanced technologies.

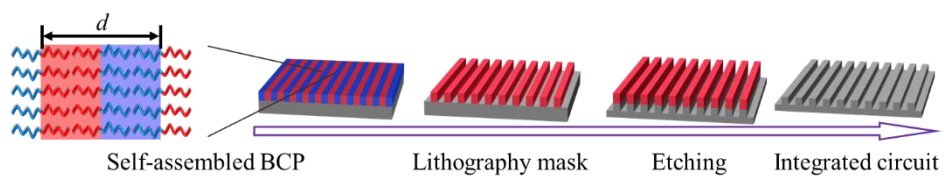
One of the key advantages of BCPs is their tunable mechanical and thermal properties, which are significantly enhanced by their microphase-separated structures. These properties enable the creation of materials with improved strength and thermal stability, making them suitable for demanding applications. Additionally, the nanoscale domain spacing of BCP microphase-separated structures imparts unique optical properties, making them highly valuable for photonic and sensing applications.^{26–29} These characteristics of BCPs, which enable them to form ordered nanostructures have been exploited in a range of industrial applications.

In nanotechnology, BCPs serve as templates in nanolithography, allowing the fabrication of well-ordered and small domain spacing nanostructures crucial for advanced electronics and semiconductor manufacturing (**Figure 1.4(a)**).^{30–33} Furthermore, their self-assembled patterns facilitate the development of high-resolution, cost-effective manufacturing processes. However, the achievable periodicity of nanostructures using BCP templates is inherently limited by the molecular characteristics of the polymers, such as the degree of polymerization.^{34–36} Using advanced techniques like directed self-assembly (DSA) and specialized BCPs^{37–39}, current research has demonstrated the potential to achieve patterns as small as sub-10 nm. However, practical applications face challenges such as defect density and processing difficulties, making domain spacings smaller than 10 nm still difficult to implement in practical technologies.

In membrane technology, BCPs offer remarkable utility through their selective permeability, controlled by the morphology, size, and distribution of pores formed by microphase separation^{40–43}. These delicately controlled structures enhance the performance of applications, such as mixture purification, gas separation, and energy technologies. Furthermore, BCPs are instrumental in fabricating nanoporous carbon membranes (**Figure 1.4(b)**).^{26,44–48} By carbonizing the polymer matrix, highly ordered, nanoporous carbon materials with tunable morphologies can be achieved, enabling advanced functionalities in gas storage, molecular sieving, and catalysis. However, the difficulty of achieving precise control over pore size and shape in nanoporous carbon derived from BCP self-assembly limits the uniformity and stability of smaller structures. This inconsistency can adversely affect performance in applications like catalysis and energy storage. Therefore, to advance this technology, it is crucial to develop methods that reliably and uniformly construct smaller nanostructures for specific applications.

To enhance resolution and functionality in applications like BCP lithography or membranes, achieving diverse microphase-separated structures with domain spacing of sub-10 nm scale is critical. This requires moving beyond conventional BCP systems and focusing on strategies that enable the formation of nanostructures. Notably, high χ –low N BCPs offer significant potential, as their enhanced segregation strength and small degree of polymerization facilitate the formation of well-ordered nanostructures with sub-10 nm domain spacing, making them highly promising for advanced nanotechnologies.^{32,49–54}

(a) BCP lithography



(b) BCP nanoporous templates

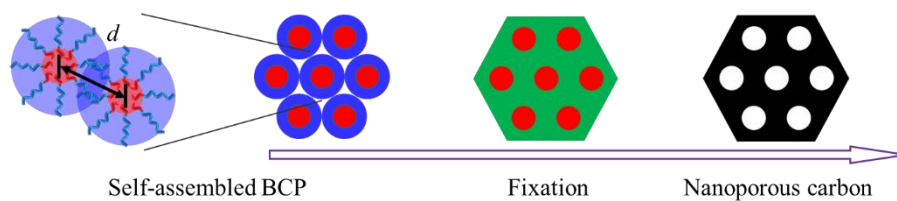


Figure 1.4. Schematic illustrations of (a) BCP lithography and (b) BCP nanoporous templates.

1.2 Strategy for Obtaining Smaller Domain Spacing with High χ -low N BCP

Achieving nanostructures with domain spacing of sub-10 nm is essential for next-generation technologies such as nanoporous materials, nanolithography masks, and photonic devices. BCPs are powerful tools for fabricating such structures, as their domain spacing scales with the degree of polymerization following $d \propto N^{2/3}$ (**Figure 1.5**).¹⁶ Reducing N is crucial to minimize d , but microphase separation requires χN to exceed a critical threshold (e.g., $\chi N > 10.5$ for symmetric BCP systems). Consequently, increasing the χ parameter is necessary for phase separation at low N .

The high χ -low N strategy addresses these constraints by utilizing BCPs with high incompatibility. This approach facilitates phase separation at even reduced chain lengths. Meanwhile, it maintains well-ordered morphologies such as LAM, GYR, and HEX structures. Notable examples include poly(trimethylsilylstyrene)-*b*-poly(lactide) (PTMSS-*b*-PLA)⁵⁵ BCPs with M.W. = 9.2 kg mol⁻¹, achieving HEX structures with $d = 12$ nm; poly(styrene)-*b*-poly(dimethylsiloxane) (PS-*b*-PDMS)³⁷ BCP with M.W. = 16 kg mol⁻¹; and poly(cyclohexylethylene)-*b*-poly(methylmethacrylate) (PCHE-*b*-PMMA)⁵⁶ BCP with M.W. = 4.9 kg mol⁻¹ constructing LAM structures with $d = 18$ and 9 nm, respectively (**Figure 1.6**). These high χ -low N BCPs exhibit enhanced segregation strength, thermal stability, and tunable morphologies, supporting a wide range of applications.⁴⁹

The high χ -low N BCPs incorporating oligosaccharides have been explored for their potential to achieve sub-10 nm nanostructures due to the high χ parameter when paired with hydrophobic polymers. These materials capitalize on the strong segregation capabilities of oligosaccharides, which facilitate phase separation at reduced chain

Figure 1.6. High χ -low N BCPs and the corresponding microphase-separated structures.^{37,55,56}

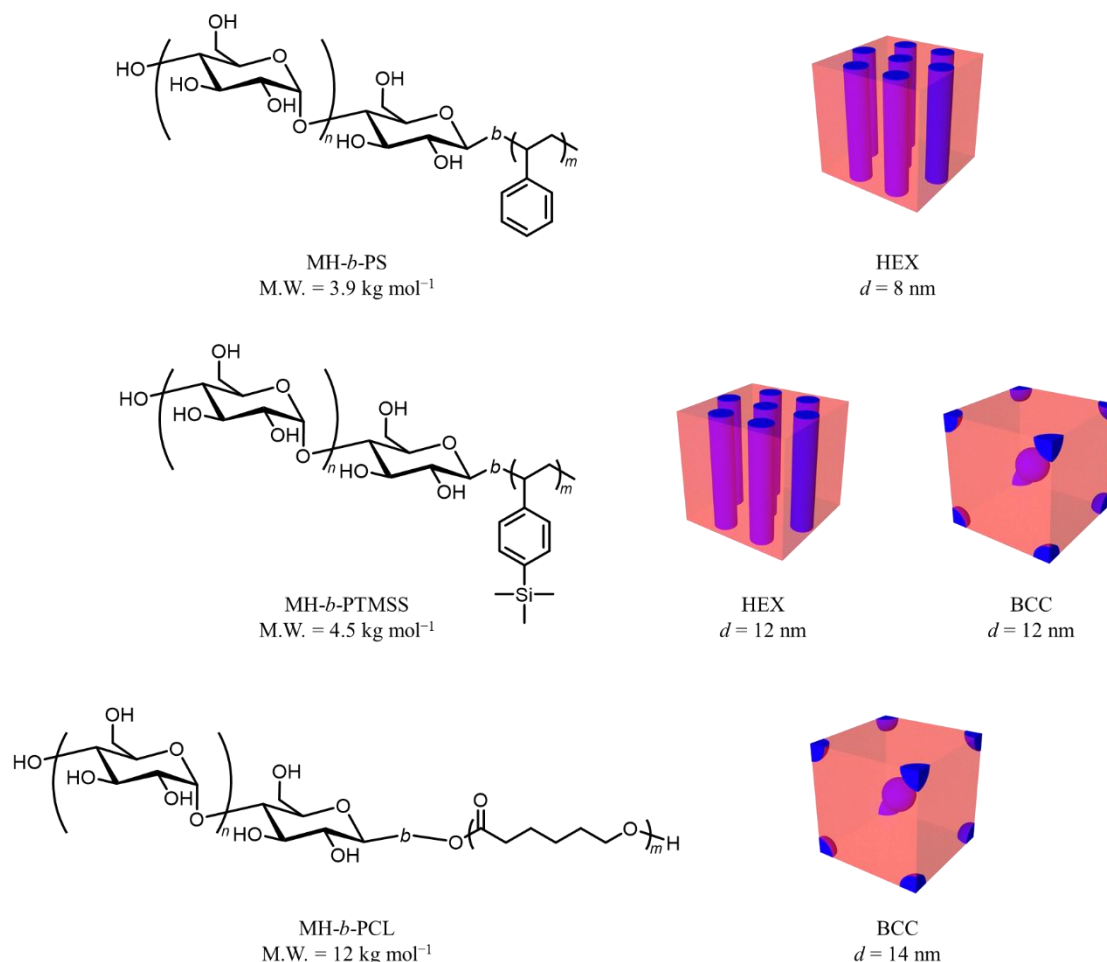


Figure 1.7. BCPs containing oligosaccharide and the corresponding microphase-separated structures.^{52,57,58}

The development of high χ -low N BCPs has enabled the formation of smaller microphase-separated structures compared to conventional BCPs.^{37,52,55–58} These advancements allow for well-ordered nanostructures at reduced molecular weights. However, due to the intrinsic limitations in polymer synthesis, such as polydispersity and decreasing degree of polymerization, achieving smaller domain spacings (sub-5 nm) remains an unexplored frontier, posing significant challenges for further miniaturization and precision in nanostructure fabrication.

1.3 The Impact of BCP Polydispersity on Microphase Separation Behavior

Polydispersity, which is the distribution of molecular weights within polymer, is a critical factor influencing the self-assembly behavior of BCPs and their resulting microphase-separated morphologies. In BCPs, the polydispersity, defined as the weight-average molecular weight divided by the number-average molecular weight, quantifies this distribution. High polydispersity significantly affects the mechanical, thermal, and optical properties of the material.^{59–61} Furthermore, when BCPs form microphase-separated structures, the impact of polydispersity becomes particularly pronounced. In BCPs with low polydispersity, polymer chains of similar lengths are more likely to interact and aggregate, resulting in well-ordered microdomains.^{54,62–67} Conversely, the BCPs with high polydispersity, the presence of varying chain lengths introduces discrepancies in the interaction between blocks, which can disrupt the uniformity of the domain sizes (**Figure 1.8**). This distribution can result in incomplete phase separation, where some domains may be too small or too large, leading to defects and instability within the microphase-separated structure.⁶⁸ Consequently, the mechanical properties of materials can be compromised, limiting their effectiveness in applications such as nanolithography and membrane technology.⁶⁹

Traditional polymerization techniques, such as free radical polymerization, often yield polymers with a wide range of molecular weights, leading to high polydispersity. While these methods are well-established, they present limitations in controlling the molecular weight and distribution of BCPs. Recently, advanced living polymerization techniques, such as atom transfer radical polymerization (ATRP) and reversible addition-fragmentation chain transfer (RAFT) polymerization, have been developed to produce

BCPs with tailored polydispersity.^{70,71} These polymerization allow for greater precision in synthesizing BCPs with desired properties, enabling better control over microphase separation behavior. However, despite the advantages of controlled polymerization methods, challenges remain. Achieving narrow polydispersity in BCPs may require extensive optimization of reaction conditions and monomer selection, complicating the synthesis process and increasing costs.^{72,73}

High-performance liquid chromatography (HPLC) has emerged as a powerful tool for refining BCPs to achieve narrow polydispersity (**Figure 1.9(a)**). This method capitalizes on differences in molecular weight or chemical composition between polymer chains, enabling precise separation and isolation of monodisperse BCP fractions. Recent work by Hawker et al. demonstrated the application of liquid chromatography for isolating monodisperse BCPs. In this approach, polymer chains are separated based on their interactions with the stationary phase, enabling the effective purification of BCPs with tailored compositions and molecular weights.⁷⁴ This method offers a practical solution for creating highly uniform BCPs, which are critical for applications requiring precise domain morphologies and sizes. Despite the notable advantages of HPLC-based methods in achieving precise control of BCP polydispersity, limitations in process complexity remain significant challenges. The process can be resource-intensive and requires careful optimization of chromatographic conditions, such as the choice of solvents and column materials, to achieve effective separation.

Another strategy for obtaining monodisperse materials involves the synthesis of block co-oligomers (BCOs) with narrow polydispersity through a stepwise addition of monomers, as demonstrated by Meijer et al (**Figure 1.9(b)**).^{64,67} This method effectively enhances the structural integrity and uniformity of the resulting materials, enabling the formation of well-ordered structures. However, a significant limitation of this approach

is that achieving narrow polydispersity may require extensive optimization of reaction conditions and monomer selection, complicating the synthesis process and increasing costs.

In summary, understanding and controlling polydispersity in BCPs are essential for optimizing their microphase separation behavior and enhancing their performance in various applications. Thus, employing well-defined monodisperse building oligomer blocks for synthesizing monodisperse block co-oligomers (BCOs) offers a promising approach (**Figure 1.10**). This strategy is expected to enable the formation of nanostructures with diverse morphologies and tunable domain spacing, depending on the specific blocks used. This strategy ensures effective microphase separation and the achievement of desired properties tailored to specific applications. Furthermore, targeting structures with domain spacing below 5 nm pushes the boundaries of nanoscale engineering, offering promising advancements in creating highly refined and functional nanostructures.

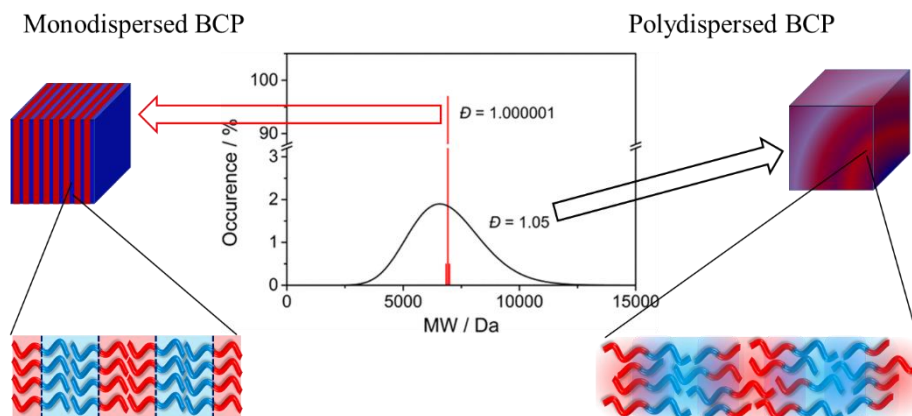


Figure 1.8. Effect of polydispersity on microphase separation behaviors.⁶⁴

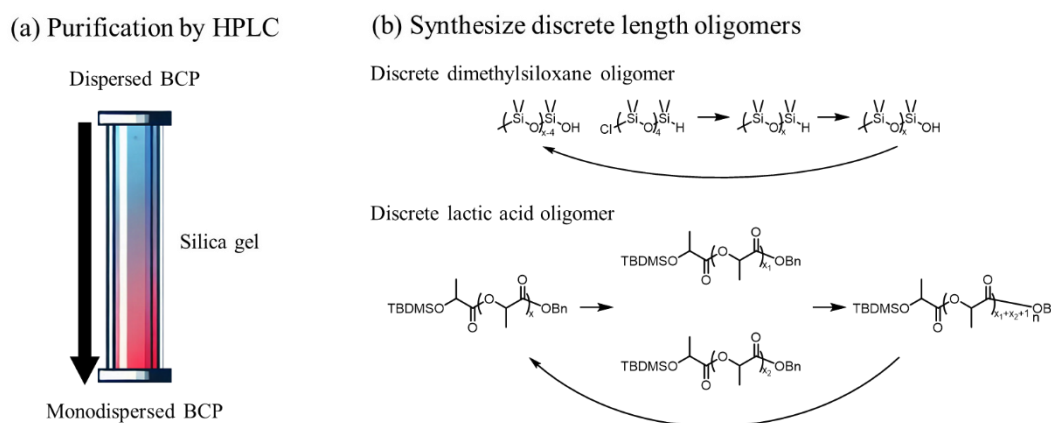


Figure 1.9. (a) Schematic illustration of HPLC purification⁷⁴ and (b) scheme of synthesizing discrete dimethylsiloxane and lactic acid oligomer.⁶⁴

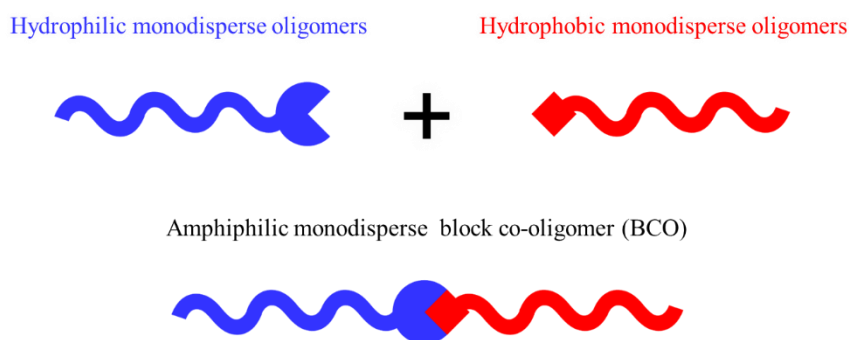


Figure 1.10. Schematic illustration of the synthesis monodisperse block co-oligomer by connecting two monodisperse oligomers.

1.4 Objective and Outline of Dissertation

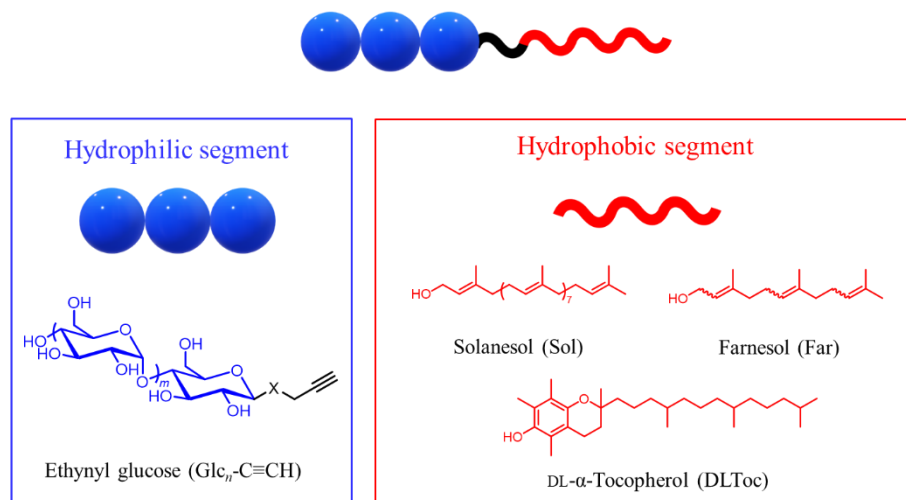
BCPs form microphase-separated structures such as LAM, GYR, HEX, and BCC structures, as described in *Section 1.1.1*, through interactions between chemically different polymer segments covalently bonded within a single macromolecule. These microphase-separated structures and their domain spacing can be precisely controlled, making them indispensable in various technological applications. As outlined in *Section 1.1.2*, these microphase-separated structures have found extensive industrial applications, including nanolithography for creating semiconductor patterns and nanoporous membrane synthesis for filtration and separation processes. Building on these applications requires materials capable of forming even smaller domain structures, specifically those with a domain spacing of less than 10 nm. Achieving such ultrasmall structures necessitates innovative material designs, particularly those emphasizing the high χ –low N concept, as discussed in *Section 1.2*. The combination of high χ and low N polymers is a key design strategy in BCPs to achieve well-ordered nanostructures with smaller domain spacing. A high χ enhances the thermodynamic driving force for phase separation, allowing distinct microphase-separated morphologies even at low N . This enables the formation of ultrasmall nanostructures, which are crucial for advanced applications in nanotechnology and materials science. However, BCPs with low N are particularly sensitive to molecular weight distribution. A narrow polydispersity (low molecular weight variation) is essential to maintain consistent and predictable morphologies as mentioned in *Section 1.3*. Polydispersity can disrupt the regularity of nanostructures, highlighting the need for precise control in designing BCPs for next-generation applications. This balance between χ and N , along with polydispersity management, forms the foundation for the development of innovative materials with tailored nanoscale properties.

This dissertation addresses these challenges by shifting focus from traditional BCPs to block co-oligomers (BCOs), synthesized through the connection of naturally derived hydrophilic and hydrophobic monodisperse blocks. Specifically, it explores the coupling of hydrophilic oligosaccharides and hydrophobic terpenoids to create monodisperse BCOs with well-defined molecular structures. These BCOs, due to their inherent uniformity and high incompatibility, are ideal for forming highly ordered nanoscale morphologies with domain spacing of far less than 10 nm. The modular nature of this approach allows for fine-tuning through chemical modifications, such as lengths of each block, varying linker groups, and incorporating chirality, providing a robust platform to control and investigate the relationships between microphase-separated structures and BCO chemical properties. The primary objective of this dissertation is therefore to establish synthetic methods for the novel sugar–terpenoid BCO system and to evaluate their microphase-separated morphologies. By leveraging the precision and diversity offered by this synthetic strategy, this research aims to establish a BCO molecular design principle for creating tailor-made materials that extend the capabilities nanotechnology applications.

An outline of this dissertation is as follows:

In *Chapter 2* describes the design, synthesis, and self-assembly behavior of monodisperse BCOs composed of hydrophilic oligosaccharides and hydrophobic terpenoids. Using natural precursors, emphasizing their structures, biocompatibility, and commercial availability, the author demonstrates a straightforward click reaction to synthesize novel BCOs with tailored segment compositions and degrees of polymerization (**Figure 1.11(a)**). The author examines how these BCOs self-assemble into well-ordered microphase-separated morphologies, such as LAM, GYR, and HEX structures with domain spacing ranging from 4 to 8 nm (**Figure 1.11(b)**). The author also explores how variations in the sugar volume fraction influence morphology and domain spacing, showcasing the versatility and tunability of these BCO systems. These features position BCOs as promising candidates for applications in advanced nanolithography, separation materials, organic electronics, and coatings. Through these investigations, the author underscores the potential of these innovative materials to expand the scope and versatility of self-assembled nanostructures in both academic and industrial contexts.

(a) Monodisperse high χ –low N block co-oligomers (BCOs)



(b) Small angle X-ray scattering (SAXS)

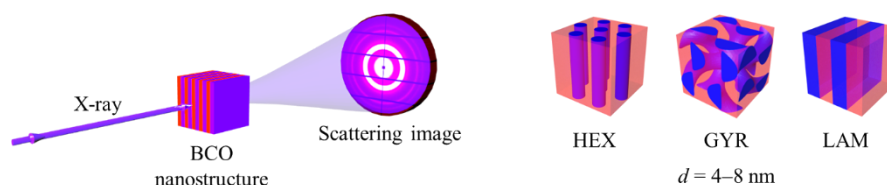


Figure 1.11. (a) Design of monodisperse high χ –low N BCO. (b) Schematic illustration of SAXS measurement and microphase-separated structures of BCOs.

In *Chapter 3*, the author focuses on the development of ultrafine three-dimensional (3D) network morphologies, including gyroid (GYR) and ABC -stacked hexagonally perforated lamellae (HPL_{ABC}) structures, achieved by sugar–terpenoid hybrid BCOs (**Figure 1.12**). These BCOs consist of glucose as the hydrophilic segment and various terpenoids, such as farnesol, phytol, and tocopherol, as the hydrophobic segment. Small-angle X-ray scattering (SAXS) studies revealed that while tocopherol facilitated 3D network structures, other terpenoids, such as farnesol and phytol, predominantly led to lamellar phases. This difference is attributed to the distinct molecular shapes and sugar volume fractions when combined with glucose. Importantly, the HPL_{ABC} and GYR morphologies were also observed in thin film states, with the HPL_{ABC} structure

demonstrating remarkable stability even after prolonged annealing at high temperatures. The author also investigates the influence of stereochemistry in tocopherol's hydrocarbon chain on microphase separation and highlights ongoing research into chirality effects. Additionally, the use of a rigid benzoate linker between BCO blocks was shown to enhance chirality effects, producing distinct morphologies. These findings contribute to a deeper understanding of molecular design principles for precise BCOs and pave the way for constructing intricate nanostructural templates with ultrasmall domain spacing.

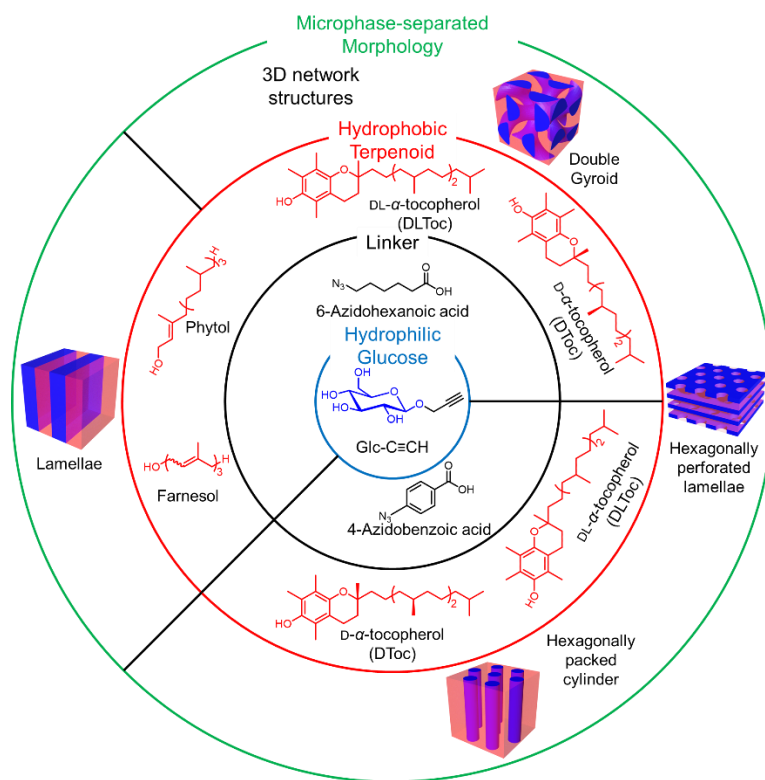


Figure 1.12. Circular schematic diagram of glucose-based BCOs and their morphologies.

In *Chapter 4*, the author systematically explores the microphase-separation behavior of sugar-rich BCOs composed of maltooligosaccharides and hydrophobic terpenoids, with sugar volume fractions ranging from 0.42 to 0.69. By SAXS measurement, the author identifies diverse nanostructures, including LAM, GYR, HEX and HPL_{ABC} in the bulk state. The identified nanostructures are considered sugar-rich, with sugar forming the matrix, as determined by the sugar volume fractions. Furthermore, GISAXS measurements confirm the formation of HPL_{ABC} structure in the thin film state, facilitated by solvent vapor annealing. Additionally, the calculated Flory-Huggins interaction parameter (χ) reveals significant incompatibility between sugar and terpenoid segments, with χ values between 24.57 and 30.34, by group-contribution method. In addition, the constructed phase diagram provided insights into phase transitions and structural behavior (**Figure 1.13**). This work contributes to the understanding of BCO microphase separation and offers a framework for designing tailored morphologies for nanofabrication applications.

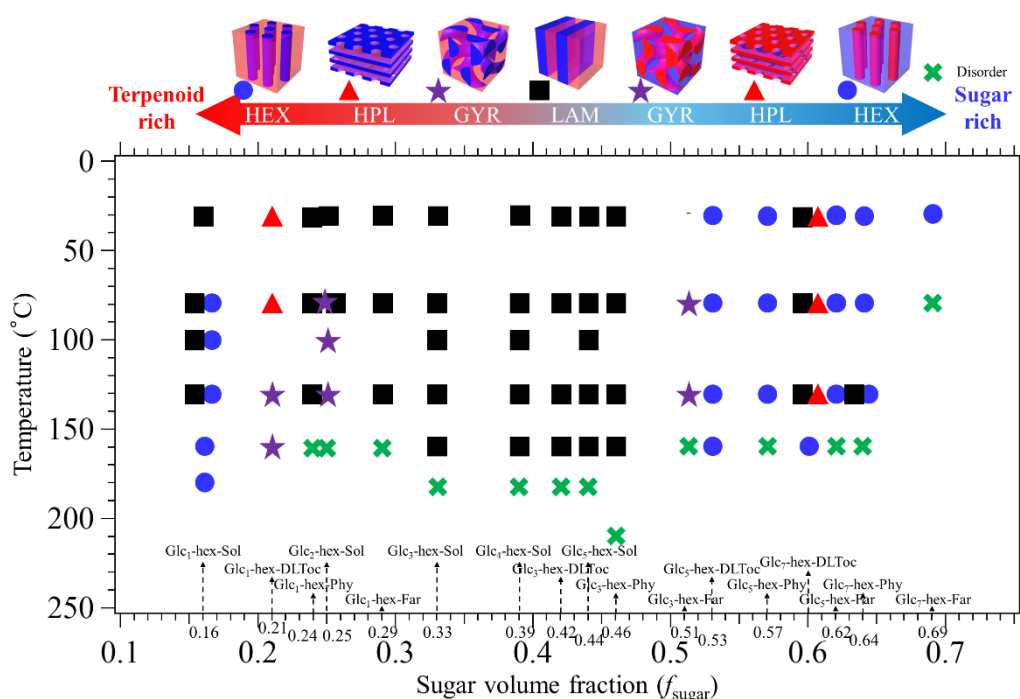


Figure 1.13. Phase diagram of sugar–terpenoid BCO system.

In the concluding *Chapter 5*, the established synthesis methods for sugar–terpenoid BCOs and the microphase separation behaviors are summarized. This comprehensive overview highlights the significance of these BCOs within microphase-separated structure design and their potential applications across various fields.

1.5 References

1. Zhang, M.; June S. M.; Long, T. E. 5.02 - *Principles of Step-Growth Polymerization (Polycondensation and Polyaddition)*. Elsevier, Amsterdam, **2012**, 7–47.
2. Matyjaszewski, K.; Spanswick, J. 3.12 - *Copper-Mediated Atom Transfer Radical Polymerization*. Elsevier, Amsterdam, **2012**, 377–428.
3. MısıR, M.; Yılmaz, S. S.; Bilgin, A. Synthesis and Characterization of ABA-Type Triblock Copolymers Using Novel Bifunctional PS, PMMA, and PCL Macroinitiators Bearing p-xylene-bis(2-mercaptoethoxy) Core. *Polymers (Basel)* **2023**, *15*, 3813.
4. Himadri Reddy P. C.; Patil, S. S.; Chandrasekaran, S. Synthesis of Novel Conducting Triblock Copolymer Poly(thiophene-co-pyrrole-co-aniline) by Chemical Oxidative Polymerization Method for Gas Sensor Application. *Synth. Met* **2024**, *306*, 117626.
5. Cichoń, K.; Kost, B.; Basko, M. Synthesis and Properties of ABA-Triblock Copolymers from Polyester A-blocks and Easily Degradable Polyacetal B-blocks. *Polym. Chem.* **2022**, *13*, 5243–5255.
6. Szczepaniak, G.; Kapil, K.; Adida, S.; Kim, K.; Lin, T.-C.; Yilmaz, G.; Murata, H.; Matyjaszewski, K. Solid-Phase Synthesis of Well-Defined Multiblock Copolymers by Atom Transfer Radical Polymerization. *J. Am. Chem. Soc.* **2024**, *146*, 22247–22256.
7. Clothier, G. K. K.; Guimarães, T. R.; Thompson, S. W.; Rho, J. Y.; Perrier, S.; Moad, G.; Zetterlund, P. B. Multiblock Copolymer Synthesis via RAFT Emulsion Polymerization. *Chem. Soc. Rev.* **2023**, *52*, 3438–3469.
8. Fang, J.; Gao, X.; Luo, Y. Synthesis of (hard-soft-hard)_x Multiblock Copolymers via

- RAFT Emulsion Polymerization and Mechanical Enhancement via Block Architectures. *Polymer (Guildf)* **2020**, *201*, 122602.
9. Yuan, H.; Chi, H.; Yuan, W. A Star-Shaped Amphiphilic Block Copolymer with Dual Responses: Synthesis, Crystallization, Self-Assembly, Redox and LCST–UCST Thermoresponsive Transition. *Polym. Chem.* **2016**, *7*, 4901–4911.
 10. Bhayo, A. M.; Abdul-Karim, R.; Musharraf, S. G.; Malik, M. I. Synthesis and Characterization of 4-Arm Star-Shaped Amphiphilic Block Copolymers Consisting of Poly(ethylene oxide) and Poly(ϵ -caprolactone). *RSC Adv.* **2018**, *8*, 28569–28580.
 11. Verduzco, R.; Li, X.; Pesek, S. L.; Stein, G. E. Structure, Function, Self-Assembly, and Applications of Bottlebrush Copolymers. *Chem. Soc. Rev.* **2015**, *44*, 2405–2420.
 12. Gibson, H. W.; Rouser, M. A.; Schoonover, D. V. Synthesis of Bottlebrush Copolymers Using a Polypseudorotaxane Intermediate. *Macromolecules* **2022**, *55*, 2271–2279.
 13. Mohammadi, E.; Joshi, S. Y.; Deshmukh, S. A. A Review of Computational Studies of Bottlebrush Polymers. *Comput. Mater. Sci.* **2021**, *199*, 110720.
 14. Tang, Z. Li, M.; Liang, S.; Zhang, M.; Biesold, G. M.; He, Y.; Hao, S.-M.; Choi, W.; Liu, Y.; Peng, J.; Lin, Z. From Controlled Synthesis, Self-Assembly, Properties to Applications. *Prog. Polym. Sci.* **2021**, *116*, 101387.
 15. Stoykovich, M. P.; Nealey, P. F. Block Copolymers and Conventional Lithography. *Mater. Today* **2006**, *9*, 20–29.
 16. De La Olvera Cruz, M. Theory of Microphase Separation in Block Copolymer Solutions. *J. Chem. Phys.* **1989**, *90*, 1995–2002.
 17. Bates, F. S.; Fredrickson, G. H. Block Copolymers-Designer Soft Materials. *Phys.*

Today **1999**, 52, 32–38.

18. Bates, F. S.; Bair, H. E.; Hartney, M. A. Block Copolymers Near the Microphase Separation Transition. *Macromolecules* **1984**, 17, 1987–1993.
19. Flory, P. J. Orwoll R. A.; Vrij, A. Statistical Thermodynamics of Chain Molecule Liquids. II. Liquid Mixtures of Normal Paraffin Hydrocarbons. *J. Am. Chem. Soc.* **1964**, 86, 3515–3520.
20. Flory, P. J. Statistical Thermodynamics of Liquid Mixtures. *J. Am. Chem. Soc.* **1965**, 87, 1833–1838.
21. Flory, P. J.; Eichinger, B. E.; Orwoll, R. A. Thermodynamics of Mixing Polymethylene and Polyisobutylene. *Macromolecules* **1968**, 1, 287–288.
22. Tambasco, M.; Lipson, J. E. G.; Higgins, J. S. Blend Miscibility and the Flory–Huggins Interaction Parameter: A Critical Examination. *Macromolecules* **2006**, 39, 4860–4868.
23. Senichev, V. Y. U.; Tereshatov, V. V. 6 – *Theories of Compatibility*. Third E. ChemTec Publishing **2017**, 135–164.
24. Tadros, T. *Flory-Huggins Interaction Parameter BT - Encyclopedia of Colloid and Interface Science*. Springer Berlin Heidelberg **2013**, 523–524.
25. Matsen, M. W.; Bates, F. S. Unifying Weak- and Strong-Segregation Block Copolymer Theories. *Macromolecules* **1996**, 29, 1091–1098.
26. Urade, V. N.; Wei, T.-C.; Tate, M. P.; Kowalski, J. D.; Hillhouse, H. W. Nanofabrication of Double-Gyroid Thin Films. *Chem. Mater.* **2007**, 19, 768–777.
27. Urbas, A. M.; Maldovan, M.; DeRege, P.; Thomas, E. L. Bicontinuous Cubic Block

- Copolymer Photonic Crystals. *Adv. Mater.* **2002**, *14*, 1850–1853.
28. Peng, S.; Zhang, R.; Chen, V. H.; Khabiboulline, E. T.; Braun, P.; Atwater, H. A. Three-Dimensional Single Gyroid Photonic Crystals with a Mid-Infrared Bandgap. *ACS Photonics*, **2016**, *3*, 1131–1137.
29. Fruchart, M.; Jeon, S. Y.; Hur, K.; Cheianov, V.; Wiesner, U.; Vitelli, V. Soft Self-Assembly of Weyl Materials for Light and Sound. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, *115*, E3655–E3664.
30. Li, X. Wang, C.; Zhou, J.; Yang, Z.; Zhang, Y.; Deng, H. Ultra-Fast Block Copolymers for Sub-5 nm Lithographic Patterning. *J. Photopolym. Sci. Technol.* **2018**, *31*, 483–486.
31. Ji, S.; Wan, L.; Liu, C. C.; Nealey, P. F. Directed Self-Assembly of Block Copolymers on Chemical Patterns: A Platform for Nanofabrication. *Prog. Polym. Sci.* **2016**, *54–55*, 76–127.
32. Shao, Y.; Hou, B.; Li, W.; Yan, X.; Wang, X.; Xu, Y.; Dong, Q.; Li, W.; He, J.; Zhang, W. B. Three-Component Bolaform Giant Surfactants Forming Lamellar Nanopatterns with Sub-5 nm Feature Sizes. *Macromolecules* **2023**, *56*, 1562–1571.
33. Hou, B.; Zhang, W.-B.; Shao, Y. Unconventional 2D Periodic Nanopatterns Based on Block Molecules. *Chinese J. Polym. Sci.* **2023**, *41*, 1508–1524.
34. Morris, M. A. Directed Self-Assembly of Block Copolymers for Nanocircuitry Fabrication. *Microelectron. Eng.* **2015**, *132*, 207–217.
35. Lo, T.-Y.; Krishnan, M. R.; Lu, K.-Y.; Ho, R.-M. Silicon-Containing Block Copolymers for Lithographic Applications. *Prog. Polym. Sci.* **2018**, *77*, 19–68.
36. Poelma, J. E.; Ono, K.; Miyajima, D.; Aida, T.; Satoh, K.; Hawker, C. J. Cyclic Block

- Copolymers for Controlling Feature Sizes in Block Copolymer Lithography. *ACS Nano* **2012**, *6*, 10845–10854.
37. Jung, Y. S.; Chang, J. B.; Verploegen, E.; Berggren, K. K.; Ross, C. A. A Path to Ultranarrow Patterns Using Self-Assembled Lithography. *Nano Lett.* **2010**, *10*, 1000–1005.
 38. Xiong, S.; Wan, L.; Ishida, Y.; Chapuis, Y.-A.; Craig, G. S. W.; Ruiz, R.; Nealey, P. F. Directed Self-Assembly of Triblock Copolymer on Chemical Patterns for Sub-10-nm Nanofabrication via Solvent Annealing. *ACS Nano* **2016**, *10*, 7855–7865.
 39. Maekawa, S.; Seshimo, T.; Dazai, T.; Sato, K.; Hatakeyama-Sato, K.; Nabae, Y.; Hayakawa, T. Chemically Tailored Block Copolymers for Highly Reliable Sub-10-nm Patterns by Directed Self-Assembly. *Nat. Commun.* **2024**, *15*, 5671.
 40. Oh, J.; Suh, H. S.; Ko, Y.; Nah, Y.; Lee, J. C.; Yeom, B.; Char, K.; Ross, C. A.; Son, J. G. Universal Perpendicular Orientation of Block Copolymer Microdomains Using a Filtered Plasma. *Nat. Commun.* **2019**, *10*, 2912.
 41. Phillip, W. A.; O'Neill, B.; Rodwogin, M.; Hillmyer, M. A.; Cussler, E. L.; Phillip, W. A. Self-Assembled Block Copolymer Thin Films as Water Filtration Membranes. *ACS Appl. Mater. Interfaces* **2010**, *2*, 847–853.
 42. Li, L.; Schulte, L.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S.; Clausen, L. D. Gyroid Nanoporous Membranes with Tunable Permeability. *ACS Nano* **2011**, *5*, 7754–7766.
 43. Li, L.; Szweczykowski, P.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S. Ultrafiltration by Gyroid Nanoporous Polymer Membranes. *J. Memb. Sci.* **2011**, *384*, 126–135.

44. Crossland, E. J. W.; Kamperman, M.; Nedelcu, M.; Ducati, C.; Wiesner, U.; Smilgies, D.-M.; Toombes, G. E. S.; Hillmyer, M. A.; Ludwigs, S.; Steiner, U.; Snaith, H. J. A Bicontinuous Double Gyroid Hybrid Solar Cell. *Nano Lett.* **2008**, *9*, 2807–2812.
45. Zalusky, A. S.; Olayo-Valles, R.; Taylo, C. J.; Hillmyer, M. A. Mesoporous Polystyrene Monoliths. *J. Am. Chem. Soc.* **2001**, *123*, 1519–1520.
46. Wang, X.-B.; Lo, T.-Y.; Hsueh, H.-Y.; Ho, R.-M. Double and Single Network Phases in Polystyrene-block-poly(L-lactide) Diblock Copolymers. *Macromolecules* **2013**, *46*, 2997–3004.
47. Barriga, H. M. G.; Holme, M. N.; Stevens, M. M. The Next Generation of Smart Lipid Nanoparticles?. *Angew. Chemie. Int. Ed.* **2019**, *58*, 2958–2978.
48. Park, W. I.; Kim, Y.; Jeong, J. W.; Kim, K.; Yoo, J. K.; Hur, Y. H.; Kim, J. M.; Thomas, E. L.; Alexander-Katz, A.; Jung, Y. S. Host-Guest Self-Assembly in Block Copolymer Blends. *Sci. Rep.* **2013**, *3*, 3190.
49. Sinturel, C.; Bates, F. S.; Hillmyer, M. A. High χ –Low N Block Polymers: How Far Can We Go? *ACS Macro Lett.* **2015**, *4*, 1044–1050.
50. Ding, S.-P.; Zhang, Z.-K.; Ye, Z.; Du, B.-Y.; Xu, J.-T. Fabrication of High χ –Low N Block Copolymers with Thermally Stable Sub-5 nm Microdomains Using Polyzwitterion as a Constituent Block. *ACS Macro Lett.* **2021**, *10*, 1321–1325.
51. Yoshida, K.; Tanaka, S.; Yamamoto, T.; Tajima, K.; Borsali, R.; Isono, T.; Satoh, T. Chain-End Functionalization with a Saccharide for 10 nm Microphase Separation: “classical” PS-*b*-PMMA versus PS-*b*-PMMA-Saccharide. *Macromolecules* **2018**, *51*, 8870–8877.
52. Cushen, J. D.; Otsuka, I.; Bates, C. M.; Halila, S.; Fort, S.; Rochas, C.; Easley, J. A.;

- Rausch, E. L.; Thio, A.; Borsali, R.; Willson, C. G.; Ellison, C. J. Oligosaccharide/Silicon-Containing Block Copolymers with 5 nm Features for Lithographic Applications. *ACS Nano* **2012**, *6*, 3424–3433.
53. Nowak, S. R.; Lachmayr, K. K.; Yager, K. G.; Sita, L. R. Stable Thermotropic 3D and 2D Double Gyroid Nanostructures with Sub-2-nm Feature Size from Scalable Sugar–Polyolefin Conjugates. *Angew. Chemie. Int. Ed.* **2021**, *60*, 8710–8716.
54. Zha, R. H.; Waal, B. F. M. D.; Lutz, M.; Teunissen, A. J. P.; Meijer, E. W. End Groups of Functionalized Siloxane Oligomers Direct Block-Copolymeric or Liquid-Crystalline Self-Assembly Behavior. *J. Am. Chem. Soc.* **2016**, *138*, 5693–5698.
55. Cushen, J. D.; Bates, C. M.; Rausch, E. L.; Dean, L. M.; Zhou, S. X.; Willson, C. G.; Ellison, C. J. Thin Film Self-Assembly of Poly(trimethylsilylstyrene-*b*-D,L-lactide) with Sub-10 nm Domains. *Macromolecules* **2012**, *45*, 8722–8728.
56. Kennemur, J. G.; Yao, L.; Bates, F. S.; Hillmyer, M. A. Sub-5 nm Domains in Ordered Poly(cyclohexylethylene)-block-poly(methyl methacrylate) Block Polymers for Lithography. *Macromolecules* **2014**, *47*, 1411–1418.
57. Aissou, K.; Otsuka, I.; Rochas, C.; Fort, S.; Halila, S.; Borsali, R. Nano-Organization of Amylose-*b*-Polystyrene Block Copolymer Films Doped with Bipyridine. *Langmuir* **2011**, *27*, 4098–4103.
58. Otsuka, I.; Isono, T.; Rochas, C.; Halila, S.; Fort, S.; Satoh, T.; Kakuchi, T.; Borsali, R. Phase Transition Induced by Caramelization in Sugar-Based Block Copolymers. *ACS Macro Lett.* **2012**, *1*, 1379–1382.
59. Shiba, K.; Niidome, T.; Katoh, E.; Xiang, H.; Han, L.; Mori, T.; Katayama, Y. Polydispersity as a Parameter for Indicating the Thermal Stability of Proteins by

- Dynamic Light Scattering. *Anal. Sci.* **2010**, *26*, 659–663.
60. Tretiakov, K. V.; Hyžorek, K. Strong Impact of Particle Size Polydispersity on the Thermal Conductivity of Yukawa Crystals. *Materials (Basel)*. **2024**, *17*, 4955.
61. Liu, H.; Dong, S.; Tang, L.; Krishnan, N. M. A.; Sant, G.; Bauchy, M. Effects of Polydispersity and Disorder on the Mechanical Properties of Hydrated Silicate Gels. *J. Mech. Phys. Solids* **2019**, *122*, 555–565.
62. Song, S.; Zhou, H.; Manners, I.; Winnik, M. A. Block Copolymer Self-Assembly: Polydisperse Corona-Forming Blocks Leading to Uniform Morphologies. *Chem* **2021**, *7*, 2800–2821.
63. Lynd, N. A.; Hillmyer, M. A. Effects of Polydispersity on the Order–Disorder Transition in Block Copolymer Melts. *Macromolecules* **2007**, *40*, 8050–8055.
64. Genabeek, B. V.; Waal, B. F. M. D.; Gosens, M. M. J.; Pitet, L. M.; Palmans, A. R. A.; Meijer, E. W. Synthesis and Self-Assembly of Discrete Dimethylsiloxane–Lactic Acid Diblock Co-oligomers: The Dononacontamer and Its Shorter Homologues. *J. Am. Chem. Soc.* **2016**, *138*, 4210–4218.
65. Ren, J. M.; Lawrence, J.; Knight, A. S.; Abdilla, A.; Zerdan, R. B.; Levi, A. E.; Oschmann, B.; Gutekunst, W. R.; Lee, S.-H.; Li, Y.; McGrath, A. J.; Bates, C. M.; Qiao, G. G.; Hawker, C. J. Controlled Formation and Binding Selectivity of Discrete Oligo(methyl methacrylate) Stereocomplexes. *J. Am. Chem. Soc.* **2018**, *140*, 1945–1951.
66. Lawrence, J.; Goto, E.; Ren, J. M.; McDearmon, B.; Kim, D. S.; Ochiai, Y.; Clark, P. G.; Laitar, D.; Higashihara, T.; Hawker, C. J. A Versatile and Efficient Strategy to Discrete Conjugated Oligomers. *J. Am. Chem. Soc.* **2017**, *139*, 13735–13739.

67. Genabeek, B. V.; Waal, B. F. M. D.; Ligt, B.; Palmans, A. R. A.; Meijer, E. W. Phase Behavior Differences between Disperse and Discrete Low Molecular Weight Block Co-Oligomers. *ACS Macro Lett.* **2017**, *6*, 674–678.
68. Han, Y.; Cui, J.; Jiang, W. Effect of Polydispersity on the Self-Assembly Structure of Diblock Copolymers under Various Confined States: A Monte Carlo Study. *Macromolecules* **2008**, *41*, 6239–6245.
69. Bates, F. S.; Fredrickson, G. H. Block Copolymer Thermodynamics: Theory and Experiment. *Annu. Rev. Phys. Chem.* **1990**, *41*, 525–557.
70. Matyjaszewski, K. Controlled Radical Polymerization. *Curr. Opin. Solid State Mater. Sci.* **1996**, *1*, 769–776.
71. Matsumura, S.; Hlil, A. R.; Lepiller, C.; Gaudet, J.; Guay, D.; Shi, Z.; Holdcroft, S.; Hay, A. S. Stability and Utility of Pyridyl Disulfide Functionality in RAFT and Conventional Radical Polymerizations. *J. Polym. Sci. Part A Polym. Chem.* **2008**, *46*, 7207–7224.
72. Vasilieva, Y. A.; Thomas, D. B.; Scales, C. W.; McCormick, C. L. Direct Controlled Polymerization of a Cationic Methacrylamido Monomer in Aqueous Media via the RAFT Process. *Macromolecules* **2004**, *37*, 2728–2737.
73. Parkatzidis, K.; Wang, H. S.; Truong, N. P.; Anastasaki, A. Recent Developments and Future Challenges in Controlled Radical Polymerization. *Chem* **2020**, *6*, 1575–1588.
74. Zhang, C.; Bates, M. W.; Geng, Z.; Levi, A. E.; Vigil, D.; Barbon, S. M.; Loman, T.; Delaney, K. T.; Fredrickson, G. H.; Bates, C. M.; Whittaker, A. K.; Hawker, C. J. Rapid Generation of Block Copolymer Libraries Using Automated Chromatographic Separation. *J. Am. Chem. Soc.* **2020**, *142*, 9843–9849.

Chapter 2

*Synthesis of Monodisperse High χ –Low N
Block Co-oligomers for
Ultrasmall Microphase-Separated Structures*

2.1 Introduction

Ordered nanostructures such as lamellar (LAM), gyroid (GYR), cylindrical, and spherical morphologies generated by block copolymer (BCP) microphase separation are highly promising nanotemplates for the low-cost, large-scale, and high-throughput production of sub-10 nm nanomaterials and nanodevices.^{1–4} In particular, directed self-assembly (DSA)-assisted BCP lithography has attracted considerable attention as a next-generation nanopatterning technology because it is more cost-effective and scalable than competing approaches.^{5–8} However, the development of BCP systems for the formation of highly ordered ultrasmall microphase-separated structures, which enable nanopatterning of a few nanometers, is still one of the key challenges in this field.

Previous studies have shown that decreasing the degree of polymerization (N) while increasing the Flory–Huggins interaction parameter (χ) is the most feasible and reliable method for achieving periodic microphase-separated structures with a domain spacing (d) < 10 nm.⁹ For example, poly(cyclohexylethylene)-*b*-poly(methyl methacrylate),¹⁰ poly(methyl methacrylate)-*b*-poly(dimethyl siloxane),¹¹ poly(3-hydroxystyrene)-*b*-poly(*tert*-butylstyrene),¹² poly(glycerol monomethacrylate)-*b*-poly(styrene),¹³ poly(styrene)-*b*-poly(3,4-dihydroxystyrene),¹⁴ poly(3-hydroxystyrene)-*b*-poly(dimethyl siloxane),¹⁵ oligosaccharide-containing BCPs,¹⁶ and polyhedral oligomeric silsesquioxane-containing BCPs¹⁷ have reportedly shown sub-10-nm periodicity. However, these BCPs are synthesized partially or entirely by polymerization reactions. As a result, it is virtually impossible for all growing polymer chains to terminate at the same length; therefore, the BCPs exhibit a range of molecular weight distributions. Such a dispersity is particularly detrimental for low-molecular-weight BCPs targeting a domain spacing of few nanometers (i.e., $d \approx 5$ nm) since at that scale, a single monomer unit size rapidly approaches d . In other words, in such low molecular weight regimes, increasing

or decreasing the number of BCP monomer units by only a single unit would impact the resulting self-assembly structural properties, such as the morphology, d , defects, roughness, and ordering.^{18–20} Indeed, seminal works by Meijer *et al.*²¹ and Hawker *et al.*²² have demonstrated that d increased with BCP dispersity increasing. More importantly, in the low-molecular-weight ($\sim 2500 \text{ g mol}^{-1}$) region, increasing the dispersity resulted in a loss of microphase separation, despite the fact that the monodisperse counterparts could form well-ordered nanostructures.²³ Another problem of conventional BCPs is synthesis reproducibility, whereby it is virtually impossible to reproduce BCPs showing exactly the same molecular weights and compositions, thereby causing batch-dependent variation in the resulting nanostructures. Given the importance of monodispersity in constructing ultrasmall nanostructures, a paradigm shift from conventional polydisperse BCPs to monodisperse block co-oligomer (BCO) systems is highly desirable.

Although several monodisperse BCP/BCO systems have been reported, their syntheses rely on either chromatographic fractionation of polydisperse polymers²² or iterative reactions to grow monomer units in a step-by-step manner,^{21,23–25} both of which require laborious efforts and time-consuming processes, thereby posing a major hurdle to meaningful progress in the fundamental science of monodisperse BCPs/BCOs. Therefore, the preparation of a readily available monodisperse BCO system that can form various microphase-separated morphologies showing ultrasmall periodicity is particularly challenging.

To develop such ideal BCO systems, the author herein proposes a combination of sugars and terpenoids. According to the results of Satoh *et al.* about oligosaccharide-based BCPs,^{26–30} strong segregation between hydrophilic saccharidic blocks and hydrophobic isoprene-based hydrocarbon chains would be expected, which allows microphase separation with a molecular-weight below 2000 g mol^{-1} . More importantly,

oligosaccharide and terpenoid blocks showing defined and discrete degrees of polymerization (DPs) are commercially available, and a series of BCOs featuring monodispersity and discrete DPs can be synthesized readily from them, providing rapid access to various ultrasmall nanostructures showing diverse morphologies, features, and sizes. Thus, the author herein employ a series of sugars from monosaccharide (*i.e.*, glucose) to heptasaccharide (*i.e.*, maltoheptaose) as oligosaccharide blocks, while farnesol (3,7,11-trimethyldodeca-2,6,10-trien-1-ol; mixture of isomers), DL- α -DLTocopherol (2,5,7,8-tetramethyl-2-(4,8,12-trimethyltridecyl)]chroman-6-ol), and solanesol ((2E,6E,10E,14E,18E,22E,26E,30E)-3,7,11,15,19,23,27,31,35-nonamethylhexatriaconta-2,6,10,14,18,22,26,30,34-nonaen-1-ol)—which are a family of terpenoids containing three, four, and nine isoprene units, respectively—are selected as hydrophobic blocks. Using this BCO system, the author attempts the construction of LAM, GYR, and hexagonally close-packed cylindrical (HEX) morphologies by adjusting the DP of each block, and the *d* values of the resulting organic BCP/BCO-based microphase-separated structures are examined.

2.2 Experimental Section

2.2.1 Materials

Copper(I) bromide (CuBr, >99.995%) was purchased from Sigma Aldrich and used as received. Propargylamine (>95%), acetic anhydride (>97%), Anhydrous tetrahydrofuran (THF, >99.5%; water content, <0.001%), anhydrous DMF (>99.5%; water content, <0.001%), and anhydrous CH₂Cl₂ (>99.5%; water content, <0.001%) were purchased from Kanto Chemical Co., Inc. and used as received. *N,N,N',N'',N''*-Pentamethyldiethylenetriamine (PMDETA, >98.0%), solanesol (>93.0%), farnesol (mixture of isomers; >95%), DL- α -tocopherol (>96%), 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide (EDC, >98.0%), and 4-dimethylaminopyridine (DMAP, >99.0%) were purchased from Tokyo Chemical Industry Co., Ltd. (TCI) and used as received. Maltotriose (>97.5%), maltotetraose (>97.0%), and maltohexaose (>97.0%) were purchased from Hayashibara Co., Ltd., and used as received. Dowex® 50WX2 hydrogen form was washed by decantation with MeOH before use. 6-Azido-1-hexanoic acid,⁴³ propargyl- β -D-glucopyranoside (Glc₁-C $\equiv$ CH),⁴⁴ propargyl- β -D-maltopyranoside (Glc₂-C $\equiv$ CH),⁴⁵ *N*-maltotriosyl-3-acetamido-1-propyne (Glc₃-C $\equiv$ CH),⁴⁶ and *N*-maltoheptaosyl-3-acetamido-1-propyne (Glc₇-C $\equiv$ CH)⁴⁷ were prepared according to previous reported methods.

2.2.2 Instruments

The size exclusion chromatography (SEC) in THF was performed at 40 °C using a Shodex GPC-101 system equipped with a Shodex K-G guard column and a set of two Shodex K-805L columns (linear, 8 mm $\times$ 300 mm; bead size, 5 μ m; exclusion limit, 4 $\times$ 106) at a flow rate of 1.0 mL min⁻¹. The SEC in DMF (containing 0.01 M LiCl) was performed at 40 °C using a Jasco high performance liquid chromatography system (PU-980 Intelligent HPLC pump, CO-965 Column oven, RI-930 Intelligent RI detector, and Shodex DEGAS KT-16) equipped with a Shodex Asahipak GF-310 HQ column (linear, 7.6 mm $\times$ 300 mm; pore size, 20 nm; bead size, 5 μ m; exclusion limit, 4 $\times$ 104) and a Shodex Asahipak GF-7 M HQ column (linear, 7.6 mm $\times$ 300 mm; pore size, 20 nm; bead size, 9 μ m; exclusion limit, 4 $\times$ 107) at a flow rate of 0.6 mL min⁻¹. The number-average molecular weight ($M_{n,SEC}$) and dispersity (D_{SEC}) of the sample were calculated on the basis of a polystyrene (PSt) calibration. The ¹H (400 MHz) and ¹³C NMR (100 MHz) spectra were recorded using a JEOL JNM-ECS400 instrument. Matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI-TOF MS) measurement was performed with the reflector mode using an AB Sciex TOF/TOF 5800 system equipped with a 349-nm Nd:YAG laser. 500 shots were accumulated for the spectra and an acceleration voltage were adjusted between 10 and 30 kV depending on both the molecular weight and the nature of each sample. Samples for the MALDI-TOF MS were prepared by mixing a THF solution of a sample (5.0 mg mL⁻¹, 1.0 μ L) and a matrix (2,5-dihydroxybenzoic acid, 10 mg mL⁻¹, 5.0 μ L). For the measurement, the mixed solution of the sample and matrix (1.0 μ L) was loaded onto a sample plate, which was coated with a solution of NaI (1.0 μ L, 1.0 mmol L⁻¹) as the cationic agent in acetone, was used. The Fourier transform infrared spectroscopy (FT-IR) analysis was carried out using a PerkinElmer Frontier MIR spectrometer equipped with a single reflection diamond

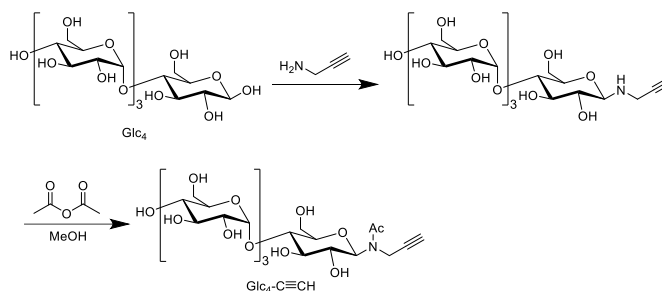
universal attenuated total reflection (ATR) accessory. Atomic force microscopy (AFM) phase images were realized using a molecular imaging PicoPlus atomic force microscope operating in the tapping mode with a silicon cantilever (PPP-NCHR and SSS-NCHR, NANOSENSORS) having a resonant frequency of 330 kHz and a force constant of 42 N m⁻¹. The AFM images were processed using Gwyddion software. Small-angle X-ray scattering (SAXS) experiments for bulk samples were performed at BL-6A beamline of the Photon Factory of High Energy Accelerator Research Organization (KEK, Tsukuba, Japan). The X-ray wavelength and exposure time were 1.50 Å (8.27 keV) and 60 s, respectively. A PILATUS3 1M (Dectris Ltd., Switzerland) detector, with 981 × 1043 pixels at a pixel size of 172 × 172 µm, and a counter depth of 20 bits (1,048,576 counts), was used for data acquisition. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate. The bulk samples were put into 1.5 mm diameter glass capillaries. After that, the bulk samples were annealed under vacuum at 70, 100, and 130 °C for 36 h. The SAXS data were acquired under ambient condition, and 1D profiles were obtained as plots of scattering intensity as functions of scattering vector (q), where $q = (4\pi/\lambda) \sin(\theta/2)$ (λ , wavelength; θ , scattering angle). Grazing incidence small-angle X-ray scattering (GISAXS) experiments for thin film samples were performed at BL11 beamline of the ALBA synchrotron (Barcelona, Spain) or at 3C beamline of the Pohang Accelerator Laboratory (PAL; Pohang, Korea). At the ALBA, the X-ray wavelength and exposure time were 1.00 Å and 30 s, respectively. A PILATUS3 1M (Dectris Ltd., Switzerland) detector, with 981 × 1043 pixels at a pixel size of 172 × 172 µm, and a counter depth of 20 bits (1,048,576 counts), was used for data acquisition. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate. The GISAXS profiles were acquired under ambient condition. At the PAL, scattering data were measured at room temperature in vacuum using X-ray radiation sources with a

wavelength of 1.21 Å and a two-dimensional (2D) charge-coupled detector (CCD) (model Rayonix 2D SX 165, Rayonix, Evanston, IL, USA); each scattering image was normally collected for 10–30 s. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate.

2.2.3 Synthesis of Block Co-Oligomers

Synthesis of N-maltotetraosyl-3-acetamido-1-propyne (Glc₄-C≡CH)

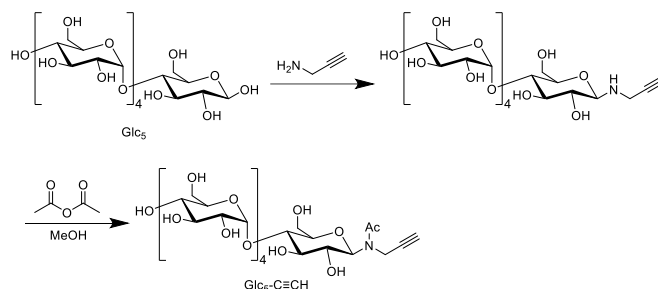
Scheme 2.1. Synthesis of Glc₄-C≡CH



Synthesis of propargyl-functionalized oligosaccharide was conducted as follows (Method A): Maltotetraose (2.00 g, 3.00 mmol) and propargylamine (3.80 mL, 60.0 mmol) were stirred under a nitrogen atmosphere for 72 h. The reaction mixture was dissolved in minimum amount of dry MeOH and precipitated into CH₂Cl₂. The precipitate was filtered and washed with CH₂Cl₂. The obtained precipitate was dissolved in a mixture of acetic anhydride and dry MeOH (1/2 (v/v), 100 mL) and stirred for 48 h. The excess of acetic anhydride was removed by co-evaporation with a mixed solvent of toluene and MeOH. The resulting residue was freeze dried to give Glc₄-C≡CH as a white solid (1.86 g, yield: 85.9%).

¹H NMR (400 MHz, D₂O): δ (ppm) 5.52 and 5.09 (rotamers, 1H, (HO)CHN(Ac)), 5.40-5.42 (m, 3H, H-1^{GlcII-IV}), 3.36-4.30 (m, 26H, H-2,-3,-4,-5,-6^{GlcI-IV}, NCH₂), 2.72 and 2.55 (m, 1H, rotamers, CCH), 2.20-2.30 (m, 3H, CH₃),

HRMS (ESI): Calcd.; for C₂₉H₄₇NO₂₁Na⁺ [M + Na]⁺ 768.25383, found 768.25360

Synthesis of *N*-maltopentaosyl-3-acetamido-1-propyne (*Glc*₅-C≡CH)**Scheme 2.2.** Synthesis of *Glc*₅-C≡CH

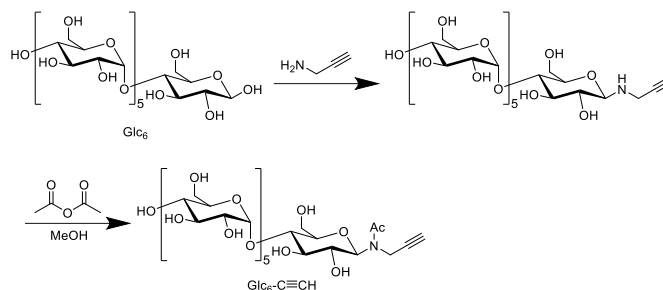
Method A was used for the reaction of maltopentaose (5.00 g, 6.03mmol) with propargylamine (6.65 g, 121 mmol) and acetic anhydride in MeOH (1/20 (v/v), 100 mL) to give *Glc*₅-C≡CH as a white solid (5.49 g, yield: 99.0%).

^1H NMR (400MHz, D_2O): δ (ppm) 5.54 and 5.09 (rotamers, 1H, $\text{CHN}(\text{Ac})$), 5.39-5.44 (m, 4H, $\text{H-1}^{\text{GlcII-V}}$), 3.36-4.32 (m, 32H, $\text{H-2,-3,-4,-5,-6}^{\text{GlcI-V}}$, NCH_2), 2.75 and 2.58 (t, 1H, rotamers, $J=2.3$ Hz, CCH), 2.32 and 2.24 (s, 3H, CH_3).

HRMS (ESI): Calcd. For $\text{C}_{35}\text{H}_{57}\text{NO}_{31}\text{Na}^+$ $[\text{M} + \text{Na}]^+$ 930.30779, found 930.30610

Synthesis of N-maltohexaosyl-3-acetamido-1-propyne (Glc₆-C≡CH)

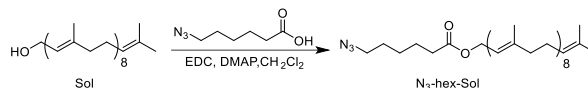
Scheme 2.3. Synthesis of Glc₆-C≡CH



Method A was used for the reaction of maltohexaose (3.00g, 3.03 mmol) with propargylamine (3.88 ml, 60.6 mmol) and acetic anhydride in MeOH (1/20 (v/v), 100 mL) to give Glc₆-C≡CH as a white solid (2.80g, yield: 88.4%).

¹H NMR (400 MHz, D₂O): δ (ppm) 5.54 and 5.09 (rotamers, 1H, $\underline{\text{CHN}}(\text{Ac})$), 5.39-5.44 (m, 5H, $\underline{\text{H-1}}^{\text{GlcII-VI}}$), 3.36-4.32 (m, 38H, $\underline{\text{H-2,-3,-4,-5,-6}}^{\text{GlcI-VI}}$, NCH_2), 2.75 and 2.58 (t, 1H, rotamers, $J = 2.3$ Hz, CCH), 2.32 and 2.24 (s, 3H, $\underline{\text{CH}_3}$).

HRMS (ESI): Calcd. for C₄₁H₆₇NO₃₁Na⁺ [M + Na]⁺ 1092.35947, found 1092.35962.

Synthesis of solanesyl 6-azidohexanoate (*N*₃-hex-Sol)**Scheme 2.4.** Synthesis of *N*₃-hex-Sol

A typical esterification procedure is as follows (method B): 6-Azidohexanoic acid (173 mg, 1.10 mmol) was added to a stirred solution of solanesol (3.00 g, 4.75 mmol), DMAP (871 mg, 7.13 mmol), and EDC·HCl (1.37 g, 7.13 mmol) in anhydrous CH₂Cl₂ (20 mL). After stirring at room temperature for 72 h, the reaction mixture was concentrated and purified by silica gel column chromatography (*n*-hexane/AcOEt = 9/1 (v/v), *R*_f = 0.44) to give *N*₃-hex-Sol as a white solid (3.51 g, yield: 95.8%).

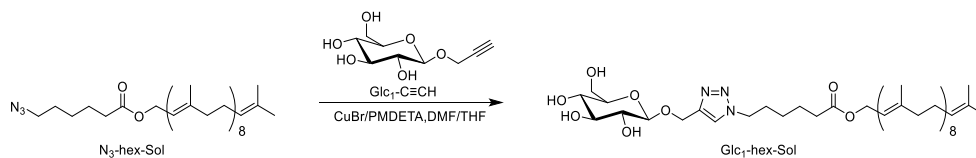
¹H NMR (400 MHz, CDCl₃): δ (ppm) 5.33 (d, 1H, *J* = 7.2 Hz, CHCH₂O), 5.12 (t, 8H, *J* = 6.1 Hz, CH), 4.60 (d, 2H, *J* = 6.7 Hz, CH₂O), 3.27 (t, 2H, *J* = 7.0 Hz, CH₂N₃), 2.32 (t, 2H, *J* = 7.4 Hz, COCH₂), 1.26-2.10 (m, 68H, CH₃, CHCH₂CH₂, CH₂CH₂CH₂CH₂CH₂).

¹³C NMR (100 MHz, CDCl₃): δ (ppm) 173.6, 142.5, 135.7, 135.2, 135.1, 131.4, 124.5, 124.4, 124.3, 123.7, 118.4, 61.4, 51.4, 39.9, 39.7, 34.2, 29.8, 28.7, 26.9, 26.8, 26.4, 25.9, 24.6, 17.8, 16.6, 16.2.

HRMS (ESI): Calcd. for C₅₁H₈₃O₂N₃Na⁺ [*M* + Na]⁺ 792.63775, found 792.63938.

Synthesis of Glc₁-hex-Sol by click reaction

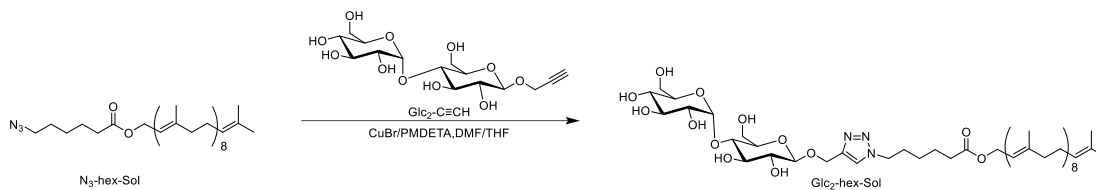
Scheme 2.5. Synthesis of Glc₁-hex-Sol



A typical click reaction procedure is as follows (method C). N₃-hex-Sol (1.20 g, 1.56 mmol), Glc₁-C≡CH (408 mg, 1.87 mmol), and copper(I) bromide (CuBr; 22.3 mg, 156 μ mol) were placed into a Schlenk flask, which was evacuated and back-filled with argon three times. A solution of *N,N,N',N'',N'''*-pentamethyldiethylenetriamine (PMDETA; 10.3 mg, 59.8 mmol) in a mixed solvent of DMF (5.0 mL) and THF (5.0 mL) was degassed by the argon bubbling, and the mixture was then transferred into the Schlenk flask under an argon atmosphere. The reaction mixture was stirred at 60 °C for 72 h and treated with Dowex to remove Cu catalyst. The resulting product was purified by reprecipitation from the DMF solution into a mixed solvent of acetonitrile and H₂O (7/3 (v/v)) to give Glc₁-hex-Sol as a white solid (1.03 g, yield: 66.9%). $M_{n,SEC}$ = 2,190; D_{SEC} = 1.01 (DMF).

¹H NMR (400 MHz, DMF-*d*₇): See **Figure S2.2**.

HRMS (ESI): Calcd. for C₆₀H₉₇O₈N₃Na⁺ [M+Na]⁺ 1010.71679, found 1010.71725.

Synthesis of Glc₂-hex-Sol by click reaction**Scheme 2.6.** Synthesis of Glc₂-hex-Sol

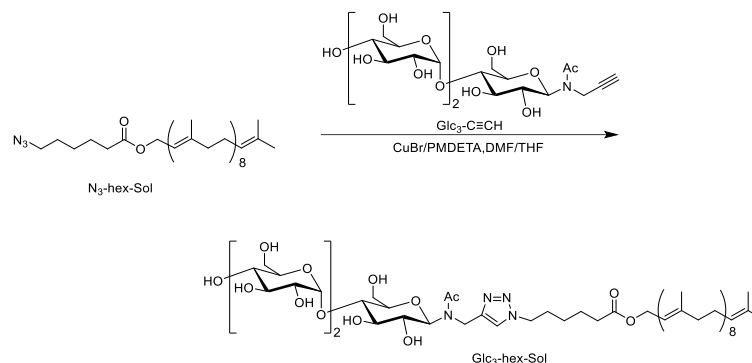
Method C was used for the click reaction of N₃-hex-Sol (6.00 g, 7.79 mmol) and Glc₂-C≡CH (3.80 g, 9.35 mmol) in a mixed solvent of DMF (25.0 mL) and THF (25.0 mL) with CuBr (112 mg, 779 μmol) and PMDETA (134 mg, 779 μmol) as a catalyst. The resulting product was purified by reprecipitation using THF as a good solvent and a mixed solvent of acetonitrile and H₂O (7/3 (v/v)) as a poor solvent to give Glc₂-hex-Sol as a white solid (6.29 g, yield: 70.2%). $M_{n,SEC} = 2,870$; $D_{SEC} = 1.04$ (DMF).

¹H NMR (400 MHz, DMF-*d*₇): See **Figure S2.3**.

HRMS (ESI): Calcd. for C₆₆H₁₀₇O₁₃N₃Na⁺ [M + Na]⁺ 1172.76961, found 1172.76780.

Synthesis of Glc₃-hex-Sol by click reaction

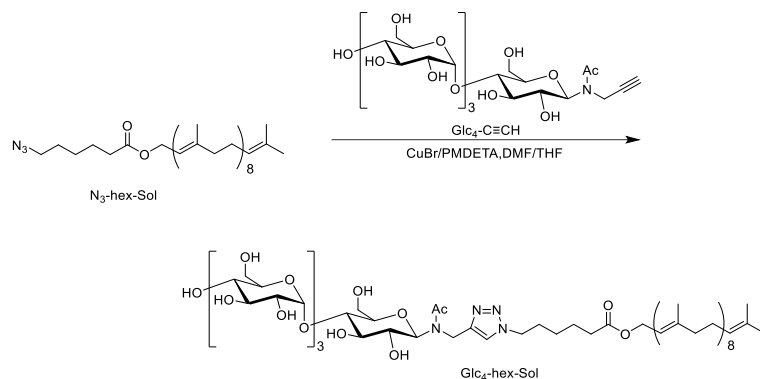
Scheme 2.7. Synthesis of Glc₃-hex-Sol



Method C was used for the click reaction of N₃-hex-Sol (1.00 g, 1.30 mmol) and Glc₃-C≡CH (908 mg, 1.56 mmol) in a mixed solvent of DMF (10.0 mL) and THF (6.0 mL) with CuBr (18.6 mg, 130 μ mol) and PMDETA (22.5 mg, 130 μ mol) as a catalyst. The resulting product was purified by reprecipitation using THF as a good solvent and a mixed solvent of acetonitrile and H₂O (7/3 (v/v)) as a poor solvent to give Glc₃-hex-Sol as a white solid (1.67 g, yield: 95.1%). $M_{n,SEC}$ = 3,470; D_{SEC} = 1.02 (DMF).

¹H NMR (400 MHz, DMF-*d*₇): See **Figure S2.4**.

HRMS (ESI): Calcd. for C₇₄H₁₂₀O₁₈N₄Na⁺ [M + Na]⁺ 1375.84898, found 1375.85015.

Synthesis of Glc₄-hex-Sol by click reaction**Scheme 2.8.** Synthesis of Glc₄-hex-Sol

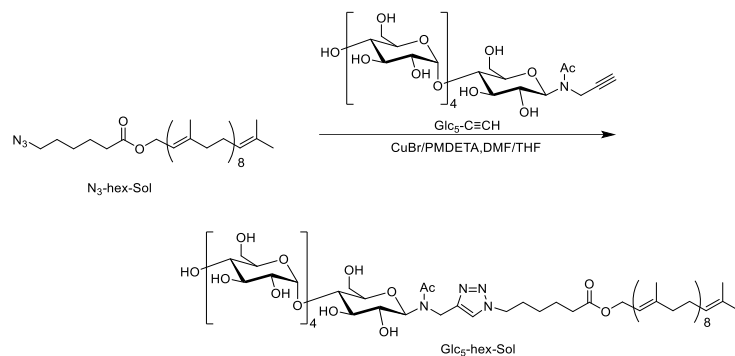
Method C was used for the click reaction of N₃-hex-Sol (500 mg, 0.650 mmol) and Glc₄-C≡CH (581 mg, 0.780 mmol) in a mixed solvent of DMF (10.0 mL) and THF (6.0 mL) with CuBr (9.3 mg, 65 μmol) and PMDETA (11.3 mg, 65 μmol) as a catalyst. The resulting product was purified by reprecipitation using THF as a good solvent and a mixed solvent of acetonitrile and H₂O (7/3 (v/v)) as a poor solvent to give Glc₄-hex-Sol as a white solid (0.873 g, yield:88.3%). $M_{n,SEC} = 3,470$; $D_{SEC} = 1.03$ (DMF).

¹H NMR (400 MHz, DMF-*d*₇): See **Figure S2.5**.

HRMS (ESI): Calcd. for C₈₀H₁₃₁O₂₃N₄⁺ [M + H]⁺ 1515.91986, found 1515.92241.

Synthesis of Glc₅-hex-Sol by click reaction

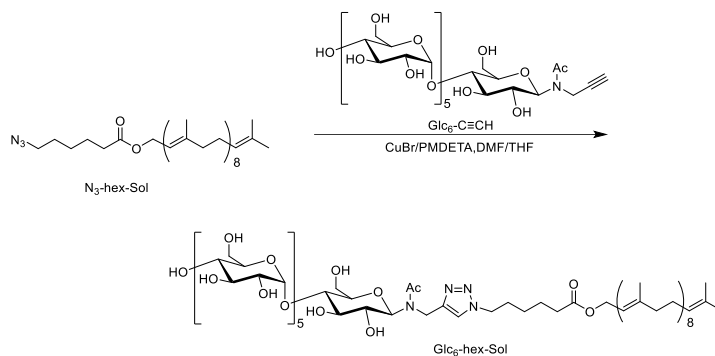
Scheme 2.9. Synthesis of Glc₅-hex-Sol



Method C was used for the click reaction of N₃-hex-Sol (150 mg, 0.194 mmol) and Glc₅-C≡CH (212 mg, 0.234 mmol) in a mixed solvent of DMF (1.5 mL) and THF (1.5 mL) with CuBr (2.8 mg, 20 μ mol) and PMDETA (3.4 mg, 20 μ mol) as a catalyst. The resulting product was purified by reprecipitation using DMF as a good solvent and a mixed solvent of acetonitrile and H₂O (7/3 (v/v)) as a poor solvent to give Glc₅-hex-Sol as a white solid (176 mg, yield: 54.0%). $M_{n,SEC} = 3,730$; $D_{SEC} = 1.02$ (DMF).

¹H NMR (400 MHz, DMF-*d*₇): See **Figure S2.6**.

HRMS (ESI): Calcd. for C₈₆H₁₄₀O₂₈N₄Na⁺ [M + Na]⁺ 1699.95693, found 1699.95463.

Synthesis of Glc₆-hex-Sol by click reaction**Scheme 2.10.** Synthesis of Glc₆-hex-Sol

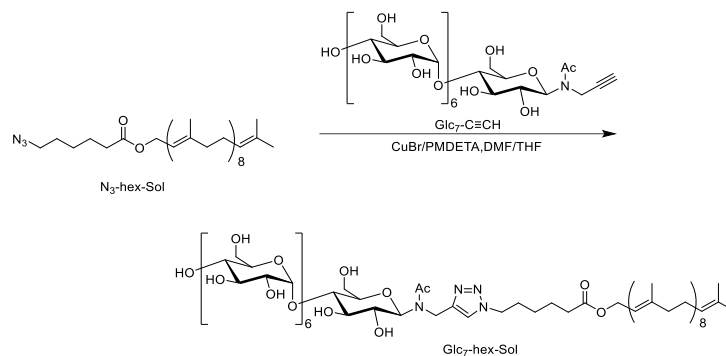
Method C was used for the click reaction of N₃-hex-Sol (150 mg, 0.194 mmol) and Glc₆-C≡CH (173 mg, 0.162 mmol) in a mixed solvent of DMF (1.5 mL) and THF (1.5 mL) with CuBr (2.3 mg, 16.2 μmol) and PMDETA (2.8 mg, 16.2 μmol) as a catalyst. The resulting product was purified by reprecipitation using DMF as a good solvent and acetone as a poor solvent to give Glc₆-hex-Sol as a white solid (212 mg, yield: 59.3%). $M_{n,SEC} = 4,140$; $D_{SEC} = 1.04$ (DMF).

¹H NMR (400 MHz, DMF-*d*₇): See **Figure S2.7**.

HRMS (ESI): Calcd. for C₉₂H₁₅₁O₃₃N₄⁺ [M + H]⁺ 1840.02551, found 1840.03129.

Synthesis of Glc₇-hex-Sol by click reaction

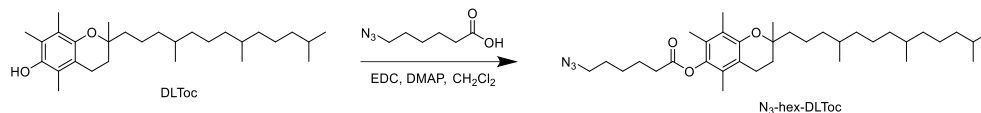
Scheme 2.11. Synthesis of Glc₇-hex-Sol



Method C was used for the click reaction of N₃-hex-Sol (150 mg, 0.194 mmol) and Glc₇-C≡CH (288 mg, 0.234 mmol) in a mixed solvent of DMF (1.5 mL) and THF (1.5 mL) with CuBr (2.8 mg, 19.5 μ mol) and PMDETA (3.4 mg, 19.5 μ mol) as a catalyst. The resulting product was purified by reprecipitation using DMF as a good solvent and a mixed solvent of acetonitrile and H₂O (7/3 (v/v)) as a poor solvent. Further purification by reprecipitation using DMF as a good solvent and acetone as a poor solvent gave Glc₇-hex-Sol as a white solid (251 mg, yield: 64.3%). $M_{n,SEC} = 5,150$; $D_{SEC} = 1.04$ (DMF).

¹H NMR (400 MHz, DMF-*d*₇): See **Figure S2.8**.

HRMS (ESI): Calcd. for C₉₈H₁₆₀O₃₈N₄Na₂²⁺ [M + 2Na]²⁺ 1023.52475, found 1023.52689.

Synthesis of tocopheryl 6-azidohexanoate (*N*₃-hex-DLToc)**Scheme 2.12.** Synthesis of *N*₃-hex-DLToc

Method B was used for the reaction of DL- α -Tocopherol (7.00 g, 16.26 mmol) and 6-azidohexanoic acid (3.32 g, 21.12 mmol) with DMAP (2.58 g, 21.12 mmol) and EDC·HCl (4.05 g, 21.12 mmol) in anhydrous CH₂Cl₂ (50 mL). The crude was purified by silica gel column chromatography (*n*-hexane/AcOEt = 1/4 (v/v), *R*_f = 0.13) to give *N*₃-hex-DLToc as a pale-yellow viscous liquid (1.90 g, yield: 57.7%).

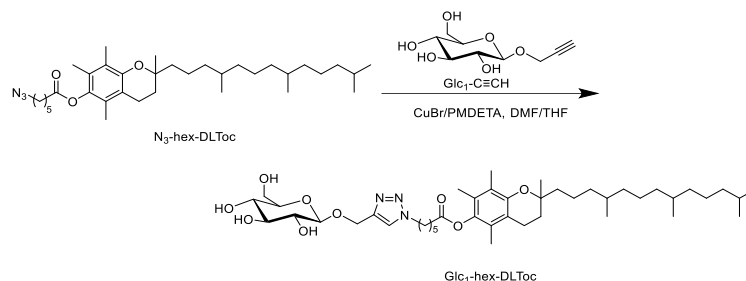
¹H NMR (400 MHz, CDCl₃): δ (ppm) 3.31 (t, 2H, *J* = 7.2 Hz, N₃CH₂), 2.68-2.52 (m, 4H, COCH₂, Ar-CH₂), 2.12-1.92 (m, 9H, Ar-CH₃), 1.90-0.96 (m, 37H, H^{Toc}, N₃CH₂CH₂CH₂CH₂), 0.94-0.78 (m, 12H, CH₃).

¹³C NMR (100 MHz, CDCl₃): δ (ppm) 172.2, 149.5, 140.5, 126.7, 125.0, 123.2, 117.5, 75.1, 51.3, 39.5, 39.4, 37.6, 37.5, 37.5, 37.4, 34.0, 32.9, 32.8, 28.7, 28.1, 26.5, 25.0, 24.8, 24.6, 22.8, 22.8, 21.1, 20.7, 19.9, 19.8, 19.7, 19.7, 13.1, 12.27, 11.96.

HRMS (ESI): Calcd. for C₃₅H₅₉O₃N₃Na⁺ [*M* + Na]⁺ 592.44486, found 592.44528.

Synthesis of Glc₁-hex-DLToc by click reaction

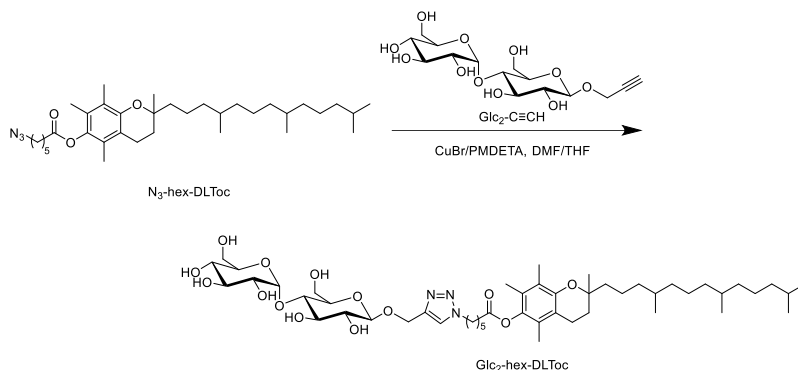
Scheme 2.13. Synthesis of Glc₁-hex-DLToc



Method C was used for the click reaction of N₃-hex-DLToc (2.00 g, 3.51 mmol) and Glc₁-C≡CH (512 mg, 2.35 mmol) in a mixed solvent of DMF (10 mL) and THF (10 mL) with CuBr (101 mg, 0.71 mmol) and PMDETA (122 mg, 0.71 mmol) as a catalyst. The resulting product was purified by silica gel column chromatography (CH₂Cl₂/MeOH = 9/1 (v/v), R_f = 0.27) to give Glc₁-hex-DLToc as a white solid (1.48 g, yield: 53.5%). $M_{n,SEC}$ = 1,790; D_{SEC} = 1.01 (DMF).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S2.11**.

HRMS (ESI): Calcd. for C₄₄H₇₃O₉N₃Na⁺ [M + Na]⁺ 810.52390, found 810.52444.

Synthesis of Glc₂-hex-DLToc by click reaction**Scheme 2.14.** Synthesis of Glc₂-hex-DLToc

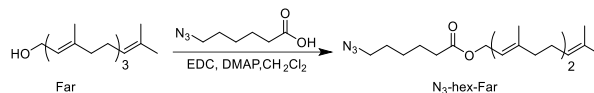
Method C was used for the click reaction of N₃-hex-DLToc (800 mg, 1.40 mmol) and Glc₂-C≡CH (357 mg, 0.94 mmol) in a mixed solvent of DMF (5 mL) and THF (5 mL) with CuBr (44 mg, 0.28 mmol) and PMDETA (49 mg, 0.28 mmol) as a catalyst. The resulting product was purified by silica gel column chromatography (CH₂Cl₂/MeOH = 4/1 (v/v), *R_f* = 0.35) to give Glc₂-hex-DLToc as a yellow solid (320 mg, yield: 31.3%). *M_{n,SEC}* = 2,240; *D_{SEC}* = 1.02 (DMF).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S2.12**.

HRMS (ESI): Calcd. for C₅₈H₉₇O₁₉N₃H⁺ [M + H]⁺ 1153.677415, found 1153.67595.

Synthesis of farnesyl 6-azidohexanoate (N₃-hex-Far)

Scheme 2.15. Synthesis of N₃-hex-Far



Method B was used for the reaction of farnesol (mixture of isomers; 6.00 g, 27.0 mmol) and 6-azidohexanoic acid (5.52 g, 35.1 mmol) with DMAP (4.29 g, 35.1 mmol) and EDC·HCl (6.74 g, 35.1 mmol) in anhydrous CH₂Cl₂ (50 mL). The crude was purified by silica gel column chromatography (*n*-hexane/AcOEt = 9/1 (v/v), *R_f* = 0.31) to give N₃-hex-Far as a pale-yellow viscous liquid (8.21 g, yield: 84.2%).

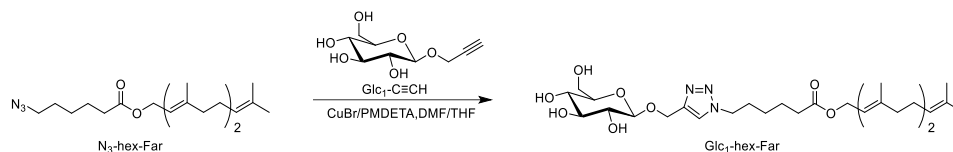
¹H NMR (400 MHz, CDCl₃): δ (ppm) 5.35 (t, 1H, *J* = 7.2 Hz, CHCH₂O), 5.20-5.04 (m, 2H, CH), 4.70-4.52 (m, 2H, CH₂O), 3.28 (t, 2H, *J* = 7.2 Hz, CH₂N₃), 2.42-2.26 (m, 2H, COCH₂), 2.22-1.92 (m, 8H, CHCH₂CH₂), 1.83-1.51 (m, 16H, CH₃, CH₂CH₂CH₂CH₂CH₂), 1.49-1.31 (m, 2H, CH₂CH₂CH₂CH₂CH₂).

¹³C NMR (100 MHz, CDCl₃): δ (ppm) 173.6 (C=O), 142.5 (OCH₂CHC), 135.6 (OCH₂CHCCH₂CH₂CHC), 131.5 (C(CH₃)₂), 124.3 and 123.8 (OCH₂CHCCH₂CH₂CHCCH₂CH₂CHC), 118.3 (OCH₂CHC), 61.4 (OCH₂CHC), 51.3 (N₃CH₂), 39.8 and 39.6 (C(CH₃)CH₂), 34.2 (COCH₂), 28.7 (N₃CH₂CH₂), 26.8 (N₃CH₂CH₂CH₂), 26.3 and 26.3 (CH₂CH₂CH), 24.6 (COCH₂CH₂), 24.5 (C(C_{trans}H₃)(C_{cis}H₃)), 17.8 (C(C_{trans}H₃)(C_{cis}H₃)), 16.6 and 16.1 (C(CH₃)CH₂).

HRMS (ESI): Calcd. for C₂₁H₃₅O₂N₃Na⁺ [*M* + Na]⁺ 384.26215, found 384.26257.

Synthesis of Glc₁-hex-Far by click reaction

Scheme 2.16. Synthesis of Glc₁-hex-Far



Method C was used for the click reaction of N₃-hex-Far (420 mg, 1.16 mmol) and Glc₁-C≡CH (350 mg, 1.61 mmol) in a mixed solvent of DMF (5.0 mL) and THF (5.0 mL) with CuBr (20.0 mg, 139 μmol) and PMDETA (122 mg, 111 μmol) as a catalyst. The resulting product was purified by reprecipitation using DMF as a good solvent and water as a poor solvent to give to give Glc₁-hex-Far as a white solid (280 mg, yield: 42.0%). $M_{n,SEC} = 1,540$; $D_{SEC} = 1.015$ (DMF).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S2.14**.

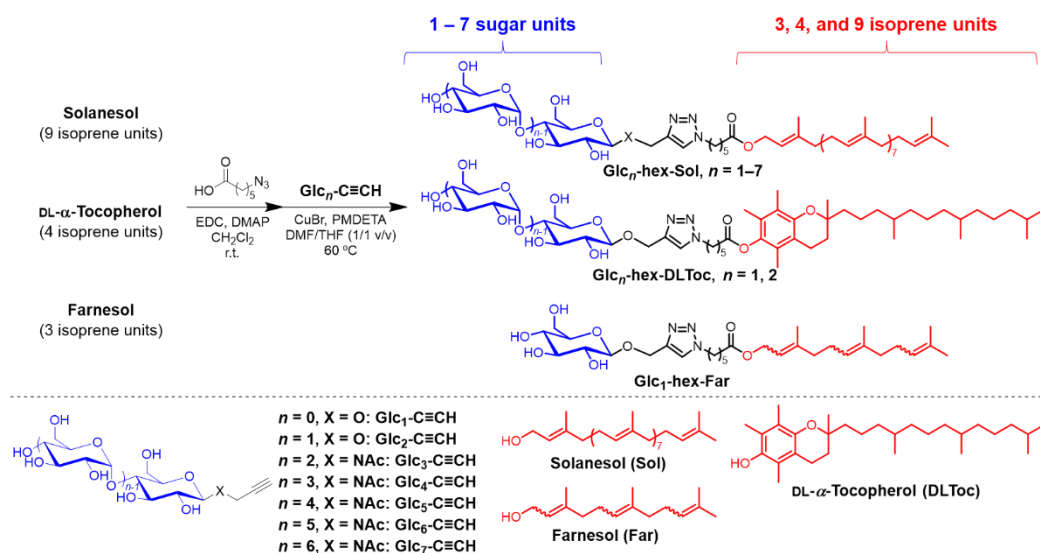
HRMS (ESI): Calcd. for $C_{30}H_{50}O_8N_3Na^+ [M + Na]^+$ 580.35924, found 580.36002.

2.3 Result and Discussion

2.3.1 Synthesis of Block Co-oligomers (BCOs)

BCO synthetic procedure relies on the “click” reaction between terpenoid (*i.e.*, farnesol, DL- α -tocopherol, and solanesol) and sugar units, as depicted in **Scheme 2.17**. Solanesol-based BCOs (Glc_{*n*}-hex-Sol; *n* = 1–7) were synthesized from the azido-functionalized solanesol (N₃-hex-Sol) with propargyl-functionalized glucose (Glc₁-C $\equiv$ CH), maltose (Glc₂-C $\equiv$ CH), maltotriose (Glc₃-C $\equiv$ CH), maltotetraose (Glc₄-C $\equiv$ CH), maltopentaose (Glc₅-C $\equiv$ CH), maltohexaose (Glc₆-C $\equiv$ CH), and maltoheptaose (Glc₇-C $\equiv$ CH) by the “click” reactions in the presence of a Cu catalyst in a dimethylformamide (DMF) and tetrahydrofuran (THF) mixed solvent. Following completion of the reaction, the Cu catalyst was removed by treating the reaction mixture with a cation-exchange resin, and the resulting residue was precipitated in a selective solvent to remove unreacted starting materials, thereby affording the desired BCOs in moderate to good yields. The reaction products did not exhibit any strong infrared (IR) absorption at 2100 cm^{–1}, suggesting near-quantitative consumption of the azido group (**Figure S2.1**). Proton nuclear magnetic resonance (¹H NMR) spectra were reasonably assigned to the expected BCO chemical structure (**Figures S2.2–8**), and the size exclusion chromatography (SEC) elution peak clearly shifted toward the higher-molecular-weight region upon increasing the number of glucose units in the BCO (Figure 2.1(a)). More importantly, matrix-assisted laser desorption/ionization–time-of-flight mass spectrometry (MALDI-TOF MS) analysis confirmed the presence of monodisperse products (**Figure 2.1(b)** and **Figure S2.9**). It should be emphasized that the successful multigram-scale synthesis could be attributed to the existing commercially available starting materials and simple purification of synthesized products. Similarly, tocopherol- and farnesol-based BCOs (Glc₁-hex-DLToc, Glc₂-hex-DLToc, and Glc₁-hex-Far) were prepared and characterized (**Figures**

S2.9–15).



Scheme 2.17. Synthetic schemes for preparation of the monodisperse and discrete Glc_n-hex-Sol ($n = 1-7$), and Glc_n-hex-DLToc ($n = 1$ and 2), and Glc₁-hex-Far.

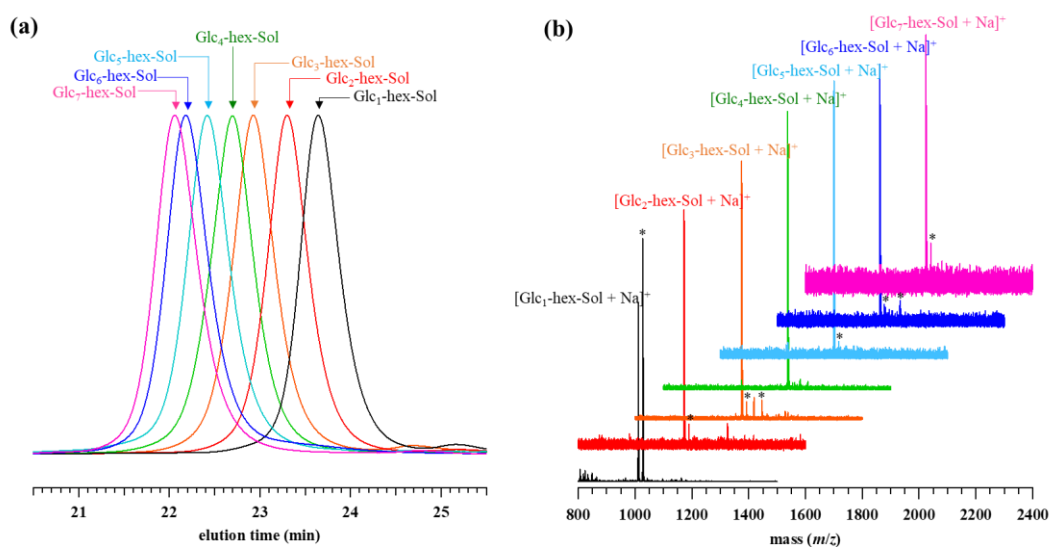


Figure 2.1. (a) SEC traces, and (b) MALDI-TOF mass spectra for Glc_n-hex-Sol ($n = 1-7$). Asterisks indicate peaks attributed to $[M + K]^+$ or $[M + Ag]^+$.

2.3.2 Nanostructural Formation of Solanesol-Based BCOs

To gather fundamental information regarding the microphase separation behavior, a series of thermally annealed solanesol-based BCOs (Glc_n-hex-Sol; $n = 1-7$) was subjected to small-angle X-ray scattering (SAXS) (**Figure 2.2(a)**). Unless otherwise noted, bulk samples were annealed at 130 °C for 36 h and then quenched to room temperature. The SAXS profiles of Glc₁-hex-Sol, Glc₂-hex-Sol, Glc₃-hex-Sol, Glc₄-hex-Sol, and Glc₅-hex-Sol showed higher-order scattering peaks and a sharp primary peak (q^*), demonstrating the formation of well-ordered periodic nanostructures (**Table 2.1**). It is rather surprising that even the BCO containing only one glucose unit, *i.e.*, Glc₁-hex-Sol, had self-assembled into the HEX morphology with a domain spacing ($d = 2\pi/q^*$) of 5.5 nm (cylinder-to-cylinder distance = $2d/\sqrt{3} = 6.4$ nm; cylinder diameter = $[8f_{\text{sugar}} \cdot d^2/(\sqrt{3} \cdot \pi)]^{1/2} = 2.7$ nm),²³ which is the smallest ever among structures that have been self-assembled from saccharide-based block BCPs. For example, d values of 5.8 and 6.6 nm were reported for LAM-forming cellobiose-*block*-polypropylene³¹ and HEX-forming maltotriose-*block*-polycaprolactone systems,³² respectively, in the bulk states. In addition, an LAM morphology showing relatively large $d = 12.7$ nm had formed through self-assembly. Considering the multiple diffraction peaks present in the wide-angle X-ray scattering (WAXS) profiles (**Figure 2.2(b)**), the coexisting LAM morphology should be a crystallization-driven rather than a microphase-separated structure (**Figures S2.16 and 17**). Indeed, *in situ* SAXS measurements obtained while heating the samples gave only the scattering pattern characteristic of HEX ($q/q^* = 1, \sqrt{3}, \sqrt{4}$, and $\sqrt{7}$; **Figure S2.17**), confirming absence of the LAM-morphology at elevated temperatures.

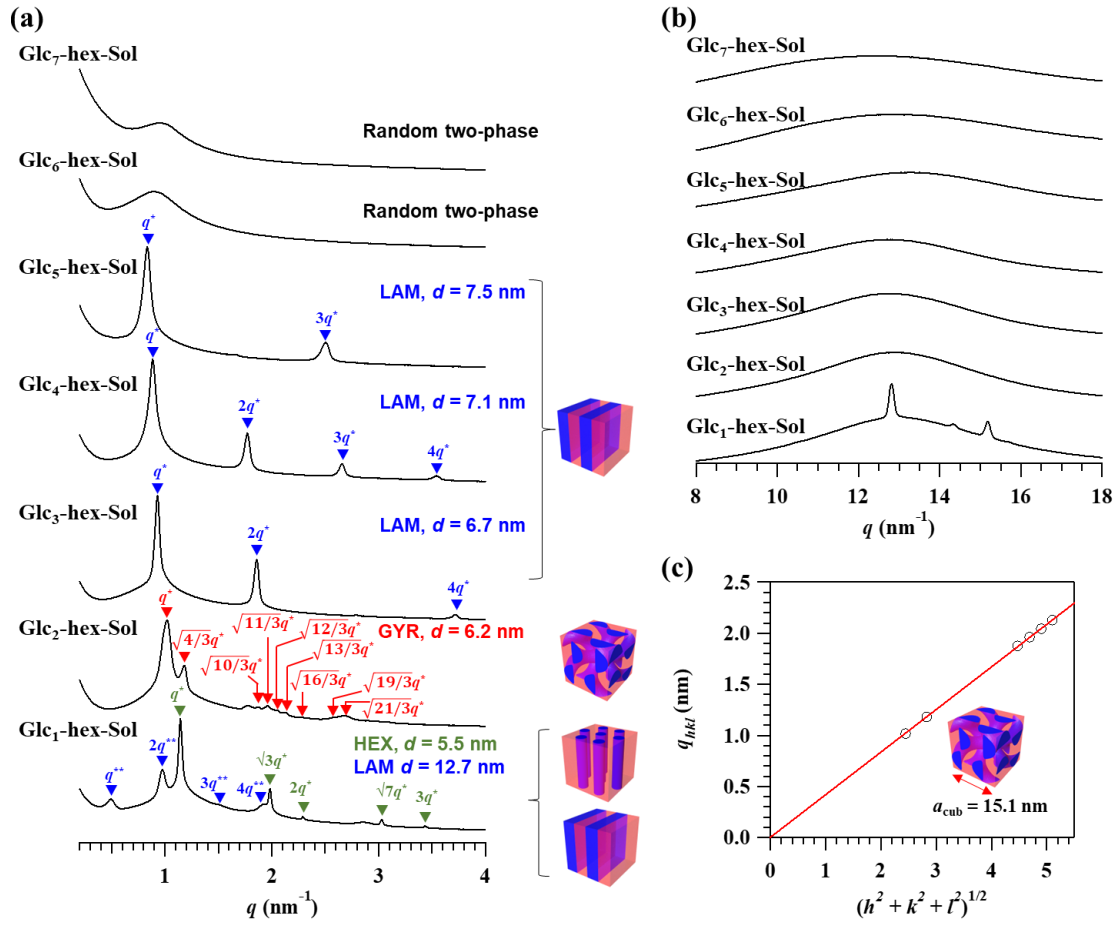


Figure 2.2. Morphological analyses for the thermally annealed bulk Glc_{*n*}-hex-Sol (*n* = 1–7) samples. (a) SAXS profiles revealed the formation of ordered nanostructures, with the exceptions of Glc₆-hex-Sol and Glc₇-hex-Sol. (b) WAXS profiles of Glc_{*n*}-hex-Sol (*n* = 1–7) demonstrating amorphous BCOs, with the exception of Glc₁-hex-Sol. Glc₂-hex-Sol was annealed at 100 °C for 36 h while all other samples were annealed at 130 °C for 36 h. (c) The q_{hkl} versus $(h^2 + k^2 + l^2)^{1/2}$ plot based on the SAXS pattern for Glc₂-hex-Sol validated space group assignment, where *h*, *k*, and *l* are the Miller indices of the corresponding planes. The lattice parameter of GYR (a_{cub}) was calculated from the slope of the linear fit.

Table 2.1. Molecular parameters and bulk morphological characteristics of Glc_{*n*}-hex-Sol (*n* = 1–7), Glc₁-hex-Far, and Glc_{*n*}-hex-DLToc (*n* = 1 and 2)

BCO	DP _{Glc} ^a	DP _{isoprene} ^a	M.W.	<i>f</i> _{sugar} ^b	Bulk morphology ^c (annealing condition)	<i>d</i> ^c (nm)
Glc ₁ -hex-Sol	1	9	988.44	0.16	HEX/LAM (130 °C, 36 h)	5.5/12.7
Glc ₂ -hex-Sol	2	9	1150.58	0.25	GYR (100 °C, 36 h)	6.2
Glc ₃ -hex-Sol	3	9	1353.78	0.33	LAM (130 °C, 36 h)	6.7
Glc ₄ -hex-Sol	4	9	1515.92	0.39	LAM (130 °C, 36 h)	7.1
Glc ₅ -hex-Sol	5	9	1678.06	0.44	LAM (130 °C, 36 h)	7.5
Glc ₆ -hex-Sol	6	9	1840.2	0.48	random two-phase	-
Glc ₇ -hex-Sol	7	9	2002.34	0.52	random two-phase	-
Glc ₁ -hex-DLToc	1	4	802.09	0.21	GYR (80 °C, 6 h)	5.2
Glc ₂ -hex-DLToc	2	4	964.23	0.31	LAM (80 °C, 6 h)	6.3
Glc ₁ -hex-Far	1	3	579.72	0.28	LAM (80 °C, 6 h)	4.2

^a DPs BCO glucose and isoprene units (DP_{Glc} and DP_{isoprene}, respectively). ^b The saccharide volume fraction (*f*_{sugar}) was calculated based on densities of 1.36, 0.90, and 0.95 g cm^{−3} for the saccharide, solanesol, farnesol, and tocopherol blocks, respectively. ^c The morphology and *d* were determined from bulk-sample SAXS data.

The SAXS profile of Glc₂-hex-Sol thermally annealed at 100 °C for 36 h showed scattering peaks at $q = 1.017, 1.179, 1.875, 1.961, 2.042,$ and 2.128 nm^{-1} , which were assignable to the (211), (220), (420), (332), (422), and (431) crystallographic planes of the GYR phase, respectively (**Figure 2.2(a)**).³³ Note that this is the first-ever example of GYR-forming saccharide-based BCPs. Since the maltose block is the minor component, the interwoven network and surrounding matrix should be composed of maltose and solanesol, respectively. The cubic lattice parameter a_{cub} was determined to be 15.1 nm from the slope of a plot of q_{hkl} versus $(h^2 + k^2 + l^2)^{1/2}$ ($a_{\text{cub}} = 2\pi(h^2 + k^2 + l^2)^{1/2}/q_{hkl}$), where h , k , and l are Miller indices (**Figure 2.2(c)**). The lateral distance between interwoven networks was calculated to be 6.5 nm ($= \sqrt{3}a_{\text{cub}}/4$),³⁴ which is approximately the fully extended molecular length (ca. 7 nm). Thus, low BCO molecular weight should be responsible for the GYR nanomorphology.

SAXS profiles according to the LAM structures showing q/q^* ratios of 1:2:3:4 after increasing the number of glucose units to more than 3 (*i.e.*, for Glc₃-hex-Sol, Glc₄-hex-Sol, and Glc₅-hex-Sol) (**Figure 2.2(a)**); d was in the range 6.7–7.5 nm and increased in ca. 0.4 nm increments with each glucose unit added. Interestingly, third- and second-order scattering peaks were suppressed in the SAXS profiles of Glc₃-hex-Sol and Glc₅-hex-Sol, respectively, suggesting that the LAM-domain (*i.e.*, saccharide/solanesol) volume ratios were 1/2 and 1/1 for Glc₃-hex-Sol and Glc₅-hex-Sol, respectively. According to classical BCP theory, 1/2 volume fractions should lead to HEX rather than LAM structural formations.³⁵ However, the rigid monodisperse oligosaccharide molecules encumbered BCO molecules from packing into higher-curvature morphologies, thus preferentially forming LAM structures even at such asymmetric volume ratios. For LAM structure, d is the sum of the lamellar microdomain thickness for the two constitutional blocks. Given

the 1:1 volume ratio of Glc₅-hex-Sol as revealed by the SAXS analysis, the lamellar microdomain thickness for each block should be approximately 3.8 nm.

Further increasing the number of glucose units resulted in poor ordering (*i.e.*, random two phase) in the bulk (**Figure 2.2(a)**). Despite thermally annealing Glc₆-hex-Sol and Glc₇-hex-Sol up to 180 °C for 36 h, their SAXS profiles only exhibited a single broad peak without any higher-order scattering. The reduced chain mobility associated with high glass transition temperatures (T_g s) owing to the longer oligosaccharide molecules (*e.g.*, 145 and 150 °C for maltohexaose and maltoheptaose, respectively³⁶) should be responsible for restricting the self-assembly process.

BCO thin films were then prepared by spin-coating a toluene/DMF BCO solution onto silicon substrates. To confirm the ordered nanostructures in the BCO thin films, the author investigated Glc_{*n*}-hex-Sol ($n = 1-5$) thin films by grazing incidence small-angle X-ray scattering (GISAXS) measurements and atomic force microscopy (AFM). GISAXS analysis revealed that the thin films presented horizontally-orientated LAM morphologies, regardless of the number of glucose units (**Figure S2.18**). In addition, the AFM images of the Glc₃-hex-Sol and Glc₄-hex-Sol thin films clearly showed terrace formations (**Figure 2.3**), which agreed with the horizontally orientated LAM formations observed by GISAXS. The height difference between two consecutive layers (~6 and ~8 nm for Glc₃-hex-Sol and Glc₄-hex-Sol, respectively) roughly matched d , as determined by SAXS and listed in **Table 2.1**. The key morphological features of the Glc_{*n*}-hex-Sol thin films were consistent with horizontal orientations retained over large areas and relatively low distributions of LAM thickness. Such structural uniformity should be a direct result of the BCO monodispersity.

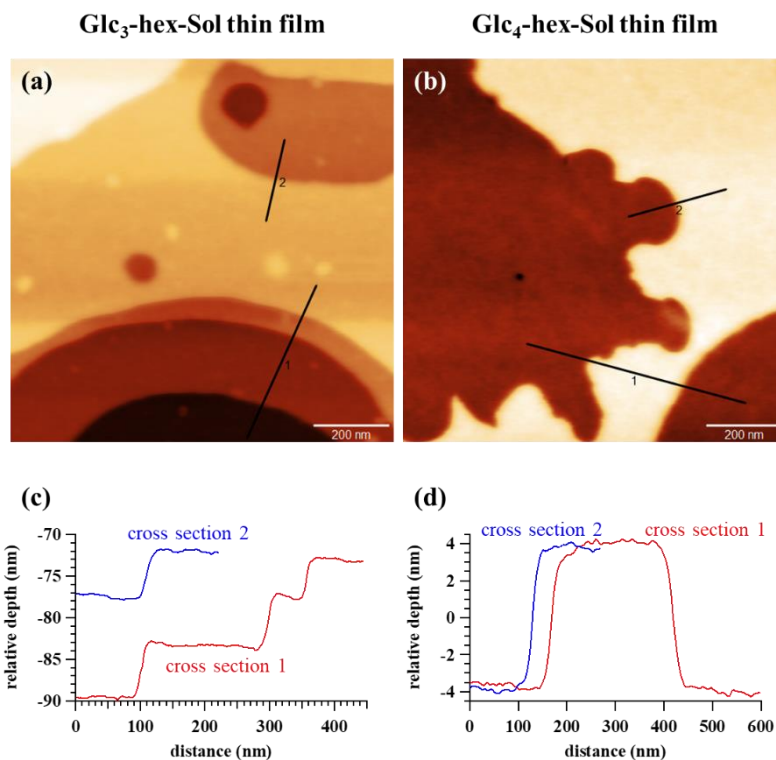


Figure 2.3. Thin-film morphologies of Glc₃-hex-Sol (left) and Glc₄-hex-Sol (right). (a and b) AFM height images and (c and d) corresponding cross-sectional profiles indicating the formation of 6–8 nm-thick horizontal lamellae. Thin-film samples were prepared by spin-coating the BCO solution onto the hydrophilic surface of a silicon substrate followed by thermal annealing at 85 °C for 1 h.

2.3.3 Fine-Tuning Nanostructures by Varying Dispersity

The most important feature of the present BCO system is its monodispersity, which should allow high degrees of ordering in the bulk. Previous studies have suggested the possibility of tailoring BCP microphase separation—including size, morphology, and stability—by tuning the constitutional-block dispersities.^{18,19} Thus, the author hypothesized that BCO mixtures with different numbers of glucose units could further expand the morphologies, features, and sizes accessible from the current BCO system. To test this hypothesis, the author investigated the effects of $\bar{D}_{\text{Glc}}$ on microphase-separated structures. By mixing different Glc_{*n*}-hex-Sol molecules ($n = 1\text{--}5$), polydisperse versions of Glc₃-hex-Sol and Glc₄-hex-Sol were artificially prepared through variation in $\bar{D}_{\text{Glc}}$ while fixing the average number of glucose units. For example, Glc₁-hex-Sol and Glc₅-hex-Sol mixed in a 1:1 molar ratio showed the same average number of glucose units as Glc₃-hex-Sol but a different $\bar{D}_{\text{Glc}}$. All thermally annealed polydisperse samples underwent self-assembly into well-ordered microphase-separated structures regardless of $\bar{D}_{\text{Glc}}$, as evidenced by the multiple sharp scattering peaks in their SAXS profiles (**Figure 2.4**). Compared to the microphase-separated morphology of monodisperse Glc₃-hex-Sol, that of polydisperse Glc₃-hex-Sol shifted from LAM ($\bar{D}_{\text{Glc}} = 1.000$) to GYR ($\bar{D}_{\text{Glc}} = 1.190$ and 1.244) and finally to HEX ($\bar{D}_{\text{Glc}} = 1.301$ and 1.333) with increasing $\bar{D}_{\text{Glc}}$ (**Figures 2.4(a–h)**). The coexistence of longer and shorter oligosaccharides facilitated the formation of curved microdomains, thereby allowing the morphology to shift from a lower to a higher curvature.¹⁸ In addition to the morphological shift, d increased with increasing $\bar{D}_{\text{Glc}}$. In the Glc₄-hex-Sol series, on the other hand, d increased from 7.1 nm ($\bar{D}_{\text{Glc}} = 1.000$) to 7.8 nm ($\bar{D}_{\text{Glc}} = 1.165$) with increasing $\bar{D}_{\text{Glc}}$, while the LAM morphology remained unchanged (**Figures 2.4(i–m)**). Glc₄-hex-Sol shows a higher saccharide volume fraction (f_{sugar}) than Glc₃-hex-Sol, and therefore, is deeply

embedded in the LAM region of the phase diagram. This likely accounts for the fact that the Glc₄-hex-Sol series did not exhibit a morphological shift. In contrast, Glc₃-hex-Sol is likely located near the LAM–GYR phase boundary; therefore, slight variations in dispersity shifted the resulting morphology. Since both morphology and d value correlated with $\bar{D}_{\text{Glc}}$, the morphology can be tailored, and d can be fine-tuned by a few angstroms simply by blending discrete BCO molecules. Conversely, however, these results imply that monodisperse and discrete natures are essential in fabricating highly reproducible ultrasmall nanostructures, which is particularly important in the context of nanolithographic applications.

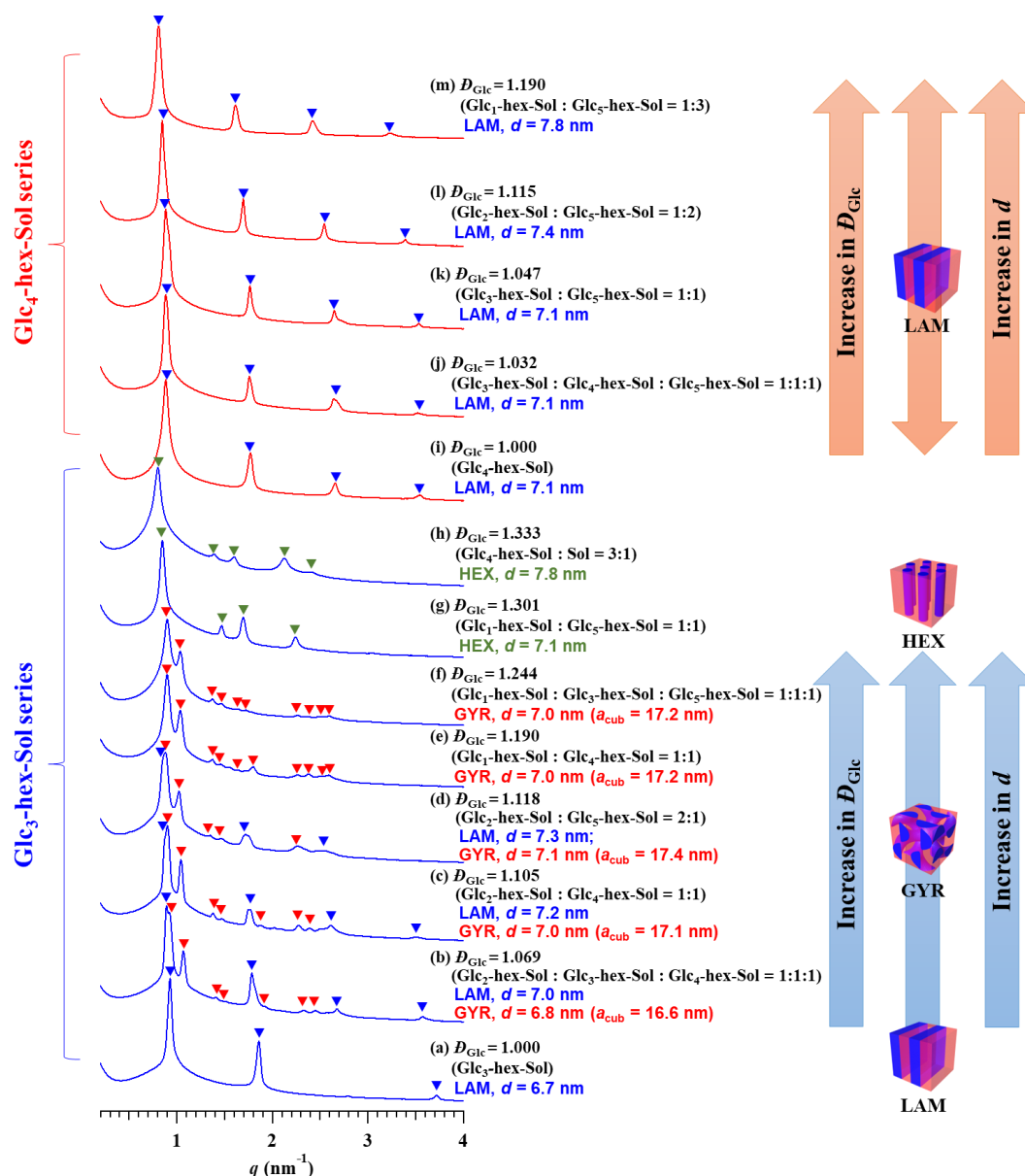


Figure 2.4. Effect of dispersity on Glc₃-hex-Sol and Glc₄-hex-Sol microphase separations. SAXS profiles of the polydisperse (a–h) Glc₃-hex-Sol and (i–m) Glc₄-hex-Sol series revealed variation in the morphology and d upon increasing D_{Glc} . Polydisperse samples were prepared by mixing different BCO molecules in given molar ratios. All samples were thermally annealed at 130 °C for 36 h. Blue, red, and green inverted triangles indicate peak assignments corresponding to the LAM, GYR, and HEX structures, respectively.

2.3.4 Further Minimizing the Feature Size by Tocopherol- and Farnesol-Based BCOs

Although solanesol-based BCOs underwent self-assembly into highly ordered nanostructures, obtained results indicated that 6 nm was the lowest achievable d value when combining solanesol with the monosaccharide. The author therefore examined the BCO nanostructures formed from shorter terpenoid blocks (*i.e.*, Glc₁-hex-DLToc, Glc₂-hex-DLToc, and Glc₁-hex-Far) by SAXS analysis. Surprisingly, the SAXS profiles of the thermally annealed Glc₁-hex-DLToc, Glc₂-hex-DLToc, and Glc₁-hex-Far (80 °C for 6 h) exhibited multiple scattering peaks corresponding to GYR ($d = 5.2$ nm; $a_{\text{cub}} = 12.6$ nm), LAM ($d = 6.3$ nm), and LAM ($d = 4.2$ nm) nanostructures, respectively (**Figure 2.5(a)** and **Figure S2.19**), despite their extremely low M.W. (580–964 g mol⁻¹) and total DP (4–6) (**Table 2.1**). To the best of knowledge, the microphase-separated structure obtained by Glc₁-hex-Far is among the smallest organic-BCP-derived LAM microphase-separated structures.^{9,14,23,31,357} Given the f_{sugar} of Glc₁-hex-Far, the sugar microdomain thickness is approximately 1.2 nm, which shows promise to an ultrahigh-resolution nanofabrication. In addition, the author spin-coated a Glc₁-hex-DLToc thin film, and the corresponding GISAXS image showed a strong scattering spot along the out-of-plane direction, indicating the formation of a horizontally orientated LAM morphology (**Figure S2.20**). Furthermore, the corresponding AFM height image clearly shows terrace formation corresponding to multilayer LAM stacking, which also supports the GISAXS result (**Figure 2.5(b)**). The height difference between two consecutive layers (*i.e.*, d for the LAM morphology) was ~4 nm (**Figure 2.5(c)**), which again confirmed the astonishing capability of the present BCO system to form ultrasmall nanostructures.

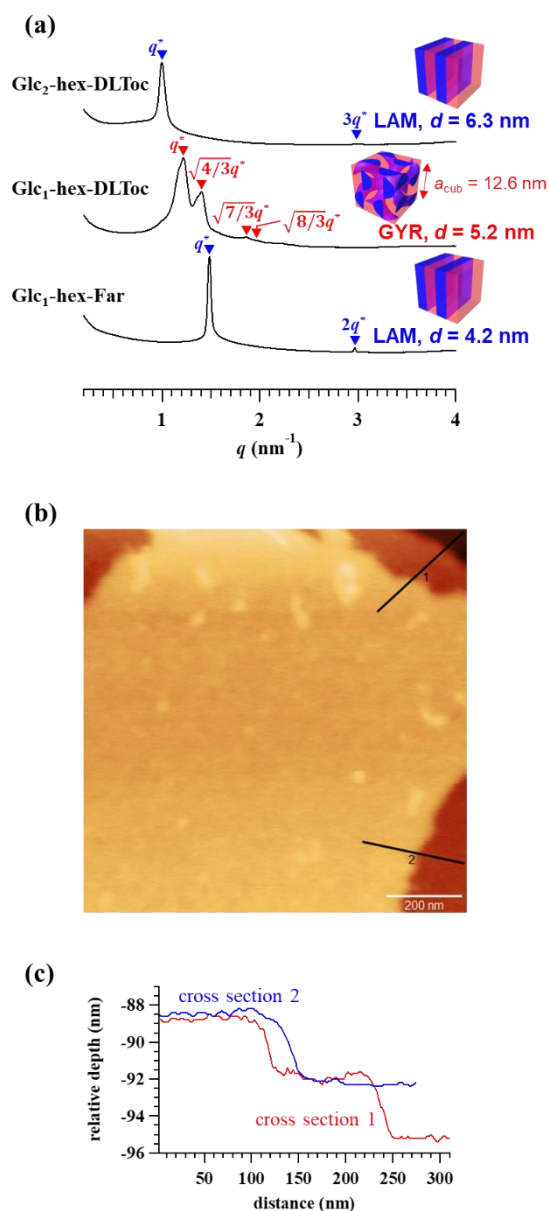


Figure 2.5. Morphological analyses of Glc₁-hex-DLToc, Glc₂-hex-DLToc, and Glc₁-hex-Far. (a) SAXS profiles for the bulk samples thermally annealed at 80 °C for 6 h revealed $d = 4\text{--}6$ nm microphase separation. (b) AFM height image, and (c) corresponding cross-sectional profiles of the as-cast Glc₁-hex-Far thin film confirmed the horizontally orientated LAM formation in ~ 4 nm-thick layers.

2.3.5 Microphase-Separation Behavior of Sugar–Terpenoid BCO Systems

One of the most important findings of this study is that the resulting BCO morphology varies from HEX to GYR and finally to LAM with increasing f_{sugar} , as summarized in the conceptual phase diagram (**Figure 2.6**). Note that the author tentatively employed the total number of glucose and isoprene units ($\text{DP}_{\text{Glc}} + \text{DP}_{\text{isoprene}}$) as the phase-diagram vertical axis because it is highly challenging to determine χ and N for the present BCO system. The observed propensity is consistent with the conventional BCP microphase separation theory.³⁵ In other words, the desired morphology and feature size can both be achieved by simply adjusting the number of BCO glucose and isoprene units, which is analogous to the molecular design of conventional BCPs based on f and N . Unfortunately, however, spherical morphology could not be obtained from the current combination of oligosaccharides and terpenoids. The fact that the most asymmetric Glc₁-hex-Sol formed a cylindrical morphology implies the difficulty in obtaining spherical morphologies by the current molecular design.

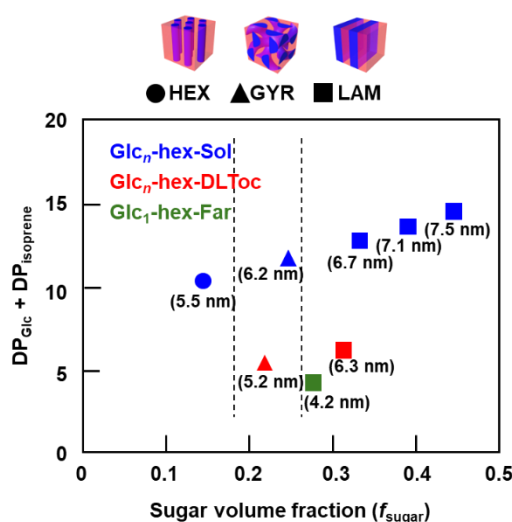


Figure 2.6. BCO-microphase-separation conceptual phase diagram generated for the phase-separated Glc_n-hex-Sol ($n = 1$ –5; blue), Glc_n-hex-DLToc ($n = 1$ and 2; red), and Glc₁-hex-Far (green) bulk morphologies. Values in parentheses are the d values listed in **Table 2.1**. The vertical and horizontal axes represent the sum of glucose and isoprene DPs and the saccharide volume fraction, respectively.

Here, an important question arises regarding the driving force for nanostructural formation, whereby it could be considered whether the observed morphologies originate from microphase separation or liquid crystalline formation. Indeed, the BCOs exhibit similar chemical structures to those of sugar lipids that are able to form both thermotropic and lyotropic liquid crystalline mesophases.^{38,39} In addition, Hillmyer recently reported a sugar-based amphiphile that could thermotropic liquid crystalline self-assembly to LAM nanostructures with a d of 3.5 nm.⁴⁰ In contrast, according to the previously described BCP-like phase behavior, nanostructural formation in the BCO system is highly possible driven by microphase separation. To eliminate the possibility of liquid crystalline behaviors, the author performed differential scanning calorimetry (DSC) analysis. Although the BCO DSC thermograms did not exhibit any transitions due to crystallization and melting during the first cooling and second heating processes, they did exhibit two baseline shifts corresponding to T_g s for the solanesol and sugar segments (**Figure S2.21**). Such thermal behavior is typical for microphase-separated BCPs.³¹ These results therefore confirmed that nanostructural formations in the oligosaccharide/terpenoid BCO system are driven by the microphase separation of highly immiscible sugar and terpenoid segments. However, it is still unclear what kind of chemical structural factors determine whether sugar lipid-like molecules behave like BCPs or liquid crystalline materials.^{41,42} At this moment, the author suspect that the BCP-like behavior of the sugar/terpenoid BCO system is related to the fact that both the constitutional segments are intrinsically difficult to crystallize, especially with the extremely high immiscibility between the two segments.

2.4 Conclusion

The author herein reported the development of a readily available monodisperse and discrete block co-oligomer (BCO) system consisting of hydrophilic sugars and hydrophobic terpenoids. Starting from readily available natural sugars and terpenoids with defined numbers of glucose and isoprene units, BCOs with the desired total degrees of polymerization (DPs) and compositions could be synthesized easily by connecting these blocks *via* a “click” reaction. The resulting BCOs self-assembled into well-ordered lamellar (LAM), gyroid (GYR), and hexagonally close-packed cylindrical (HEX) nanostructures and showed 4–8 nm periodicity through simple thermal annealing. The microphase-separated morphology shifted from cylindrical to GYR and finally to LAM upon increasing the number of glucose units (*i.e.*, the saccharide volume fraction) with a fixed hydrophobic segment length, analogous to well-established BCP phase behavior. Therefore, the desired BCO morphologies, features, and sizes can be achieved simply by changing the number of BCO glucose and isoprene units appropriately. Most importantly, the author developed a well-ordered microphase-separated structure showing 4.2 nm periodicity and 1.2 nm microdomain thickness, which is the smallest ever achieved from organic block copolymer (BCP)/BCO-based microphase-separated structures. Considering the commercial availability of all starting materials, the ease of BCO synthesis, and the facile BCO purification, the author believe that presented BCOs strongly contribute to accelerating applied research of solid and solution state self-assembly of discrete and monodisperse BCOs, which will inevitably expand their application scopes in various fields of not only the nanolithography but also organic devices, separation materials, coatings, etc.

2.5 References

1. Lazzari, M.; Liu, G.; Lecommandoux, S. *Block Copolymers in Nanoscience*, Wiley-VCH: Weinheim, 2006.
2. Olson, D. A.; Chen, L.; Hillmyer, M. A. Templating Nanoporous Polymers with Ordered Block Copolymers. *Chem. Mater.* **2008**, *20*, 869–890.
3. Kim, J. K.; Yang, S. Y.; Lee, Y.; Kim, Y. Functional Nanomaterials Based on Block Copolymer Self-Assembly. *Prog. Polym. Sci.* **2010**, *35*, 1325–1349.
4. Hu, H.; Gopinadhan, M.; Osuji, C. O. Directed Self-Assembly of Block Copolymers: A Tutorial Review of Strategies for Enabling Nanotechnology with Soft Matter. *Soft Matter* **2014**, *10*, 3867–3889.
5. Jeong, S.-J.; Kim, J. Y.; Kim, B. H.; Moon, H.-S.; Kim, S. O. Directed Self-Assembly of Block Copolymers for Next Generation Nanolithography. *Materials Today* **2013**, *16*, 468–476.
6. Stoykovich, M. P.; Kang, H.; Daoulas, K. C.; Liu, G.; Liu, C.-C.; de Pablo, J. J.; Müller, M.; Nealey, P. F. Directed Self-Assembly of Block Copolymers for Nanolithography: Fabrication of Isolated Features and Essential Integrated Circuit Geometries. *ACS Nano* **2007**, *3*, 168–175.
7. Tang, C.; Lennon, E. M.; Fredrickson, G. H.; Kramer, E. J.; Hawker, C. J. Evolution of Block Copolymer Lithography to Highly Ordered Square Arrays, *Science* **2008**, *322*, 429–432.
8. Cheng, J. Y.; Ross, C. A.; Smith, H. I.; Thomas, E. L. Templated Self-Assembly of Block Copolymers: Top-Down Helps Bottom-Up. *Adv. Mater.* **2006**, *18*, 2505–2521.

9. Sinturel, C.; Bates, F. S.; Hillmyer, M. A. High χ –Low N Block Polymers: How Far Can We Go? *ACS Macro Lett.* **2015**, *4*, 1044–1050.
10. Kennemur, J. G.; Yao, L.; Bates, F. S.; Hillmyer, M. A. Sub-5 nm Domains in Ordered Poly(cyclohexylethylene)-*block*-poly(methyl methacrylate) Block Polymers for Lithography. *Macromolecules* **2014**, *47*, 1411–1418.
11. Luo, Y.; Montarnal, D.; Kim, S.; Shi, W.; Barteau, K.; Pester, C. W.; Hustad, P. D.; Christianson, M. D.; Fredrickson, G. H.; Kramer, E. J.; Hawker, C. J. Poly(dimethylsiloxane-*b*-methyl methacrylate): A Promising Candidate for Sub-10 nm Patterning. *Macromolecules* **2015**, *48*, 3422–3430.
12. Kanimozhi, C.; Kim, M.; Larson, S. R.; Choi, J. W.; Choo, Y.; Sweat, D. P.; Osuji, C. O.; Gopalan, P. Isomeric Effect Enabled Thermally Driven Self-Assembly of Hydroxystyrene-Based Block Copolymers. *ACS Macro Lett.* **2016**, *5*, 833–838.
13. Jeong, G.; Yu, D. M.; Mapas, J. K. D.; Sun, Z.; Rzyayev, J.; Russell, T. P. Realizing 5.4 nm Full Pitch Lamellar Microdomains by a Solid-State Transformation. *Macromolecules* **2017**, *50*, 7148–7154.
14. Kwak, J.; Mishra, A. K.; Lee, J.; Lee, K. S.; Choi, C.; Maiti, S.; Kim, M.; Kim, J. K. Fabrication of Sub-3 nm Feature Size Based on Block Copolymer Self-Assembly for Next-Generation Nanolithography. *Macromolecules* **2017**, *50*, 6813–6818.
15. Azuma, K.; Sun, J.; Choo, Y.; Rokhlenko, Y.; Dwyer, J. H.; Schweitzer, B.; Hayakawa, T.; Osuji, C. O.; Gopalan, P. Self-Assembly of an Ultrahigh- χ Block Copolymer with Versatile Etch Selectivity. *Macromolecules* **2018**, *51*, 6460–6467.

16. Isono, T.; Kawakami, N.; Watanabe, K.; Yoshida, K.; Otsuka, I.; Mamiya, H.; Ito, H.; Yamamoto, T.; Tajima, K.; Borsali, R.; Satoh, T. Microphase Separation of Carbohydrate-Based Star-Block Copolymers with Sub-10 nm Periodicity. *Polym. Chem.* **2019**, *10*, 1119–1129.
17. Yu, X.; Yue, K.; Hsieh, I-F.; Li, Y.; Dong, X.-H.; Liu, C.; Xin, Y.; Wang, H.-F.; Shi, A.-C.; Newkome, G. R.; Ho, R.-M.; Chen, E.-Q.; Zhang, W.-B.; Cheng, S. Z. D. Giant Surfactants Provide a Versatile Platform for Sub-10-nm Nanostructure Engineering. *Proc. Natl. Acad. Sci. USA* **2013**, *110*, 10078–10083.
18. Lynd, N. A.; Meuler, A. J.; Hillmyer, M. A. Polydispersity and Block Copolymer Self-Assembly. *Prog. Polym. Sci.* **2008**, *33*, 875–893.
19. Jiao, G.-S.; Li, Y.; Qian, H.-J.; Lu, Z.-Y. Computer Simulation Study of Polydispersity Effect on the Phase Behavior of Short Diblock Copolymers. *Polymer* **2016**, *96*, 6–12.
20. Peters, A. J.; Lawson, R. A.; Dation, B. D.; Ludovice, P. J.; Henderson, C. L. Simulation study of the effect of molar mass dispersity on domain interfacial roughness in lamellae forming block copolymers for directed self-assembly. *Nanotechnology* **2015**, *26*, 385301
21. van Genabeek, B.; de Waal, B. F. M.; Ligt, B.; Palmans, A. R. A.; Meijer, E. W. Dispersity under Scrutiny: Phase Behavior Differences between Disperse and Discrete Low Molecular Weight Block Co-Oligomers. *ACS Macro Lett.* **2017**, *6*, 674–678.
22. Oschmann, B.; Lawrence, J.; Schulze, M. W.; Ren, J. M.; Anastasaki, A.; Luo, Y.; Nothling, M. D.; Pester, C. W.; Delaney, K. T.; Connal, L. A.; McGrath, A. J.; Clark,

- P. G.; Bates, C. M.; Hawker, C. J. Effects of Tailored Dispersity on the Self-Assembly of Dimethylsiloxane–Methyl Methacrylate Block Co-Oligomers. *ACS Macro Lett.* **2017**, *6*, 668–673.
23. van Genabeek, B.; de Waal, B. F. M.; Gosens, M. M. J.; Pitet, L. M.; Palmans, A. R. A.; Meijer, E. W. Synthesis and Self-Assembly of Discrete Dimethylsiloxane–Lactic Acid Diblock Co-oligomers: The Dononacotamer and Its Shorter Homologues. *J. Am. Chem. Soc.* **2016**, *138*, 4210–4218.
24. Jiang, Y.; Golder, M. R.; Nguyen, H. V.-T.; Wang, Y.; Zhong, M.; Barnes, J. C.; Ehrlich, D. J. C.; Johnson, J. A. Iterative Exponential Growth Synthesis and Assembly of Uniform Diblock Copolymers. *J. Am. Chem. Soc.* **2016**, *138*, 9369–9372.
25. Golder, M. R.; Jiang, Y.; Teichen, P. E.; Nguyen, H. V.-T.; Wang, W.; Milos, N.; Freedman, S. A.; Willard, A. P.; Johnson, J. A. Stereochemical Sequence Dictates Unimolecular Diblock Copolymer Assembly. *J. Am. Chem. Soc.* **2018**, *140*, 1596–1599.
26. Otsuka, I.; Isono, T.; Rochas, C.; Halila, S.; Fort, S.; Satoh, T.; Kakuchi, T.; Borsali, R. 10 nm Scale Cylinder–Cubic Phase Transition Induced by Caramelization in Sugar-Based Block Copolymers. *ACS Macro Lett.* **2012**, *1*, 1379–1382.
27. Isono, T.; Ree, B. J.; Tajima, K.; Borsali, R.; Satoh, T. Highly Ordered Cylinder Morphologies with 10 nm Scale Periodicity in Biomass-Based Block Copolymers. *Macromolecules* **2018**, *51*, 428–437.
28. Liao, Y.; Chen, W.-C.; Borsali, R. Carbohydrate-Based Block Copolymer Thin Films: Ultrafast Nano-Organization with 7 nm Resolution Using Microwave Energy.

Oligosaccharide/Silicon-Containing Block Copolymers with 5 nm Features for Lithographic Applications. *Adv. Mater.* **2017**, 20, 1701645.

29. Cushen, J. D.; Otsuka, I.; Bates, C. M.; Fort, S.; Rochas, C.; Easley, J. A.; Rausch, E. L.; Thio, A.; Borsali, R.; Willson, C. G.; Ellison, C. J. Oligosaccharide/Silicon-Containing Block Copolymers with 5 nm Features for Lithographic Applications. *ACS Nano* **2012**, 6, 3424–3433.
30. Otsuka, I.; Zhang, Y.; Isono, T.; Rochas, C.; Kakuchi, T.; Satoh, T.; Borsali, R. Sub-10 nm Scale Nanostructures in Self-Organized Linear Di- and Triblock Copolymers and Miktoarm Star Copolymers Consisting of Maltoheptaose and Polystyrene. *Macromolecules* **2015**, 48, 1509–1517.
31. Nowak, S. R.; Hwang, W.; Sita, L. R. Dynamic Sub-10-nm Nanostructured Ultrathin Films of Sugar–Polyolefin Conjugates Thermoresponsive at Physiological Temperatures. *J. Am. Chem. Soc.* **2017**, 139, 5281–5284.
32. Isono, T.; Kawakami, N.; Watanabe, K.; Yoshida, K.; Otsuka, I.; Mamiya, H.; Ito, H.; Yamamoto, T. Tajima, K.; Borsali, R.; Satoh, T. Microphase Separation of Carbohydrate-Based Star-Block Copolymers with Sub-10 nm Periodicity. *Polym. Chem.* **2019**, 1119–1129.
33. Gan, K. P.; Yoshio, M.; Sugihara, Y.; Kato, T. Guanine–oligothiophene conjugates: Liquid-Crystalline Properties, Photoconductivities and Ion-Responsive Emission of Their Nanoscale Assemblies. *Chem. Sci.* **2018**, 9, 576–585.
34. Poppe, M.; Chen, C.; Liu, F.; Poppe, S.; Tschierske, C. Formation of a Cubic Liquid Crystalline Nanostructure with π -Conjugated Fluorinated Rods on the Gyroid Minimal Surface. *Chem. Eur. J.* **2017**, 23, 7196–7200.

35. Bates, F. S.; Fredrickson, G. H. Block Copolymers—Designer Soft Materials. *Physics Today* **1999**, 52, 32–38.
36. Imamura, K.; Sakaura, K.; Ohyama, K.-i.; Fukushima, A.; Imanaka, H.; Sakiyama, T.; Nakanishi, K. Temperature Scanning FTIR Analysis of Hydrogen Bonding States of Various Saccharides in Amorphous Matrixes below and above Their Glass Transition Temperatures. *J. Phys. Chem. B* **2006**, 110, 15094–15099.
37. Hancox, E.; Liarou, E.; Town, J. S.; Jones, G. R.; Layton, S. A.; Huband, S.; Greenall, M. J.; Topham, P. D.; Haddleton, D. M. Microphase separation of highly amphiphilic, low *N* polymers by photoinduced copper-mediated polymerization, achieving sub-2 nm domains at half-pitch *Polym. Chem.* **2019**, 10, 6254–6259.
38. Goodby, J. W.; Görtz, V.; Cowling, S. J.; Mackenzie, G.; Martin, P.; Plusquellec, D.; Benvegun, T.; Boullanger, P.; Queneau, Y.; Chamber, S.; Fitremann, J. Thermotropic Liquid Crystalline Glycolipids. *Chem. Soc. Rev.* **2007**, 36, 1971.
39. Vill, V.; Hashim, R. Carbohydrate Liquid Crystals: Structure–Property Relationship of Thermotropic and Lyotropic Glycolipid. *Curr. Opin. Colloid Interface Sci.* **2002**, 7, 395–409.
40. Barreda, L.; Shen, Z.; Chen, Q. P.; Lodge, T. P.; Siepmann, J. I.; Hillmyer, M. A. Synthesis, Simulation, and Self-Assembly of a Model Amphiphile To Push the Limits of Block Polymer Nanopatterning. *Nano Lett.* **2019**, 19, 4458–4462.
41. Lamers, B. A. G.; Graf, R.; de Waal, B. F. M.; Vantomme, G.; Palmans, A. R. A.; Meijer, E. W. Polymorphism in the Assembly of Phase-Segregated Block Molecules: Pathway Control to 1D and 2D Nanostructures. *J. Am. Chem. Soc.* **2019**, 141, 15456–15463.

42. Zha, R. H.; de Waal, B. F. M.; Lutz, M.; Teunissen, A. J. P.; Meijer, E. W. End Groups of Functionalized Siloxane Oligomers Direct Block-Copolymeric or Liquid-Crystalline Self-Assembly Behavior. *J. Am. Chem. Soc.* **2016**, *138*, 5693–5698.
43. Grandjean, C.; Boutonnier, A.; Guerreiro, C.; Fournier, J.-M.; Mulard, L. A. On the Preparation of Carbohydrate–Protein Conjugates Using the Traceless Staudinger Ligation. *J. Org. Chem.* **2005**, *70*, 7123–7132.
44. Daly, R.; Vaz, G.; Davies, A. M.; Senge, M. O.; Scanlan, E. M. Synthesis and Biological Evaluation of a Library of Glycoporphyrin Compounds. *Chem. Eur. J.* **2012**, *18*, 14671–14679.
45. Post, E. A. J.; Fletcher, S. P. Controlling the Kinetics of Self-Reproducing Micelles by Catalyst Compartmentalization in a Biphasic System. *J. Org. Chem.* **2019**, *84*, 2741–2755.
46. Yoshida, K.; Tanaka, S.; Yamamoto, T.; Tajima, K.; Borsali, R.; Isono, T.; Satoh, T. Chain-End Functionalization with a Saccharide for 10 nm Microphase Separation: "classical" PS-*b*-PMMA versus PS-*b*-PMMA-Saccharide. *Macromolecules* **2018**, *51*, 8870–8877.
47. Otsuka, I.; Fuchise, K.; Halila, S.; Fort, S.; Aissou, K.; Pignot-Paintrand, I.; Chen, Y.; Narumi, A.; Kakuchi, T.; Borsali, R. Thermoresponsive Vesicular Morphologies obtained by Self-Assemblies of Hybrid Oligosaccharide-*block*-poly(N-isopropylacrylamide) Copolymer Systems. *Langmuir* **2010**, *26*, 2325–2332.

2.6 Supporting Information

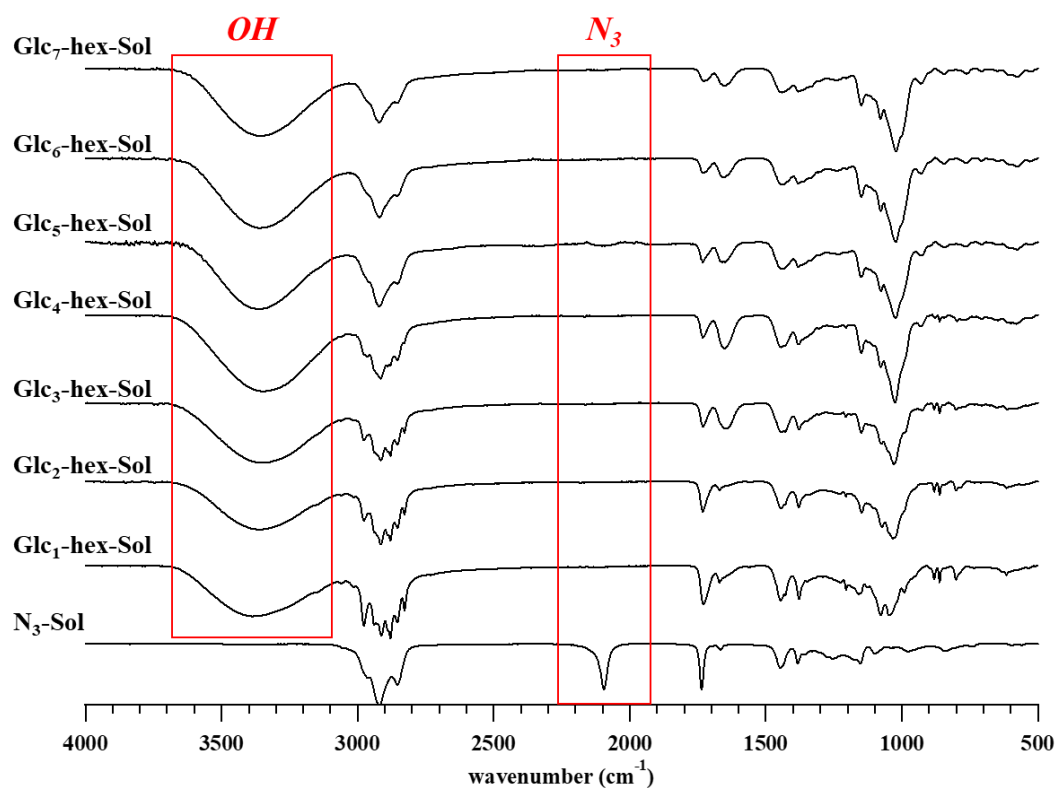


Figure S2.1. FT-IR spectra of N_3 -hex-Sol and Glc_n -hex-Sol ($n = 1-7$).

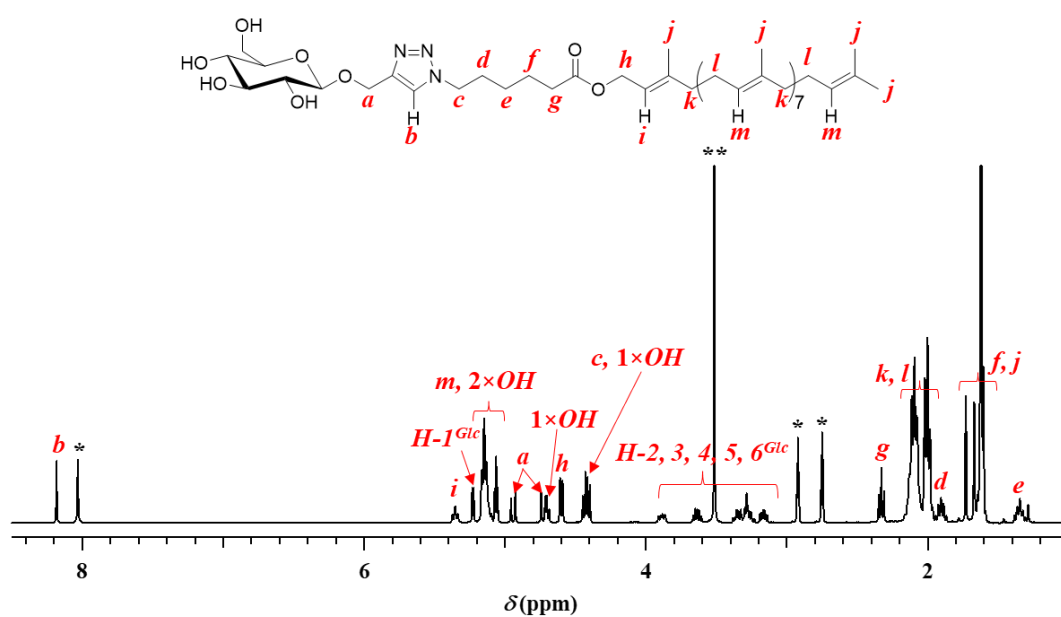


Figure S2.2. ^1H NMR spectrum of Glc_1 -hex-Sol ($\text{DMF-}d_7$, 400 MHz).

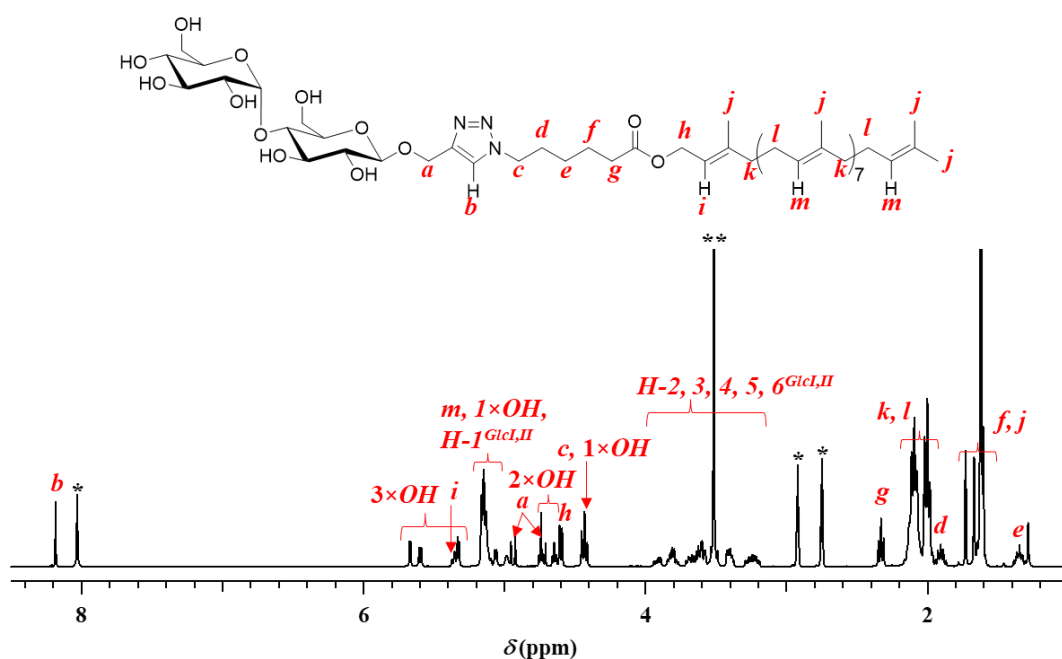


Figure S2.3. ^1H NMR spectrum of Glc₂-hex-Sol (DMF- d_7 , 400 MHz).

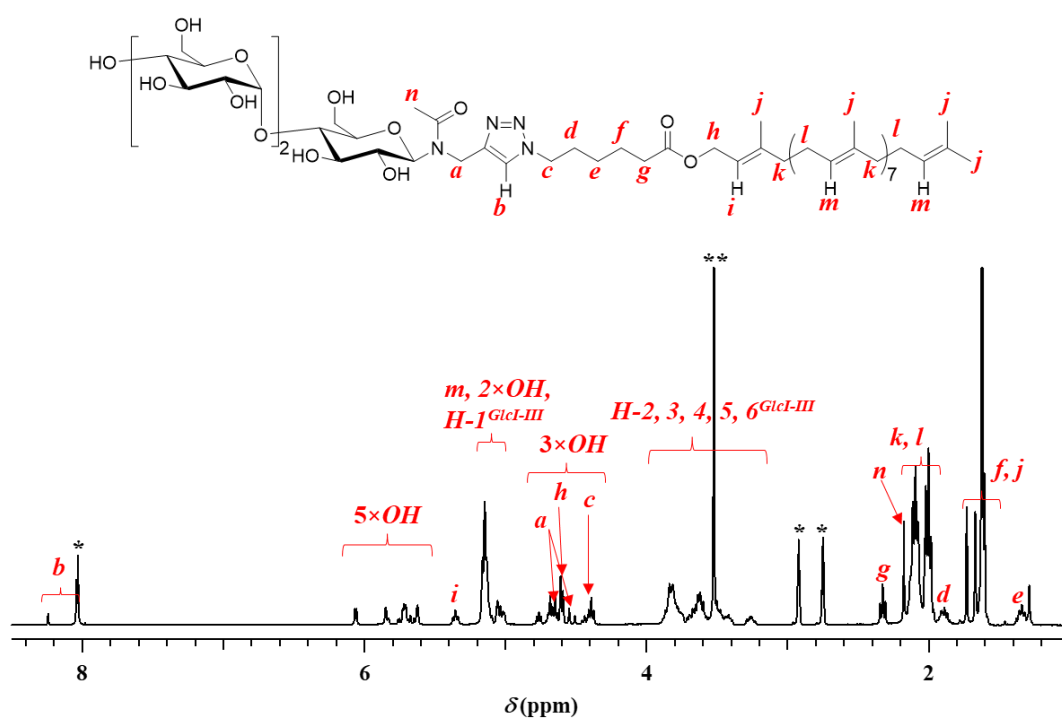


Figure S2.4. ^1H NMR spectrum of Glc₃-hex-Sol (DMF- d_7 , 400 MHz).

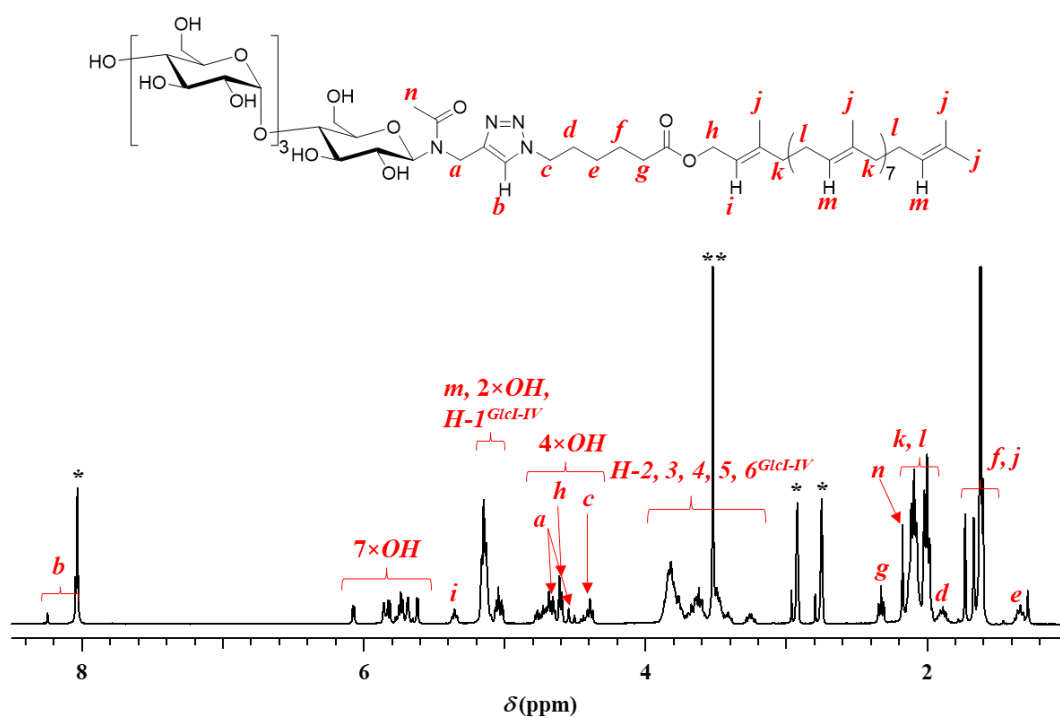


Figure S2.5. ^1H NMR spectrum of Glc4-hex-Sol (DMF- d_7 , 400 MHz).

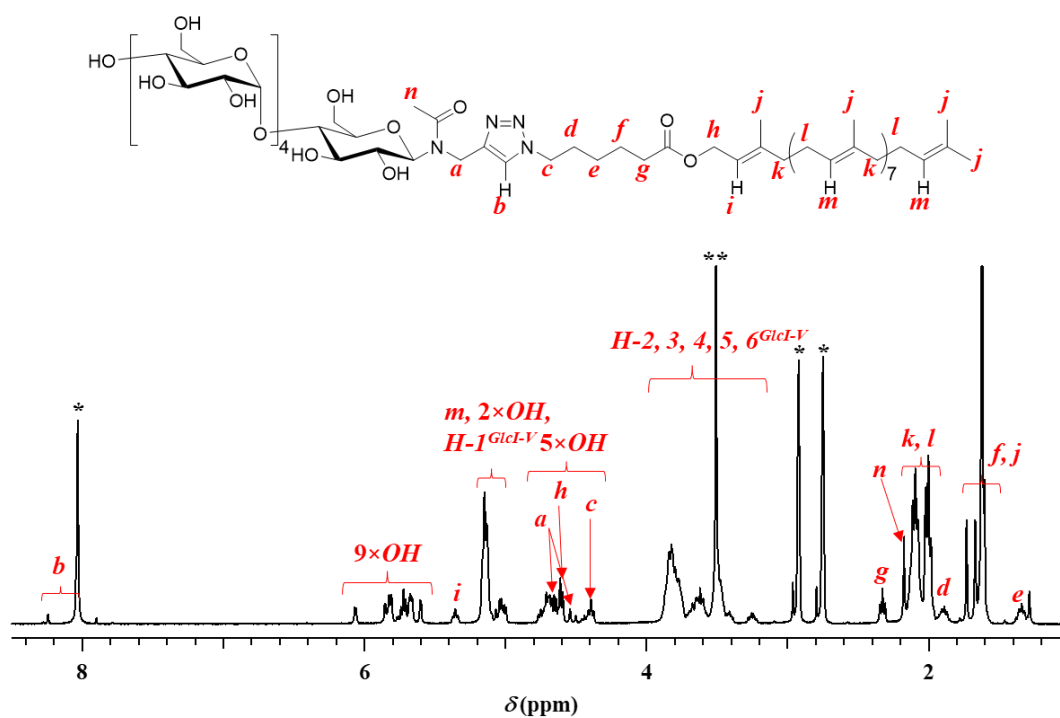


Figure S2.6. ^1H NMR spectrum of Glc5-hex-Sol (DMF- d_7 , 400 MHz).

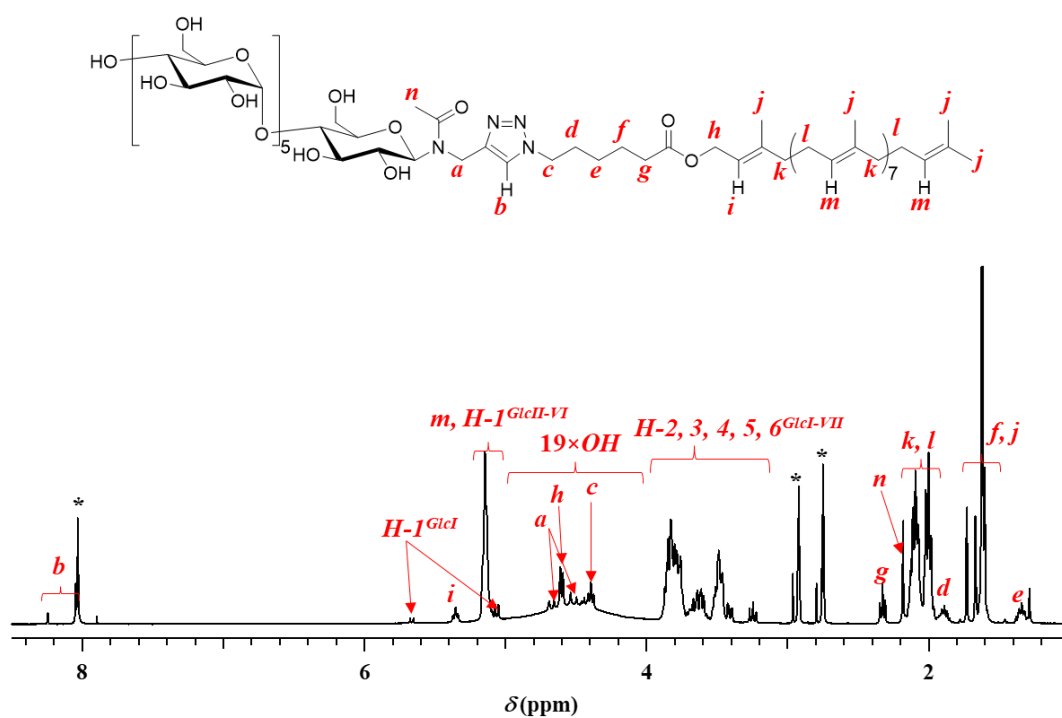


Figure S2.7. ^1H NMR spectrum of Glc₆-hex-Sol (DMF- d_7 , 400 MHz).

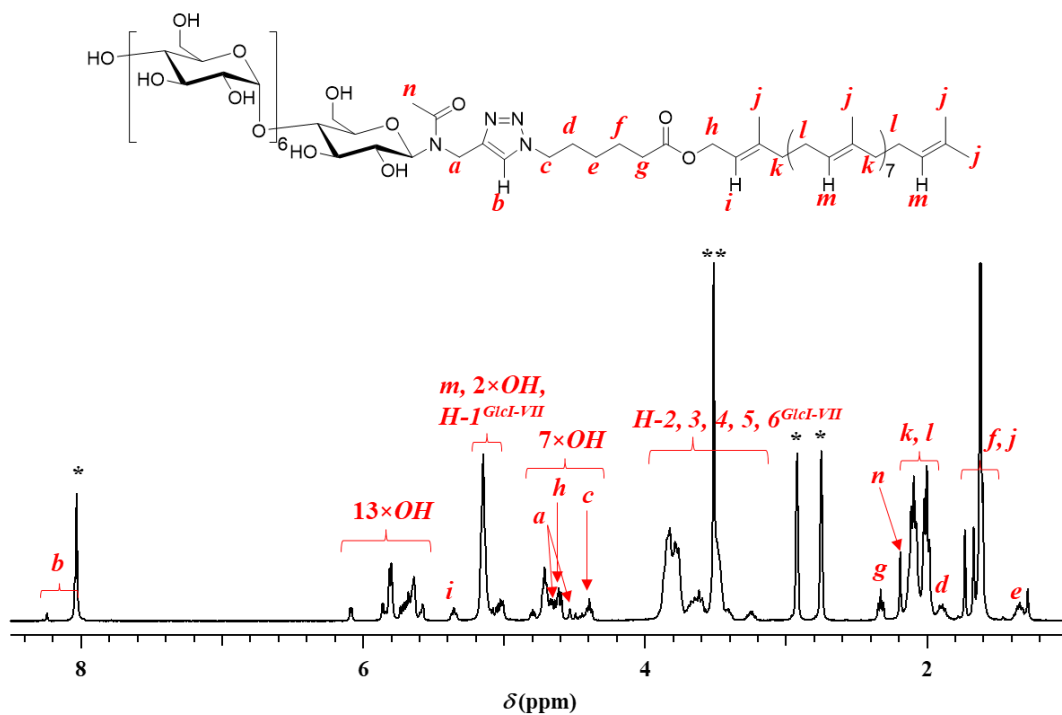


Figure S2.8. ^1H NMR spectrum of Glc₇-hex-Sol (DMF- d_7 , 400 MHz).

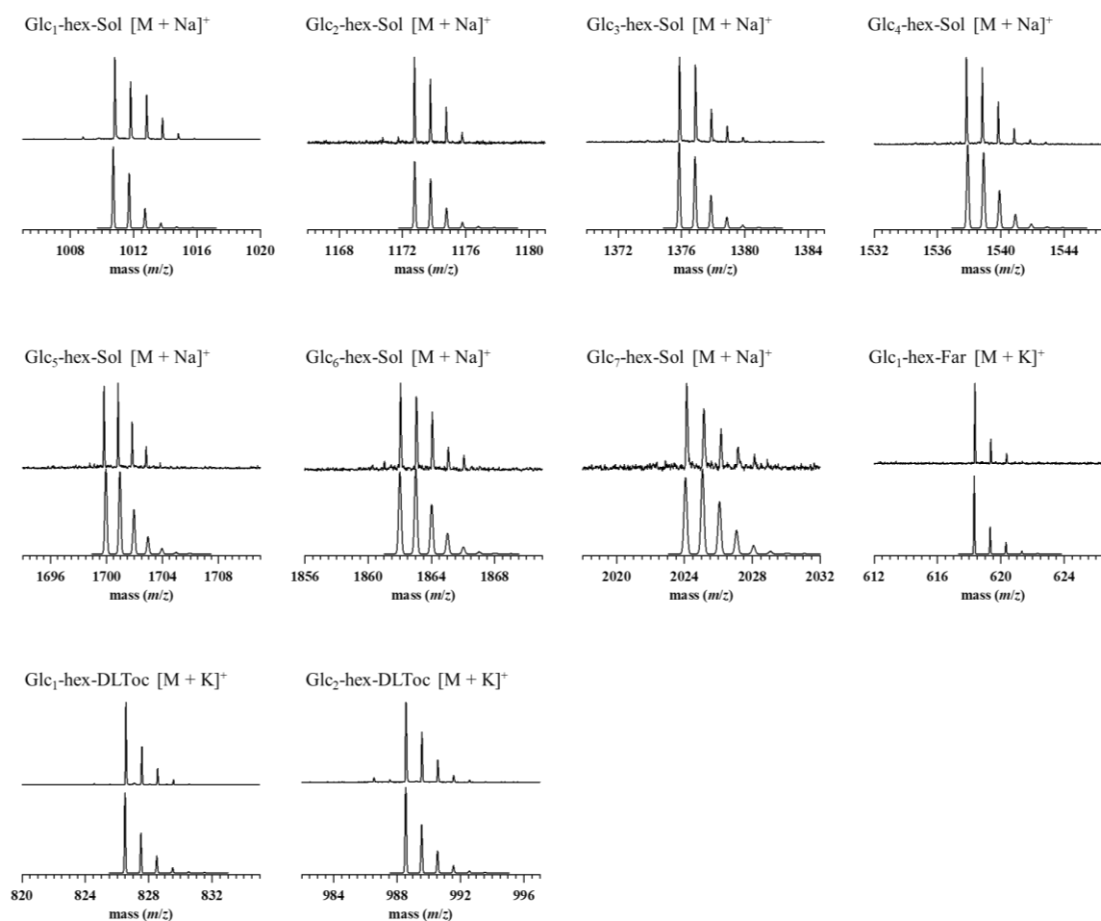


Figure S2.9. Isotope distributions of the MALDI-TOF mass spectra of $\text{Glc}_n\text{-hex-Sol}$ ($n = 1\text{--}7$; sodium adduct), $\text{Glc}_1\text{-hex-Far}$ (potassium adduct), and $\text{Glc}_n\text{-hex-DLToc}$ ($n = 1$ and 2 ; potassium adduct). The upper and lower represent the experimental and simulated spectra, respectively.

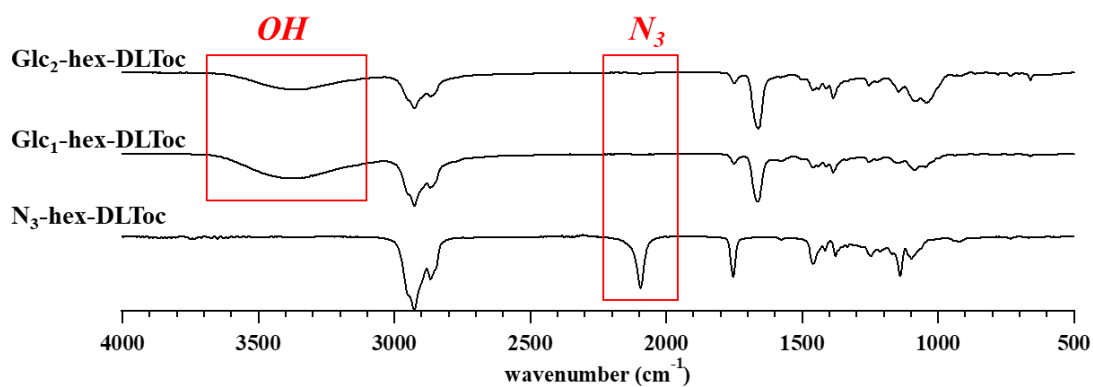


Figure S2.10. FT-IR spectra of $\text{N}_3\text{-hex-DLToc}$ and $\text{Glc}_n\text{-hex-DLToc}$ ($n = 1$ and 2).

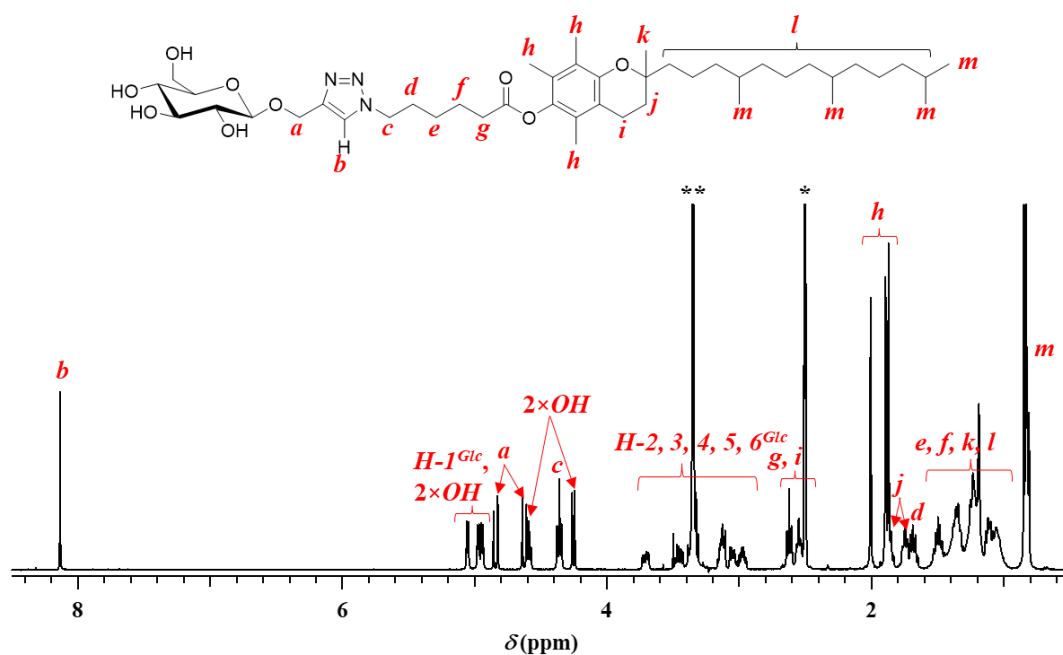


Figure S2.11. ^1H NMR spectrum of Glc₁-hex-DLToc (DMSO- d_6 , 400 MHz).

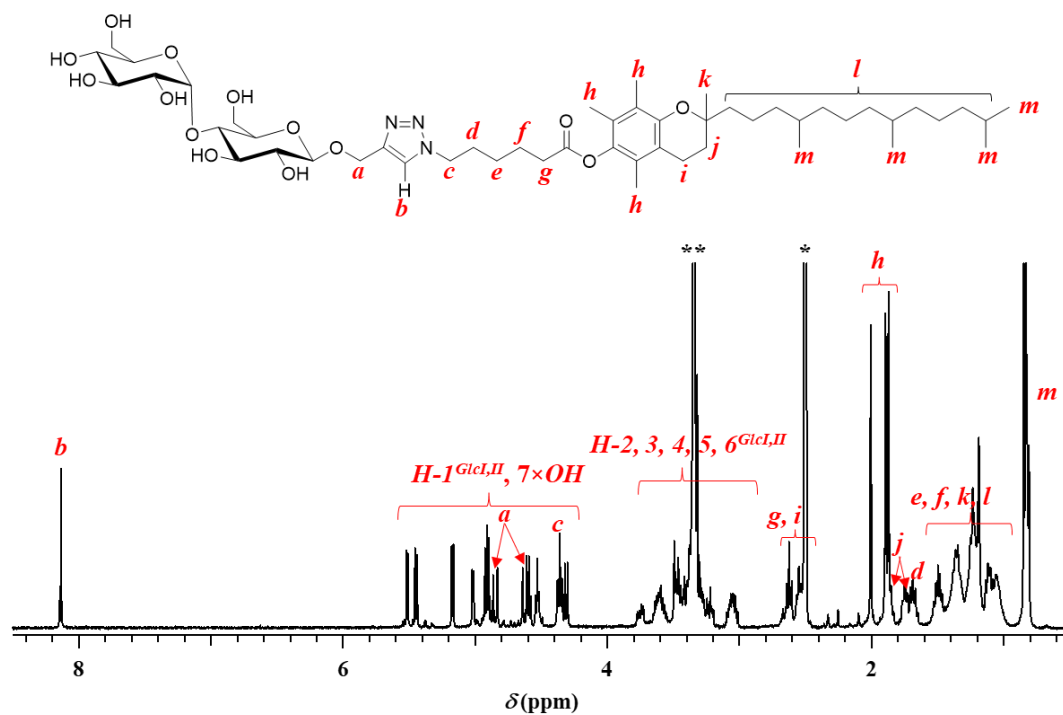


Figure S2.12. ^1H NMR spectrum of Glc₂-hex-DLToc (DMSO- d_6 , 400 MHz).

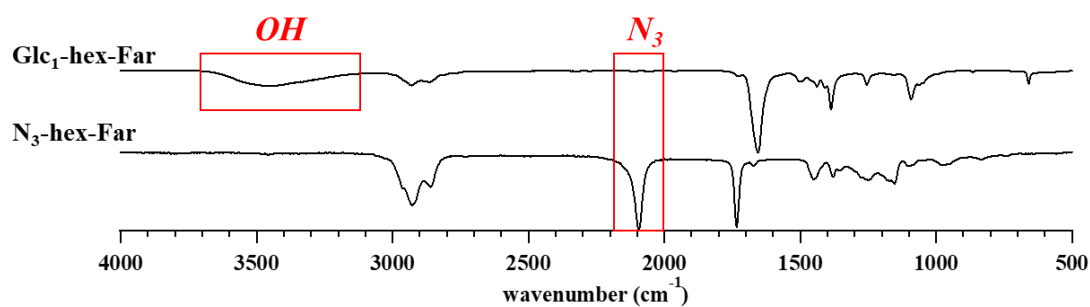


Figure S2.13. FT-IR spectra of N_3 -hex-Far and Glc_1 -hex-Far.

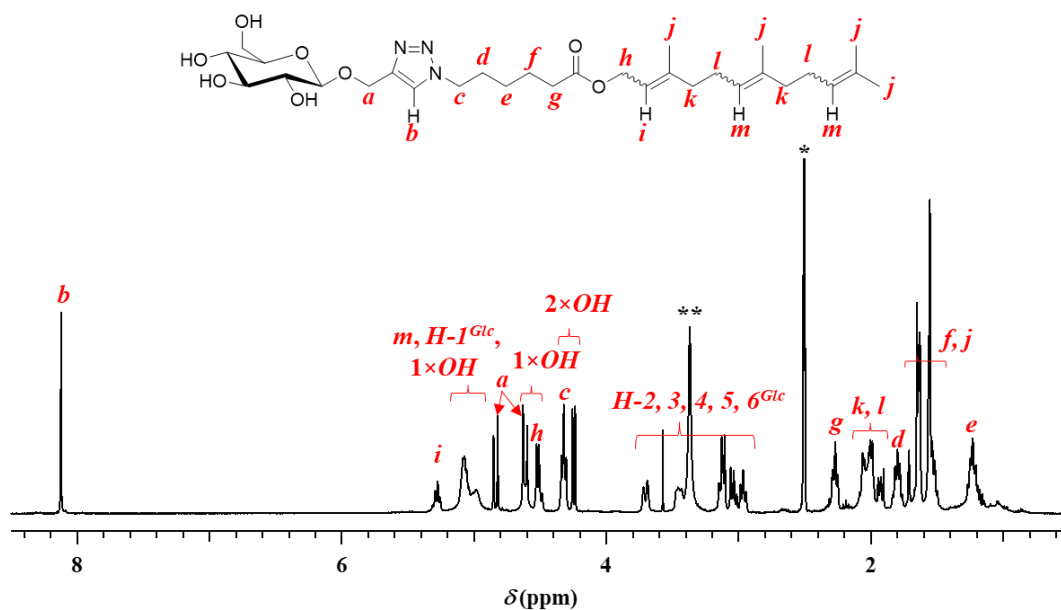


Figure S2.14. ^1H NMR spectrum of Glc_1 -hex-Far ($\text{DMSO-}d_6$, 400 MHz).

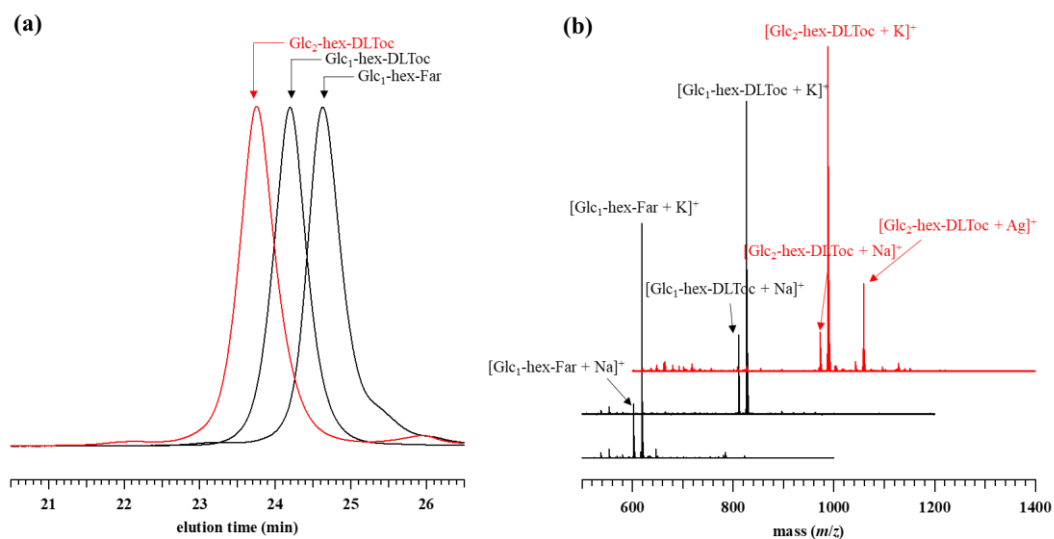


Figure S2.15. (a) SEC traces (eluent, DMF containing 0.01 M LiCl) and (b) MALDI-TOF mass spectra of Glc_1 -hex-Far and Glc_n -hex-DLToc ($n = 1$ and 2).

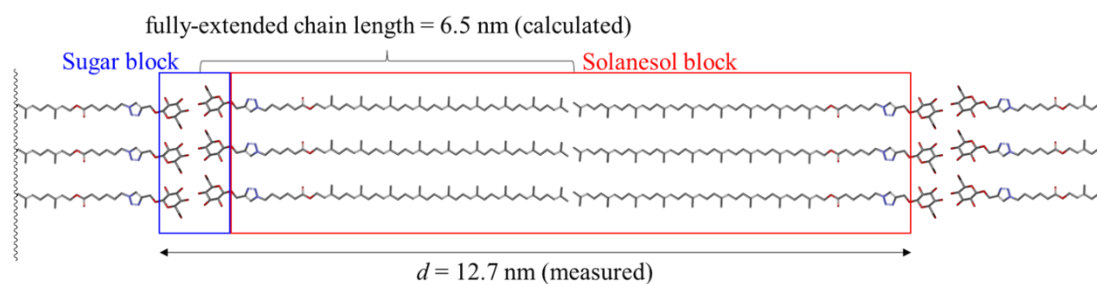


Figure S2.16. Schematic illustration for a possible molecular packing of Glc₁-hex-Sol molecules in the lamellar morphology. Since the fully-extended chain length of Glc₁-hex-Sol is ca. 6.5 nm, Glc₁-hex-Sol molecules seem to be crystallized as a dimer in a head-to-head configuration.

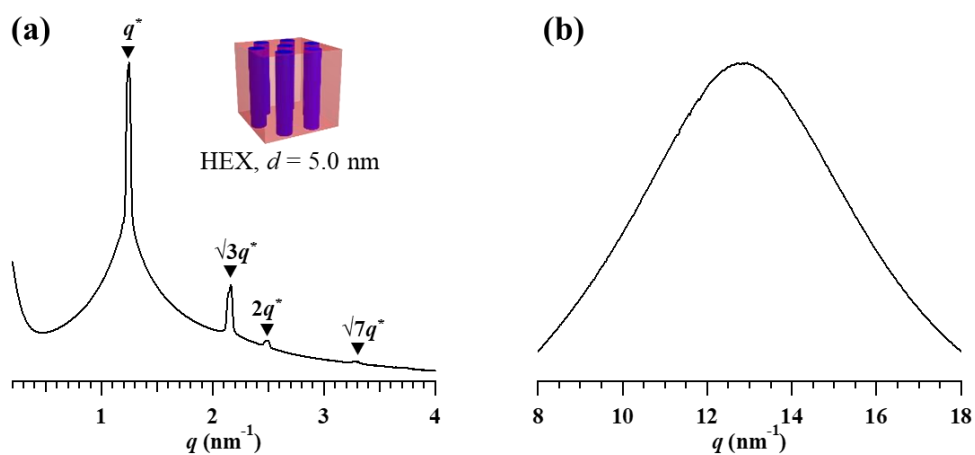


Figure S2.17. (a) *In-situ* SAXS and (b) WAXS profiles of Glc₁-hex-Sol measured at 180 °C.

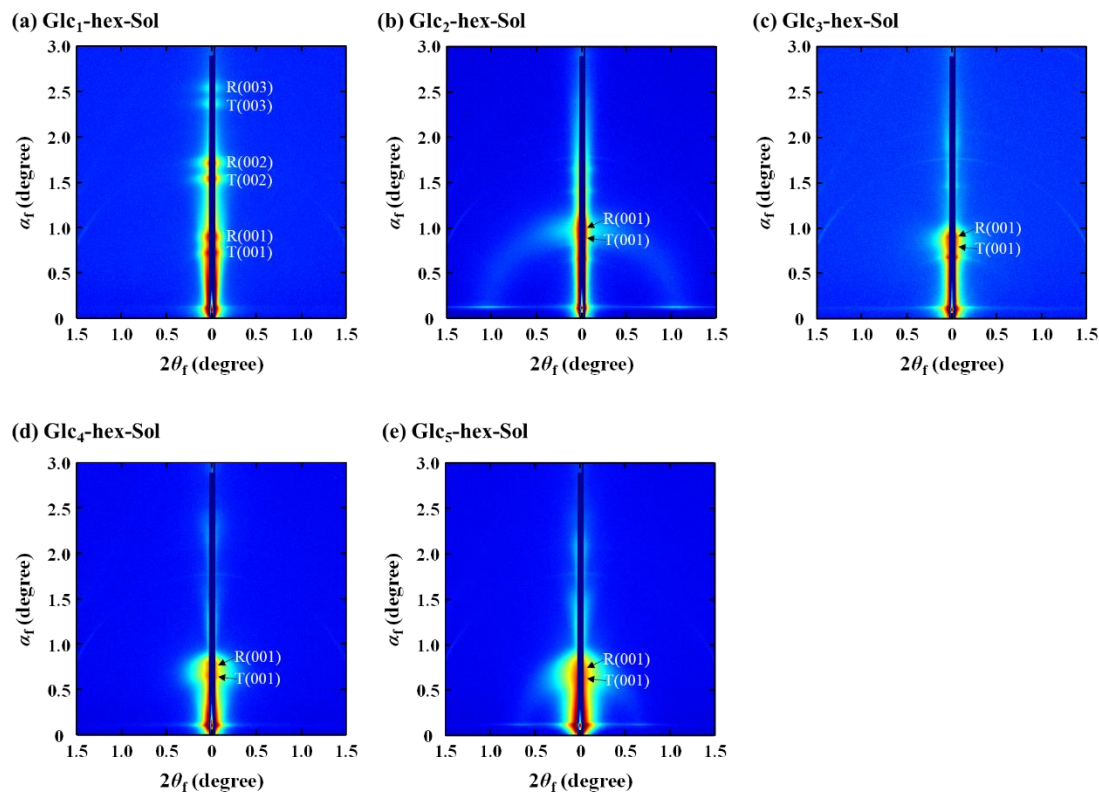


Figure S2.18. GISAXS data of $\text{Glc}_n\text{-hex-Sol}$ ($n = 1 - 5$) thin films after thermal annealing for 1 h (130 °C for $\text{Glc}_1\text{-hex-Sol}$, $\text{Glc}_4\text{-hex-Sol}$, and $\text{Glc}_5\text{-hex-Sol}$; 85 °C for $\text{Glc}_2\text{-hex-Sol}$ and $\text{Glc}_3\text{-hex-Sol}$).

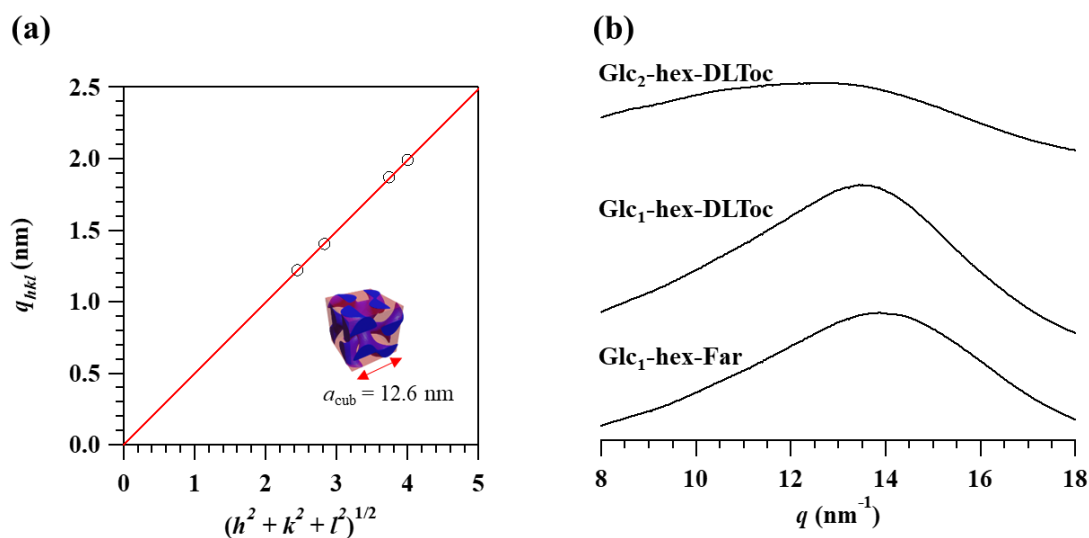


Figure S2.19. (a) A q_{hkl} versus $(h^2 + k^2 + l^2)^{1/2}$ plot based on the SAXS pattern observed in $\text{Glc}_1\text{-hex-DLToc}$. (b) WAXS profiles of (a) $\text{Glc}_1\text{-hex-Far}$, (b) $\text{Glc}_1\text{-hex-DLToc}$, and (c) $\text{Glc}_2\text{-hex-DLToc}$ after thermal annealing at 80 °C for 6 h.

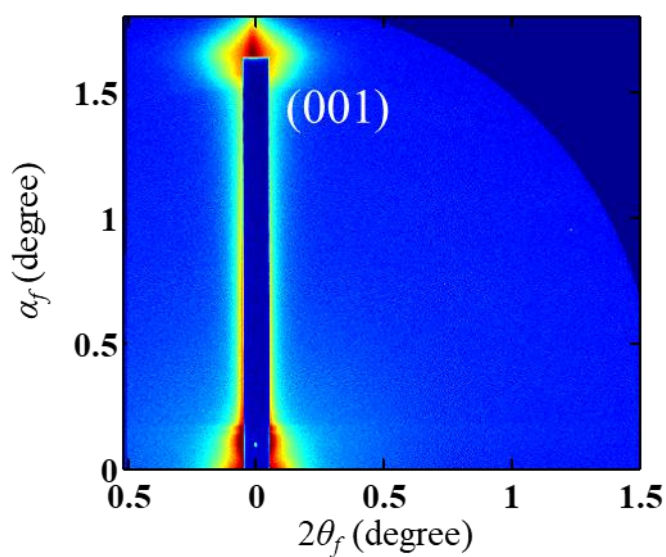


Figure S2.20. GISAXS profiles of as-cast Glc₁-hex-Far thin film.

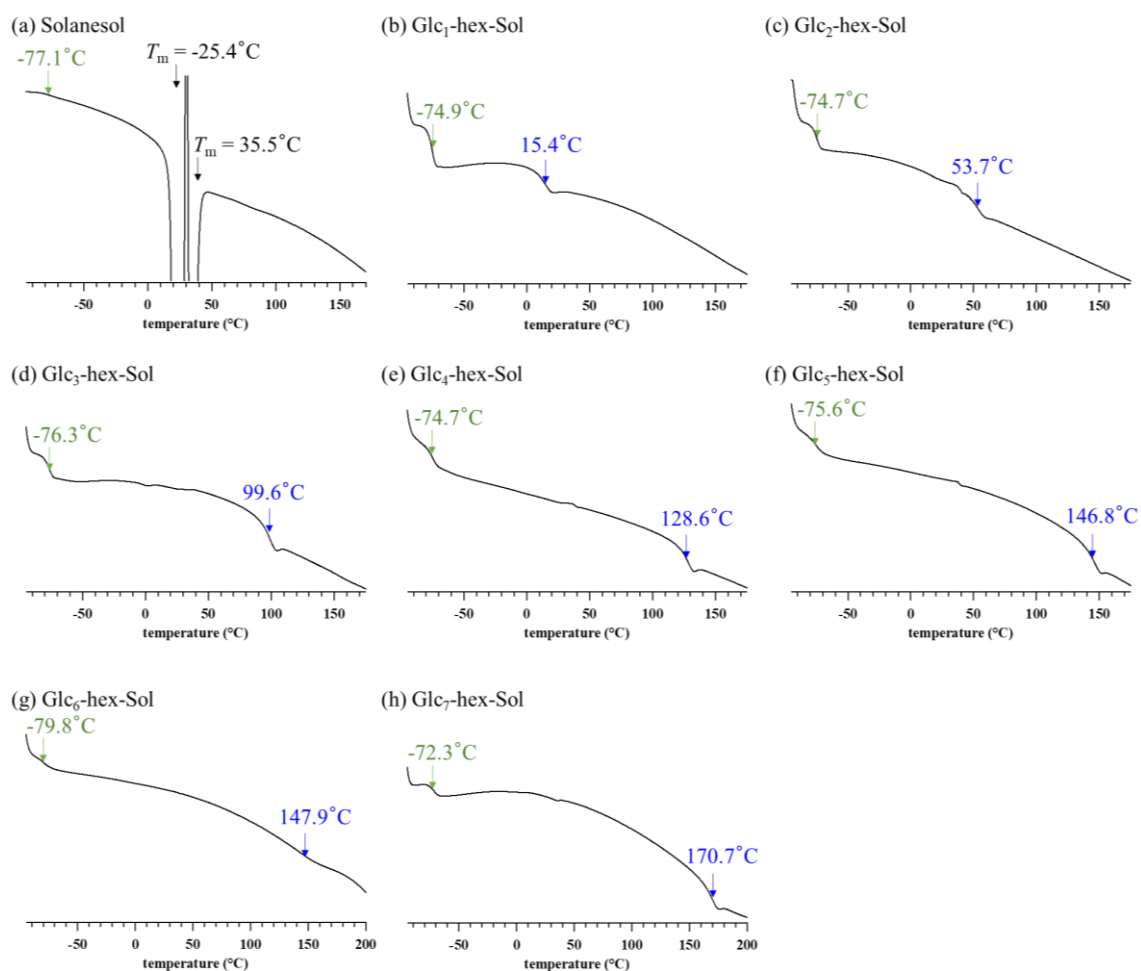


Figure S2.21. DSC traces of solanesol and Glc_{*n*}-hex-Sol (*n* = 1–7) during the second heating run (heating and cooling rate, $10^\circ\text{C min}^{-1}$).

Chapter 3

*Three-Dimensional Network
Microphase-Separation Morphologies with
Sugar–Terpenoid Block Co-oligomers*

3.1 Introduction

Block copolymers (BCPs), which consist of two chemically different block chains connected by a covalent bond, self-assemble to form microphase-separated structures with a nanoscale periodicity due to immiscible nature of the two blocks.^{1–4} According to the theoretical phase diagram based on the self-consistent field theory, a specific desired morphology can be realized by adjusting the volume fraction (f) and the segregation strength between the constituent blocks given by the product of the Flory–Huggins parameter (χ) and the degree of polymerization (N), i.e., χN . Typical morphologies include lamellae (LAM), hexagonally packed cylinders (HEX), and body-centered cubic (BCC) spheres, and the periodicities of these structures (i.e., their domain spacings, d) are known to range from a few to hundreds of nanometers, depending on the value of N . These nanostructures created by BCP are promising materials for various nanofabrication applications. For example, LAM structures vertically aligned to semiconductor substrates can be applied as lithographic masks to fabricate integrated circuits with line-and-space patterns.^{5–8} Additionally, vertically aligned HEX structures can be applied as templates for fabricating holes and pillars on a substrate through etching or infiltration processes.^{9,10}

Among the microphase-separated structures that can be obtained from BCPs, three-dimensional (3D) network morphologies, such as the bicontinuous double gyroid (GYR),^{11–15} bicontinuous double diamond (OBDD),^{16–20} hexagonally perforated lamellae (HPL),^{14–16,21–25} or the *Fddd* structure,^{26–29} are particularly attractive in the context of nanofabrication applications. For example, the unique topological structure of the GYR renders it suitable for various use in catalysis,^{30,31} filtration membranes,^{32,33} drug carriers,^{34–36} photovoltaics,²⁸ photonic crystals,^{37,38} and Weyl materials.³⁹ More specifically, GYR-, OBDD-, and *Fddd*-forming BCPs containing a selectively degradable block can be utilized to create a nanoporous polymer with a continuous nanochannel,

which can be further applied as a template for fabricating nanoporous inorganic materials.^{28,40–44} On the other hand, HPL-forming BCP thin films can be utilized as ring-shaped nanotemplates on a substrate, as demonstrated in the fabrication of phase-change memory devices.^{25,45}

Despite the promising potential of 3D network morphologies in various application fields, the construction of such morphologies is challenging because of their relatively narrow phase window.⁴⁶ In addition, the majority of these 3D network morphologies are considered to be metastable and are therefore rarely observed.^{24,46,47} Thus, before thorough optimization of the annealing conditions, delicate control of the f and χN values is necessary for designing BCPs that can produce the desired morphologies.

Reducing d to less than 10 nm is another challenge to obtaining such a 3D network morphology. Specifically, the construction of structures with ultrafine d values is essential for achieving high-performance devices that require large specific surface areas. Since the d values of microphase-separated structures are scaled by $N^{2/3}\chi^{1/6}$ in the strong segregation regime, lowering N is an efficient way to reduce d . Nevertheless, microphase separation occurs only when χN exceeds a critical value (e.g., 10.5 for symmetric BCPs), thus the use of high χ and low N BCP systems that combine two low-molecular-weight segments with a large incompatibility is necessary to realize microphase separation with ultrafine d values. Indeed, a number of combinations of different polymers have been reported to realize the concept of high χ –low N BCPs. For example, a BCP comprising polystyrene and poly(4-vinylpyridine)propane-1-sulfonate with a molecular weight of 3.1 kg mol^{−1} yielded the LAM structure with a d value of 5.7 nm,⁴⁸ and a BCP consisting of polystyrene and polydimethylsiloxane with a molecular weight of 16 kg mol^{−1} generated the HEX structure with a d value of 8 nm.⁴⁹ Although a wide variety of high χ –low N BCPs have been reported in the past few years, most of resulting morphologies have been

limited to the conventional LAM and HEX structures, and only a handful of examples related to the GYR and HPL structures have been demonstrated.^{48,50–54} It would therefore be interesting to establish a novel molecular design principle for BCPs to produce a wide range of 3D network structures with sub-10 nm dimensions.

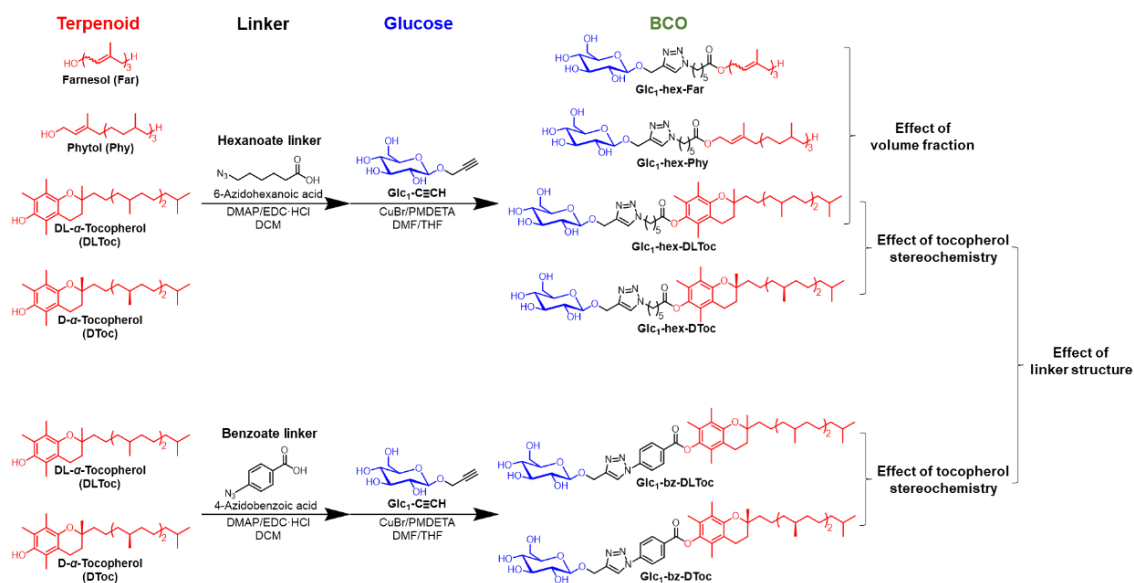
Saccharide-based high χ –low N BCP systems have been identified as promising platforms for constructing ultrasmall 3D network morphologies. In *Chapter 2*, the author introduced a strategy combining hydrophilic oligosaccharides and hydrophobic terpenoids to achieve strong segregation, enabling the formation of microphase-separated structures with d values as small as ~ 5 nm. More importantly, the author demonstrated the formation of the GYR structure with a cubic lattice parameter as small as 12.6 nm ($d_{211} = 5.2$ nm). This was accomplished using low-molecular-weight discrete block co-oligomers (BCOs) combined with hydrophilic oligosaccharides and hydrophobic terpenoid segments.⁵⁴ In another study, using several types of saccharide-*b*-polypropylene, Sita et al. obtained HPL structures with long axis periodicities (i.e., ~ 15 nm) and GYR structures with cubic lattice parameters of 12–14 nm.⁵² Moreover, some amphiphilic molecules consisting of sugar headgroup and alkyl chains, known as glycolipid, have been reported to exhibit thermotropic bicontinuous cubic liquid crystalline structures.^{55–57} In addition, by optimizing the molecular topology of the oligosaccharide–terpenoid BCOs, HPL and *Fddd* structures were achieved in the bulk state.⁵⁷ These earlier works suggest that saccharide-based low-molecular-weight BCPs (or BCOs) promising for exploring the molecular design principle that produces various 3D network structures with ultrasmall periodicities.

Thus, the author herein reports the microphase separation behavior of discrete linear BCOs consisting of glucose as the hydrophilic saccharide segment and short terpenoids as the hydrophobic segment, to determine the essential molecular parameters for creating

Three-Dimensional Network Microphase-Separation Morphologies with Sugar–Terpenoid Block Co-oligomers

ultrasmall 3D network morphologies. For this purpose, farnesol (Far), phytol (Phy), DL- α -tocopherol (DLToc), and D- α -tocopherol (DToc) are selected as the terpenoid blocks for combination with glucose to produce a series of discrete BCOs, namely Glc₁-hex-Far, Glc₁-hex-Phy, Glc₁-hex-DLToc, Glc₁-hex-DToc, Glc₁-bz-DLToc, and Glc₁-bz-DToc (**Scheme 3.1**). These terpenoids consist of three or four isoprene units and possess different molecular shapes; thus, precise control of the BCO volume fraction can be achieved. Here, two sets of BCOs with different types of bridging linkers between the blocks (i.e., hexanoate or benzoate linkers bearing pentylene or phenylene moieties) are synthesized to investigate the effect of the linker structure on the microphase separation behavior. Importantly, the sugar volume fraction (f_{sugar}) is fixed at ~ 0.3 to ensure the formation of a 3D network morphology. Morphological screening of the bulk state BCOs is then carried out using small-angle X-ray scattering (SAXS) to identify the GYR and HPL structures. Finally, the ability of these BCOs to form stable HPL morphologies in the thin film state is evaluated.

Scheme 3.1. Synthesis of the sugar–terpenoid BCOs



3.2 Experimental Section

3.2.1 Materials

Copper(I) bromide (CuBr; Sigma-Aldrich >99.995%), methanol (Sigma-Aldrich >99.8%), *N,N,N',N'',N'''*-pentamethyldiethylenetriamine (PMDETA; Tokyo Chemical Industry Co., Ltd. (TCI), >98.0%), farnesol (Far; TCI, >95.0%), DL- α -tocopherol (DLToc; TCI, >96.0%), D- α -tocopherol (DToc; TCI, >97.0%), 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDC·HCl; TCI, >98.0%), 4-dimethylaminopyridine (DMAP; TCI, >99.0%), sodium sulfate anhydrous (Na₂SO₄; TCI >99.0%), 4-azidobenzoic acid (TCI >97.0%), phytol (Phy; Wako Pure Chemical Co., =>100%), dichloromethane (CH₂Cl₂; Junsei Chemical Chemical Co., Ltd, >98.0%), anhydrous tetrahydrofuran (dry-THF, Kanto Chemical Co., Inc (Kanto), >99.5%; water content, <0.001%), anhydrous dimethylformamide (dry-DMF; Kanto, >99.5%; water content, <0.001%), and anhydrous CH₂Cl₂ (dry- CH₂Cl₂; Kanto, >99.5%; water content, <0.001%), *n*-hexane (Kanto, >95.0%), 2-propanol (Kanto, >99.7%), ethyl acetate (Kanto, >99.3%), and Silica gel 60N (Kanto, spherical neutral., particle size 63-210 μ m) were used as received. Hydrochloric acid (HCl; Kanto, 35.0–37.0%) was diluted to 1 N, and Dowex® 50WX2 hydrogen form (Sigma-Aldrich) was washed with MeOH before use. 6-Azido-1-hexanoic acid,⁵⁸ propargyl- β -D-glucopyranoside (Glc₁-C $\equiv$ CH),⁵⁹ Glc₁-hex-Far, and Glc₁-hex-DLToc⁵⁴ were prepared according to previous reported methods.

3.2.2 Instruments

The size exclusion chromatography (SEC) in DMF (containing 0.01 M LiCl) was performed at 40 °C using a Jasco high performance liquid chromatography system (PU-980 Intelligent HPLC pump, CO-965 Column oven, RI-930 Intelligent RI detector, and Shodex DEGAS KT-16) equipped with a Shodex Asahipak GF-310 HQ column (linear, 7.6 mm × 300 mm; pore size, 20 nm; bead size, 5 µm; exclusion limit, 4×10^4) and a Shodex Asahipak GF-7 M HQ column (linear, 7.6 mm × 300 mm; pore size, 20 nm; bead size, 9 µm; exclusion limit, 4×10^7) at a flow rate of 0.6 mL min⁻¹. The number-average molecular weight ($M_{n,SEC}$) and dispersity (D_{SEC}) of the sample were calculated on the basis of a polystyrene (PSt) calibration. The ¹H (400 MHz) nuclear magnetic resonance (NMR) spectra were recorded using a JEOL JNM-ECS400 instrument. The Fourier transform infrared spectroscopy (FT-IR) analysis was carried out using a PerkinElmer Frontier MIR spectrometer equipped with a single reflection diamond universal attenuated total reflection (ATR) accessory. The differential scanning calorimetry (DSC) analysis was measured under a nitrogen atmosphere by Hitachi DSC 7000X (Hitachi High-Tech Science Co., Ltd., Tokyo, Japan). All analyses were performed by utilizing 4–10 mg of samples in hermetically sealed aluminum pans with a heating/cooling rate of 10 °C min⁻¹ from room temperature to 170 °C for first heating, followed by cooling to -50 °C. The samples were then heated again to 230 °C for second heating. The thermogravimetric analysis (TGA) was measured under a nitrogen atmosphere by Hitachi TGA NEXTA STA 200 (Hitachi High-Tech Science Co., Ltd., Tokyo, Japan) with a heating rate of 10 °C min⁻¹ from 30 °C to 550 °C. Bulk sample preparation for Small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) measurements were as follows. The as-synthesized samples were annealed for 6 hours at 80, 130, 160, 180, or 210 °C under vacuum and quenched to room temperature. SAXS experiments for

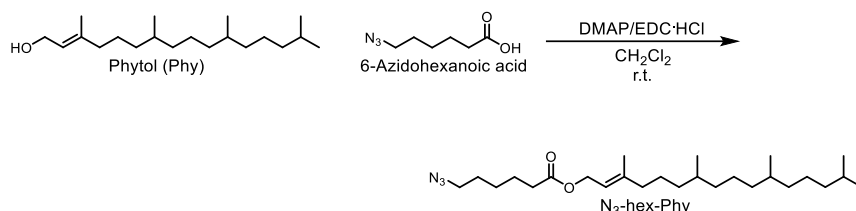
bulk samples were performed at BL-6A and BL-10C of the Photon Factory (PF, Japan). At the PF, the X-ray wavelength and exposure time were 1.50 Å and 60 s, respectively. A PILATUS3 1M detector (Dectris Ltd., Switzerland, 981×1043 pixels, 172×172 µm pixel size) and a PILATUS3 2M detector (Dectris Ltd., Switzerland, 1475×1679 pixels, 172×172 µm pixel size) were used at BL-6A and BL-10C, respectively, for data acquisition. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate. WAXS experiments for bulk samples were performed at BL-6A or BL-10C. The X-ray wavelength and exposure time were 1.50 Å and 60 s, respectively. A PILATUS3 100K (Dectris Ltd., Switzerland, 487×195 pixels, 172×172 µm pixel size) detector and a PILATUS3 2M were used at BL-6A and BL-10C, respectively, for data acquisition. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate. Thin film sample preparation for grazing incidence small-angle X-ray scattering measurement was as follows. The silicon wafer substrates ($1.3 \text{ cm} \times 1.3 \text{ cm}$) were cleaned by sonication in CH_2Cl_2 for 0.5 h and isopropanol/deionized H_2O 1/1 (v/v) for 0.5 h. Each BCO was dissolved in THF at a concentration of 1wt%, and this solution (50 µL) was spin-coated onto the cleaned silicon wafer at 3000 rpm for 1 min to produce nanoscale thin films (film thickness was determined to be 40–50 nm by reflectometry (Filmetrics F-Series model 205-0263, reflectance standard with Si, Filmetrics – A KLA Company). Grazing incidence small-angle X-ray scattering (GISAXS) experiments for thin film samples were performed at BL-6A of the Photon Factory (PF, Japan) or at 3C beamline of the Pohang Accelerator Laboratory (PAL; Pohang, Korea). At the PF, the X-ray wavelength and exposure time were 1.50 Å and 60 s, respectively. A PILATUS3 1M (Dectris Ltd., Switzerland) detector, with 981×1043 pixels at a pixel size of 172×172 µm was used for data acquisition. At the PAL, scattering data were collected at room temperature under vacuum using X-ray radiation sources with a wavelength of 1.21 Å

and a two-dimensional (2D) charge-coupled detector (CCD) (model Rayonix 2D SX 165, Rayonix, Evanston, IL, USA); each scattering image was normally collected for 10–30 s. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate.

3.2.3 Synthesis of Block Co-oligomers

Synthesis of phytol 6-azidohexanoate (*N*₃-hex-Phy) by condensation reaction

Scheme 3.2. Synthesis of *N*₃-hex-Phy



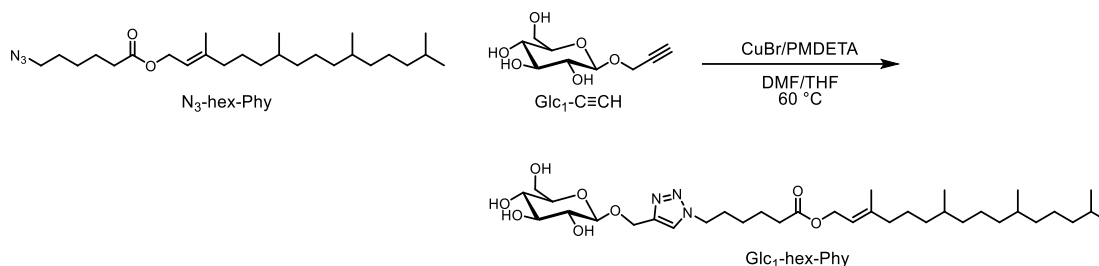
A typical procedure for the esterification is as follows (method A): DMAP (7.42 g, 60.7 mmol) and EDC·HCl (11.6 g 60.7 mmol) were added to a solution of phytol (6.00 g, 20.2 mmol) and 6-azidohexanoic acid (9.54 g, 60.7 mmol) in anhydrous CH₂Cl₂ (200 mL). The reaction mixture was stirred at room temperature for 72 h and quenched by adding HCl (1N, 100 mL). The organic layer was concentrated and purified by silica gel column chromatography (*n*-hexane/AcOEt = 9/1 (v/v), *R*_f = 0.34) to give *N*₃-hex-Phy as a colorless liquid (4.59 g, yield 52.1%).

¹H NMR (400 MHz, CDCl₃): See **Figure S3.1**.

HRMS (ESI): Calcd. for C₂₆H₄₄O₂N₃Na⁺ [*M* + Na]⁺ 458.37142, found 458.37154.

Synthesis of Glc₁-hex-Phy by click reaction

Scheme 3.3. Synthesis of Glc₁-hex-Phy



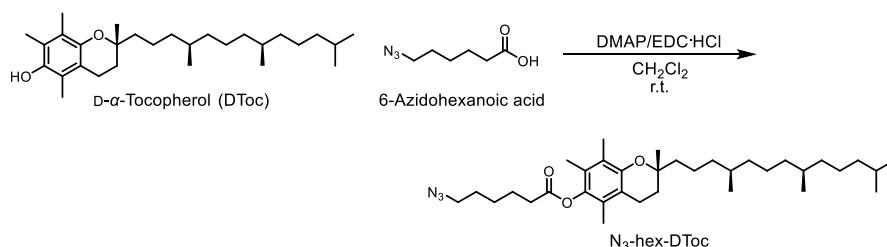
B typical procedure for the click reaction (Cu(I)-catalyzed azido-alkyne cycloaddition) is as follows (method B): N₃-hex-Phy (1.5 g, 3.44 mmol), Glc₁-C≡CH (1.3 g, 976 mmol), and CuBr (148 mg, 1.03 mmol) were placed in a Schlenk flask, which was evacuated and back-filled with argon three times. PMDETA (79 mg, 1.03 mmol) solution in a mixed solvent of anhydrous THF (15 mL) and DMF (15 mL) was transferred into the Schlenk flask under an argon atmosphere after degassing by argon bubbling. The reaction mixture was stirred at 60 °C for 72 h and quenched by adding Dowex® 50WX2 hydrogen to eliminate copper catalyst. After removing the Dowex® 50WX2 hydrogen, the mixture was concentrated and purified by silica gel column chromatography (CH₂Cl₂/Methanol = 9/1 (v/v), *R_f* = 0.21) to give Glc₁-hex-Phy as a white solid (1.01 g, yield 44.9%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S3.2**.

HRMS (ESI): Calcd. for C₃₅H₆₃O₈N₃Na⁺ [*M* + Na]⁺ 676.45074, found 676.44983.

Synthesis of *D*- α -tocopheryl 6-azidohexanoate (N_3 -hex-DToc) by condensation reaction

Scheme 3.4. Synthesis of N_3 -hex-DToc



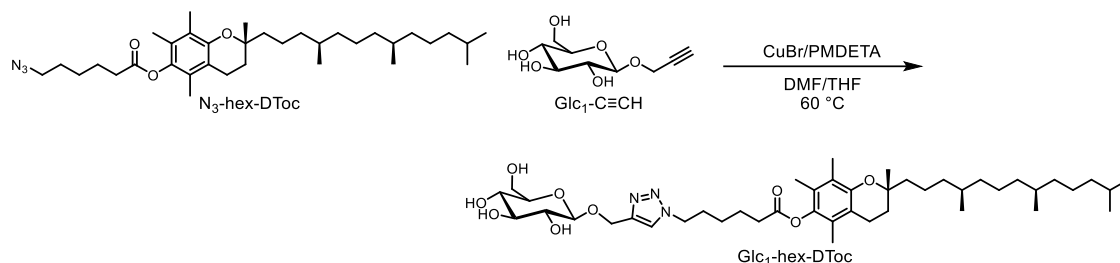
Method A was used for esterification of DToc (7.00 g 16.25 mmol) and 6-azidohexanoic acid (3.32 g 21.13 mmol) with EDC·HCl (4.05 g 21.13 mmol) as condensation agent and DMAP (2.58 g 21.13 mmol) as catalyst in anhydrous CH_2Cl_2 (200 mL). The crude product was purified by silica gel column chromatography (*n*-hexane/AcOEt = 9/1 (v/v), R_f = 0.23) to give N_3 -hex-DToc as a colorless liquid (3.32 g, yield 62.1%).

^1H NMR (400 MHz, CDCl_3): See **Figure S3.4**.

HRMS (ESI): Calcd. For $\text{C}_{35}\text{H}_{59}\text{O}_3\text{N}_3\text{Na}^+$ $[\text{M} + \text{Na}]^+$ 592.44486, found 592.44430.

Synthesis of Glc₁-hex-DToc by click reaction

Scheme 3.5. Synthesis of Glc₁-hex-DToc



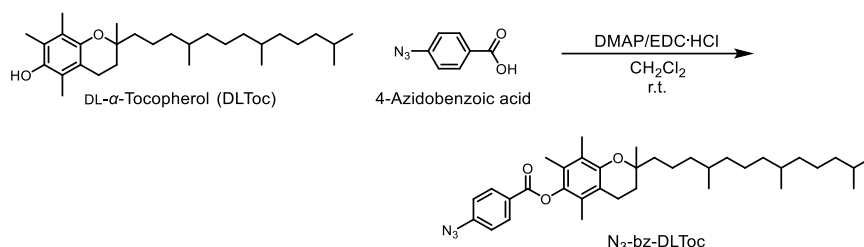
Method B was used for the click reaction of N₃-hex-DToc (700 mg, 1.23 mmol) and Glc₁-C≡CH (321 mg, 1.47 mmol) with CuBr (63.5 mg, 0.440 mmol) and PMDETA (76.5 mg, 0.440 mmol) in a mixed solvent of dry-THF (15 mL) and dry-DMF (15 mL). The crude product was purified by silica gel column chromatography (CH₂Cl₂/Methanol = 9/1 (v/v), *R_f* = 0.22) to give Glc₁-hex-DToc as a white solid (0.85 g, yield 88%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S3.5**.

HRMS (ESI): Calcd. For C₄₄H₇₃O₉N₃Na⁺ [*M* + Na]⁺ 810.52390, found 810.52399.

Synthesis of DL- α -tocopheryl 4-azidobenzoate (N_3 -bz-DLToc) by condensation reaction

Scheme 3.6. Synthesis of N_3 -bz-DLToc



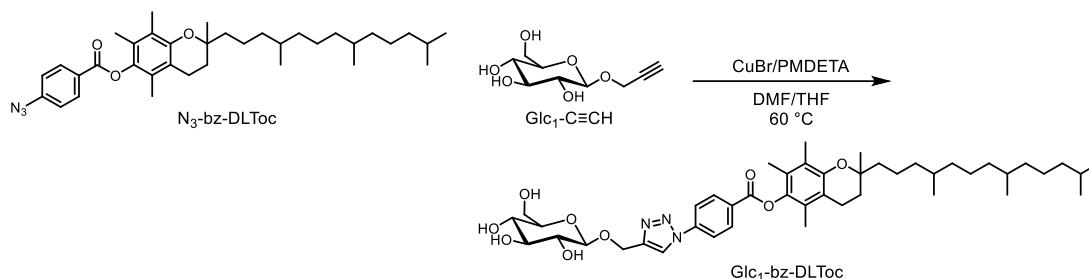
Method A was used for esterification of DLToc (10.0 g, 23.2 mmol) and 4-azidobenzoic acid (4.92 g, 30.2 mmol) with EDC·HCl (5.79g, 30.2 mmol) as condensation agent and DMAP (3.69 g, 30.2 mmol) as catalyst in anhydrous CH_2Cl_2 (200 mL). The crude product was purified by silica gel column chromatography (*n*-hexane/AcOEt = 4/1 (v/v), R_f = 0.60) to give N_3 -bz-DLToc as a colorless liquid (4.32 g, yield 32.3%).

^1H NMR (400 MHz, CDCl_3): See **Figure S3.7**.

HRMS (ESI): Calcd. for $\text{C}_{36}\text{H}_{53}\text{O}_3\text{N}_3\text{Na}^+$ [$\text{M} + \text{Na}$] $^+$ 598.39791, found 598.39787.

Synthesis of Glc₁-bz-DLToc by click reaction

Scheme 3.7. Synthesis of Glc₁-bz-DLToc



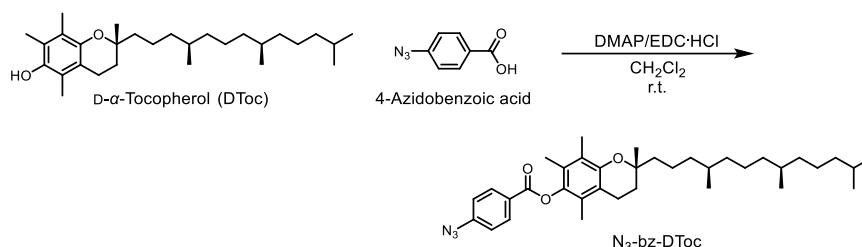
Method B was used for the click reaction of N₃-bz-Phy (1.00 g, 2.26 mmol) and Glc₁-C≡CH (642 mg, 2.94 mmol) with CuBr (97.4 mg, 0.680 mmol) and PMDETA (118 mg, 0.680 mmol) in a mixed solvent of dry-THF (10 mL) and dry-DMF (10 mL). The crude product was purified by silica gel column chromatography (CH₂Cl₂/Methanol = 17/3 (v/v), *R_f* = 0.33) to give Glc₁-bz-DLToc as a yellow solid (1.28 g, yield 46.4%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S3.8**.

HRMS (ESI): Calcd. for C₄₅H₆₇O₉N₃Na⁺ [M + Na]⁺ 816.47695, found 816.47743

Synthesis of *D*- α -tocopheryl 4-azidobenzoate (N_3 -bz-DToc) by condensation reaction

Scheme 3.8. Synthesis of N_3 -bz-DToc



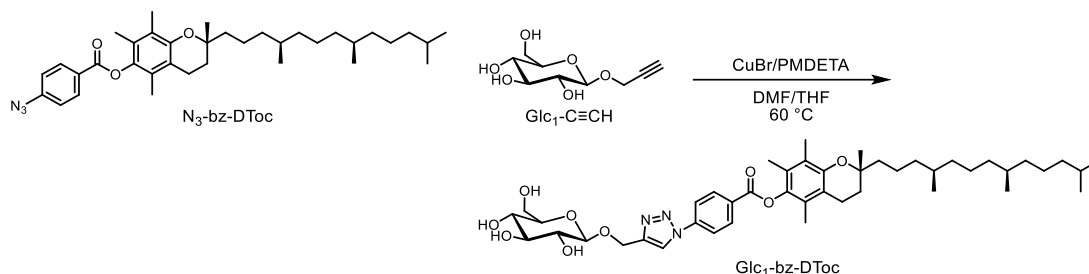
Method A was used for esterification of DToc (4.00 g, 9.29 mmol) and 4-azidobenzoic acid (1.97 g, 12.1 mmol) with EDC·HCl (2.31 g, 12.1 mmol) as condensation agent and DMAP (1.47 g, 12.1 mmol) as catalyst in anhydrous CH_2Cl_2 (200 mL). The crude product was purified by silica gel column chromatography (*n*-hexane/AcOEt = 4/1 (v/v), R_f = 0.58) to give N_3 -bz-DToc as a yellow liquid (2.45 g, yield 45.8%).

^1H NMR (400 MHz, CDCl_3): See **Figure S3.10**.

HRMS (ESI): Calcd. for $\text{C}_{36}\text{H}_{53}\text{O}_3\text{N}_3\text{Na}^+$ [$\text{M} + \text{Na}$] $^+$ 598.39791, found 598.39715.

Synthesis of Glc₁-bz-DToc by click reaction

Scheme 3.9. Synthesis of Glc₁-bz-DToc



Method B was used for the click reaction of N₃-bz-DToc (2.00 g, 3.47 mmol) and Glc₁-C≡CH (985 mg, 4.52 mmol) with CuBr (149 mg, 1.04 mmol) and PMDETA (181 mg, 0.68 mmol) in a mixed solvent of dry-THF (10 mL) and dry-DMF (10 mL). The crude product was purified by silica gel column chromatography (CH₂Cl₂/Methanol = 17/3 (v/v), *R_f* = 0.31) to give Glc₁-bz-DToc as a yellow solid (0.55 g, yield 20%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S3.11**.

HRMS (ESI): Calcd. for C₄₅H₆₇O₉N₃Na⁺ [M + Na]⁺ 816.47695, found 816.47545.

3.3 Result and Discussion

3.3.1 Synthesis of Block Co-oligomers

Initially, the microphase separation behaviors of Glc₁-hex-Far, Glc₁-hex-Phy, and Glc₁-hex-DLToc were investigated in the bulk state to determine a suitable hydrophobic block for constructing 3D network morphologies. Although the synthesis of Glc₁-hex-Far and Glc₁-hex-DLToc has been presented in *Chapter 2* details, regarding their microphase separation behaviors, such as their temperature-dependent morphological changes and order–disorder transitions, have been largely unexplored.⁵⁴ Notably, *Chapter 2* provided evidence for the formation of LAM and GYR structures from Glc₁-hex-Far and Glc₁-hex-DLToc, respectively. Thus, in the present study, Glc₁-hex-Phy was additionally prepared, which showed a sugar volume fraction between Glc₁-hex-Far and Glc₁-hex-DLToc, and it was expected to provide further details into the phase window. More specifically, Glc₁-hex-Phy was synthesized as outlined in **Scheme 3.1**. Initially, an azido-functionalized phytol bearing a hexanoate linker (N₃-hex-Phy) was prepared via a condensation reaction between phytol and 6-azidohexanoic acid. Subsequently, this N₃-hex-Phy was subjected to a copper-catalyzed azido–alkyne click reaction with propargyl- β -D-glucopyranoside (Glc₁-C $\equiv$ CH) to yield Glc₁-hex-Phy. The success of the click reaction was confirmed by proton nuclear magnetic resonance (¹H NMR) spectroscopy, Fourier-transform infrared (FT-IR) spectroscopy, size-exclusion chromatography (SEC), and electrospray ionization mass spectrometry (ESI-MS), as detailed in the Supporting information (**Figures S3.1–S3.12**). As a result, the f_{sugar} was calculated to be 0.24 based on $V_{\text{sugar segment}}/(V_{\text{sugar segment}} + V_{\text{terpenoid segment}})$, where V_{sugar} and $V_{\text{terpenoid}}$ represent the sugar and terpenoid segment volumes calculated based on known their density values. These values are listed in **Table 3.1** together with those of the other BCOs examined herein.

Table 3.1. Molecular characteristics and thermal properties of the BCOs

BCO	M.W.	$M_{n,SEC}^a$	f_{sugar}^b	f_{ter}^b	$T_{g,sugar}^c$ (°C)	T_d^d (°C)
Glc ₁ -hex-Far	580	1500	0.29	0.71	24.0	215.6
Glc ₁ -hex-Phy	654	1700	0.24	0.76	26.0	247.8
Glc ₁ -hex-DLToc	788	1800	0.21	0.79	39.4	305.4
Glc ₁ -hex-DToc	788	1900	0.21	0.79	39.9	310.8
Glc ₁ -bz-DLToc	793	1900	0.21	0.79	31.5	272.8
Glc ₁ -bz-DToc	793	2000	0.21	0.79	38.0	310.5

^aNumber-average molecular weight determined by SEC in DMF (containing 0.01 M LiCl) with polystyrene calibration. ^bSugar and terpenoid volume fractions (f_{sugar} and f_{ter} , respectively) calculated based on the known density values of glucose (1.36 g cm⁻³), farnesol (0.887 g cm⁻³), phytol (0.850 g cm⁻³), and tocopherol (0.950 g cm⁻³). ^cDetermined by DSC. ^d5% Weight loss temperature (T_d) determined using TGA.

To identify the microphase-separated structures in the bulk state, synchrotron small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) measurements were performed on the as-synthesized and thermally annealed BCOs. In addition, grazing-incidence small-angle X-ray scattering (GISAXS) measurements were conducted to investigate nanostructure formation in the thin film state. Thin film (film thickness: ~40 nm) samples were prepared by spin-coating a 1 wt% polymer solution in tetrahydrofuran (THF) onto a cleaned silicon wafer at 3000 rpm for 1 min. The bulk and thin film samples were annealed at temperatures above the glass transition temperature of the glucose block ($T_{g,sugar}$) and below the 5% weight loss temperature (T_d) for 6 h under vacuum conditions (see **Table 3.1** and **Figures S3.13** and **S3.14** in the Supporting Information for the determination of $T_{g,sugar}$ and T_d).

3.3.2 Construction of Ultrasmall Microphase-Separated Structures

Among the various BCOs, Glc₁-hex-Far and Glc₁-hex-Phy were found to only exhibit the LAM morphology in the bulk state, as judged from their SAXS profiles. As shown in **Figures 3.1(a)** and **3.2(a)**, Glc₁-hex-Far and Glc₁-hex-Phy exhibited sharp scattering peaks in their SAXS profiles, indicating the formation of highly ordered nanostructures. No obvious scattering peaks were observed in the WAXS profiles of Glc₁-hex-Far and Glc₁-hex-Phy, either with or without annealing, thereby confirming their amorphous natures (**Figures 3.1(b)** and **3.2(b)**). In terms of the thermal analysis results obtained by differential scanning calorimetry (DSC) for Glc₁-hex-Far and Glc₁-hex-Phy, heat capacity jumps were observed corresponding to the glass transition of the sugar blocks at $T_{g,sugar}$ (24–26 °C). However, no first-order transitions, such as crystallization, were observed (**Figures S3.13(a)** and **(b)**), thereby aligning with the WAXS results. As evidenced by the sharp primary peak (q^*) and an additional secondary peak at the $2q^*$ position (**Figures 3.1(a)** and **3.2(a)**), Glc₁-hex-Far and Glc₁-hex-Phy formed LAM morphologies without thermal annealing (**Figure 3.1(c)**). In the case of Glc₁-hex-Far, the primary peak became slightly broader upon elevating the annealing temperature, and disorder was observed upon annealing at 160 °C. These results suggest that the order–disorder transition temperature (T_{ODT}) is located between 130 and 160 °C. In contrast, Glc₁-hex-Phy exhibited sharp scattering peaks associated with the LAM morphology even after annealing at 160 °C. The structural difference between Glc₁-hex-Far and Glc₁-hex-Phy is only the number of isoprene units in the terpenoid block; phytol consists of four isoprene units, whereas farnesol is composed of three isoprene units. Therefore, it was clear that an increase in the degree of polymerization by one repeating unit significantly affects the thermodynamic stability of the microphase-separated structure. It was deduced that the domain spacing ($d = 2\pi/q^*$) for the 80 °C-annealed Glc₁-hex-Far was 4.2 nm, which is the

smallest value reported to date among sugar-based AB linear BCOs (**Figure 3.1(a)**)⁵⁴; the d value for 80 °C-annealed Glc₁-hex-Phy was slightly larger, i.e., 5.1 nm (**Figure 3.2(a)**). Notably, control over the d value to a precision of 1 nm was achieved by simply increasing the number of isoprene units in the terpenoid segment.

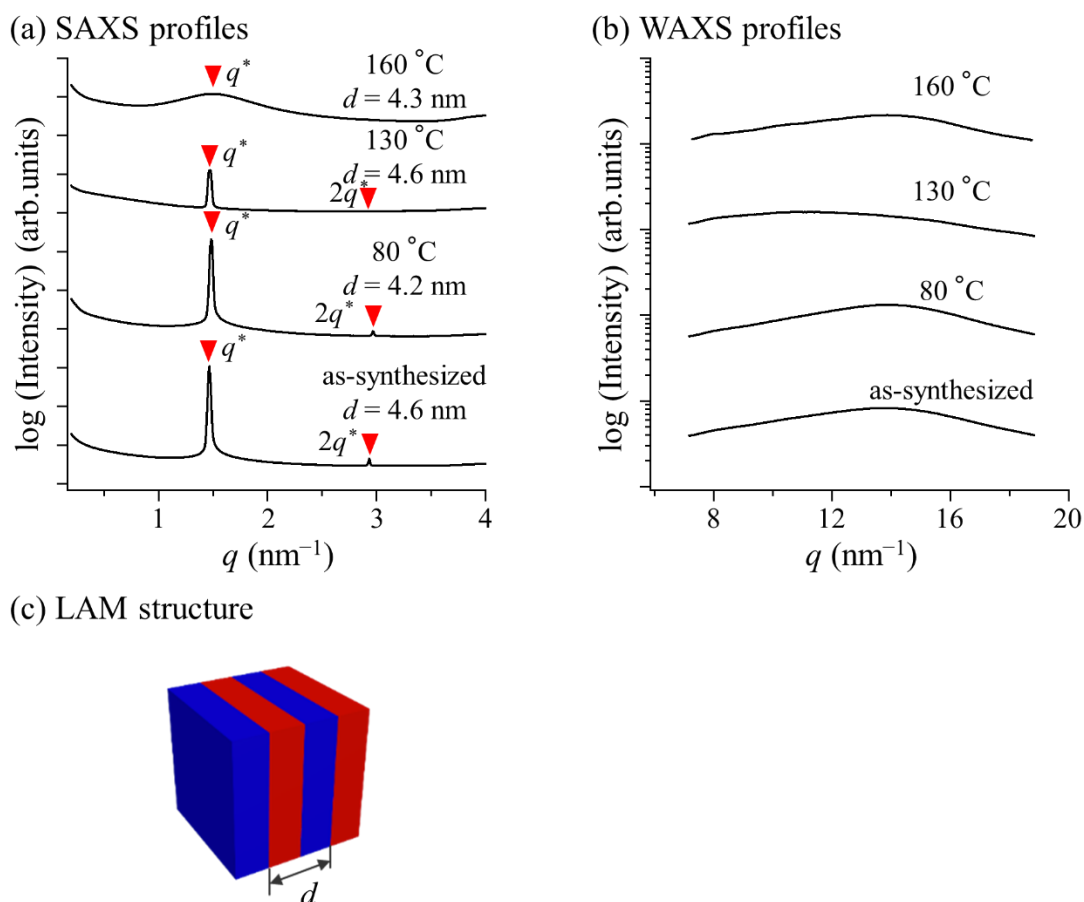


Figure 3.1. (a) SAXS and (b) WAXS profiles of the as-synthesized and thermally annealed Glc₁-hex-Far. (c) The schematic illustrations of the LAM structure.

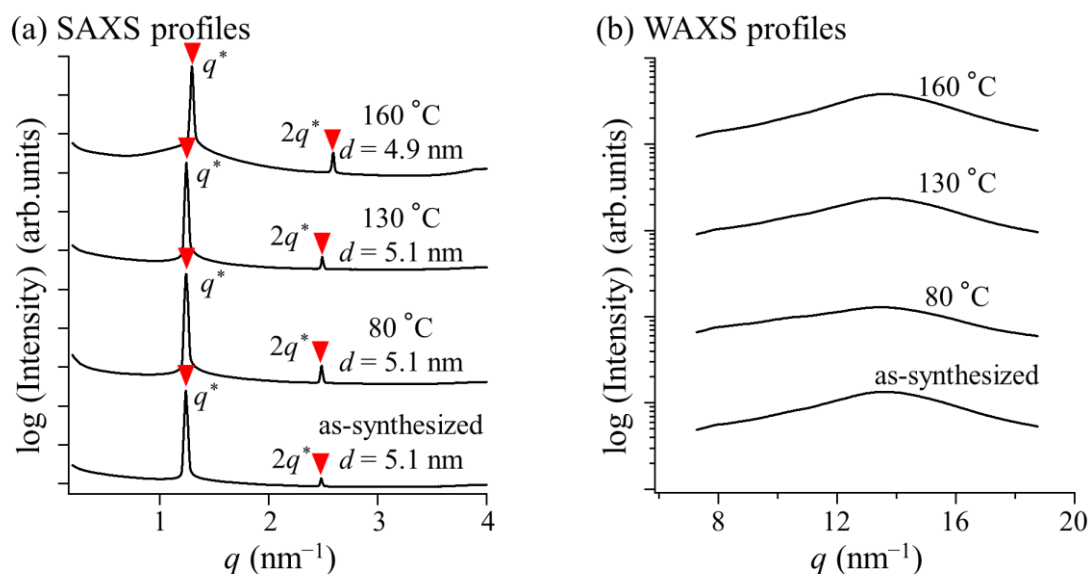


Figure 3.2. (a) SAXS and (b) WAXS profiles of the as-synthesized and thermally annealed Glc₁-hex-Phy.

The thin films generated from Glc₁-hex-Far and Glc₁-hex-Phy also exhibited LAM morphologies, as evidenced by the GISAXS results. In addition, it was found that the two-dimensional (2D) scattering pattern of the as-cast Glc₁-hex-Far film exhibited a diffraction spot derived from the (100) diffraction of the LAM structure parallel to the Si substrate (**Figure 3.3(a)**). To determine the structure in greater detail, the one-dimensional (1D) out-of-plane scattering profile was extracted from the 2D scattering image at $2\theta_f = 0.08^\circ$ (**Figure 3.3(b)**). Subsequently, the d value of the LAM structure was calculated to be 4.4 nm using Bragg's equation ($d = \lambda / (2\sin(\alpha_f/2))$) based on the peak observed at $\alpha_f = 1.62^\circ$ in the out-of-plane scattering profile. This d value was also the smallest reported to date for sugar-based linear AB-BCPs. Furthermore, it was found that the as-cast Glc₁-hex-Phy thin film also exhibited a LAM structure parallel to the substrate, as evidenced by the diffraction peak observed in the out-of-plane direction (**Figure 3.4(a)**). The out-of-plane scattering profile was extracted at $2\theta_f = 0.28^\circ$, and a d value of 4.9 nm was calculated using the scattering peak at $\alpha_f = 1.75^\circ$ (**Figure 3.4(b)**). The above results

collectively indicate that farnesol and phytol are the optimal candidates for building blocks to realize ultrasmall d values. However, these BCOs are not suitable for combination with glucose to construct 3D network morphologies.

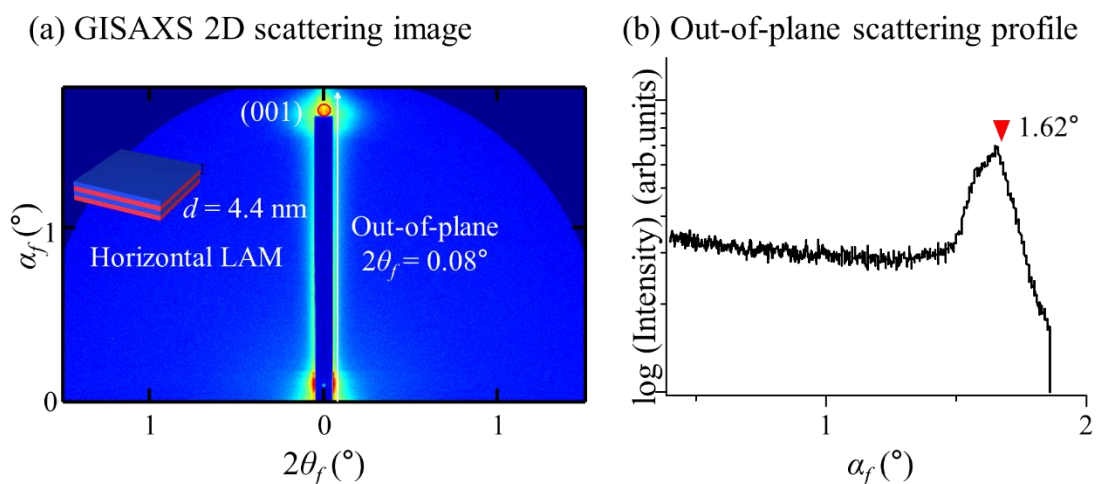


Figure 3.3. (a) Representative GISAXS 2D scattering image of the as-cast nanoscale Glc₁-hex-Far film (40–50 nm thick) with an incidence angle (α_i) = 0.09676°, a sample to detector distance (SDD) = 2947.16 mm, and an X-ray wavelength (λ) = 1.23 Å. (b) 1D out-of-plane scattering profile along the meridian line at $2\theta_f = 0.08^\circ$, as derived from (a).

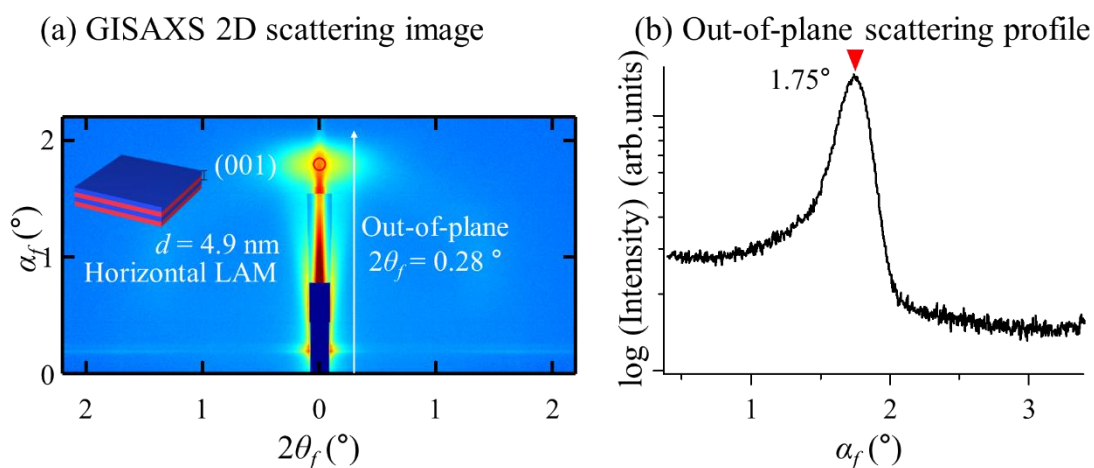


Figure 3.4. (a) Representative GISAXS 2D scattering image of the as-cast nanoscale Glc₁-hex-Phy film (40–50 nm thick) with $\alpha_i = 0.1512^\circ$; SDD = 2038.91 mm, and $\lambda = 1.50$ Å. (b) 1D out-of-plane scattering profile along the meridian line at $2\theta_f = 0.28^\circ$, as derived from (a).

3.3.3 Construction of Three-Dimensional (3D) Structures

Subsequently, the combination of glucose and tocopherol was considered to assess the suitability of this BCO for generating a 3D network morphology. Previously, the author determined the potential of Glc₁-hex-DLToc to form a GYR structure under certain annealing conditions.⁵⁴ In the current study, the microphase-separated structure of bulk Glc₁-hex-DLToc samples was re-investigated under different annealing conditions. The SAXS profile of the as-synthesized Glc₁-hex-DLToc sample exhibited scattering peaks at $q = 0.91, 1.16, 1.44, 1.83, \text{ and } 3.47 \text{ nm}^{-1}$, which were indexed to the (101), (003), (110), (113), and (009) crystallographic planes of the *ABCABC*-stacked HPL (HPL_{ABC}) structure with the $R\bar{3}m$ space group (**Figures 3.5(a) and (f)**). The lattice parameters were calculated to be $a = 1/(3(1/d_{101}^2 - 1/c^2)/4)^{1/2} = 8.8 \text{ nm}$ and $c = 3(d_{003}) = 16.2 \text{ nm}$, where a and $c/3$ correspond to the interperforation distance and the lamellar stacking periodicity, respectively. Upon thermal annealing at 80 °C, the scattering peaks became significantly sharper, and the peaks at $q = 1.05, 1.17, 1.24, 1.67, 2.02, 2.33, \text{ and } 3.50 \text{ nm}^{-1}$ were assigned to the (101), (003), (102), (110), (113), (006), and (009) reflection planes of the HPL_{ABC} structure with $a = 7.4 \text{ nm}$ and $c = 16.1 \text{ nm}$. A further increase in the annealing temperature resulted in an order–order transition from the HPL_{ABC} to the GYR structure. The scattering peaks observed in the Glc₁-hex-DLToc samples annealed at 130 and 160 °C appeared at $q/q^* = \sqrt{6}, \sqrt{8}, \sqrt{16}, \sqrt{20}, \sqrt{22}, \text{ and } \sqrt{24}$, and were assignable to the (211), (220), (321), (400), (420), and (332) reflection planes of GYR, respectively. The lattice constant $a_{\text{GYR}} = 12.1 \text{ nm}$ was calculated as follows: $a = 2\pi(h^2 + k^2 + l^2)^{1/2}/q_{hkl}$.

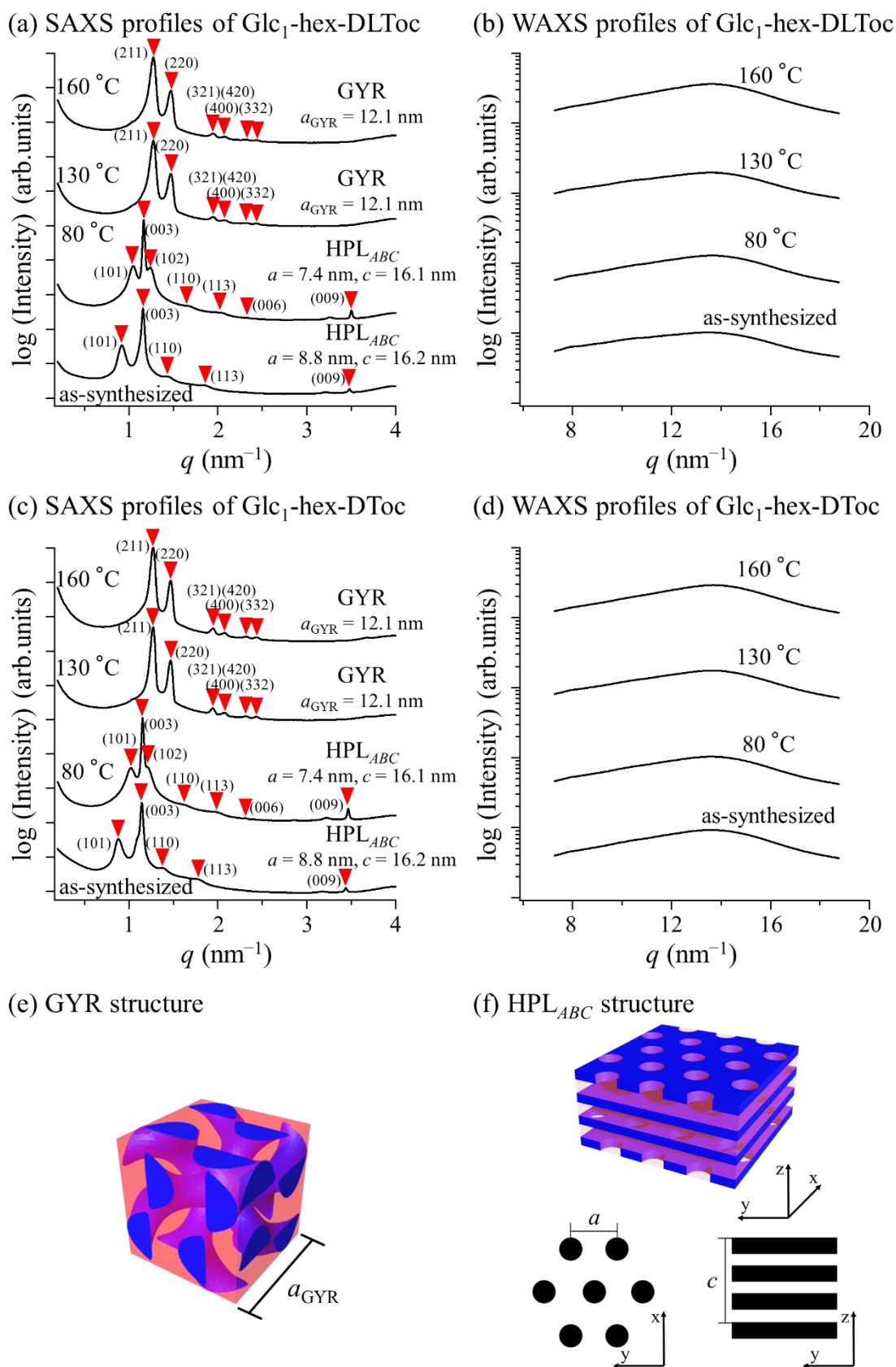


Figure 3.5. (a, c) SAXS and (b, d) WAXS profiles of the as-synthesized and thermally annealed Glc₁-hex-DLToc and Glc₁-hex-DToc specimens. Also shown are schematic illustrations of the © GYR and (f) HPL_{ABC} structures.

Notably, Glc₁-hex-DLToc was found to form a 3D network morphology, while Glc₁-hex-Phy formed only the LAM morphology, despite both BCOs possessing a terpenoid block consisting of four isoprene units. This implies that the molecular shape of the BCO plays a significant role in determining the resulting structure. Similar to the case of micelle-forming surfactants, it is proposed that the packing parameter that characterizes the geometry of the BCO molecule governs the interfacial curvature of the microphase-separated morphology. The packing parameter (P) of a sugar-based BCO is given by $P = v/al_c$, where v is the hydrocarbon volume of the hydrophobic block, a is the effective projection area of the Glc₁ block, and l_c represents the length of the hydrophobic block.⁶⁰ It is known that an amphiphilic molecule with a large P value adopts a cone-shaped geometry and tends to form a microphase-separated structure with a larger interfacial curvature, and vice versa. Comparison of the chemical structures of the DLToc and Phy blocks shows that DLToc contains an additional phenylene ring and a cyclic ether moiety, which effectively increases the hydrocarbon volume of DLToc relative to that of Phy. As a result, Glc₁-hex-DLToc exhibits a larger packing parameter than Glc₁-hex-Phy, ultimately favoring the formation of an HPL phase with a larger interfacial curvature than the LAM phase. Thus, Glc₁-hex-DLToc is a suitable candidate for the formation of ultrasmall 3D network morphologies.

Here, it would be interesting to compare the self-assembly behaviors of the BCOs with chemically similar synthetic glycolipids. **Figure 3.6** summarizes the phase behaviors of the obtained BCOs, which consist of a glucose unit and terpenoid chain with varied length, together with typical synthetic glycolipids, which consist of a glucose unit (β -anomer) and linear C12, C16, and C18 alkyl chain. There have been many studies on the lyotropic liquid crystalline behaviors of glycolipids.^{61–63} However, research into thermotropic liquid crystalline behaviors has only been pursued relatively recently.^{55,64–66}

Glycolipids typically crystallize at low temperatures. However, above the melting temperature T_m of the alkyl chain and below the clearing temperature (T_c) where hydrogen bonds in the sugar moiety are broken, the glycolipids adopt periodic nanostructures in the liquid crystalline state. The strong interaction between the glucose units through the hydrogen bonding is the dominant factor for the self-assembly, resulting in liquid crystal formation. In contrast, the obtained BCOs in this chapter show the f_{sugar} of 0.3 or lower, and thus the interaction between the glucose units should have a relatively minor impact on the self-assembly compared to the case of the glycolipids. Therefore, the BCOs are more likely self-assembled into the periodic nanostructures through microphase separation driven by the immiscibility between the glucose unit and hydrocarbon chain. Another indication that BCOs exhibit microphase separation behavior is their volume-fraction-dependent phase behavior reminiscent of conventional BCP. However, as pointed out by Meijer, BCP-like small molecules can exhibit both liquid crystalline and microphase separation behaviors depending on the delicate balance between directional interaction and immiscibility.⁶⁷ The obtained BCOs may also serve as a bridge between these liquid crystalline and BCP behaviors. This aspect is an interesting topic for further investigation.

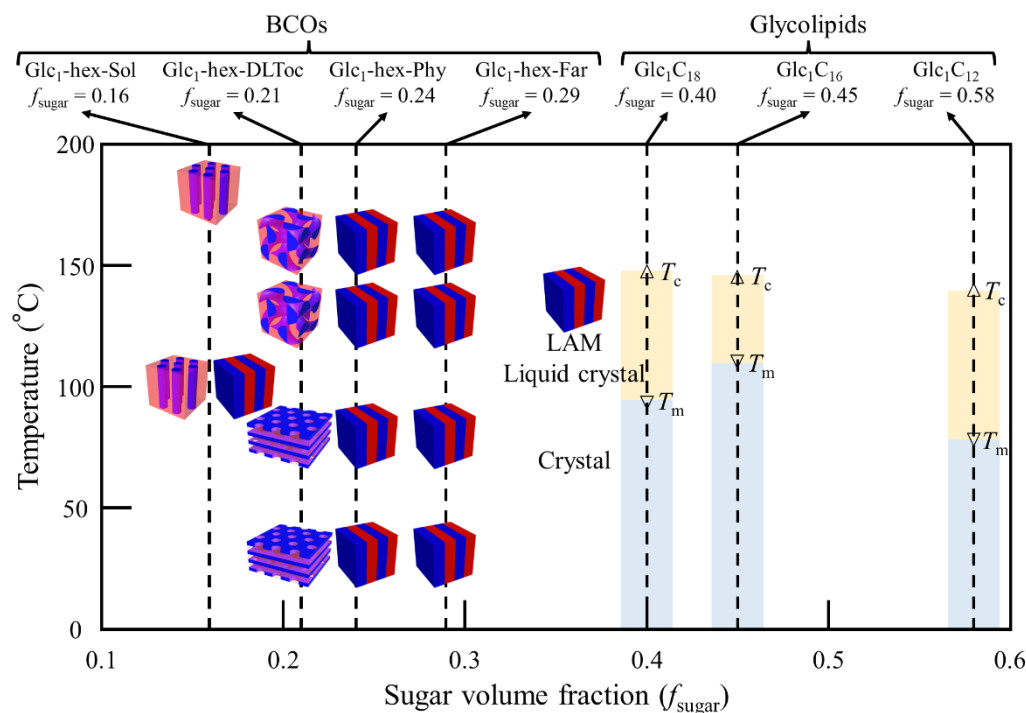


Figure 3.6. Phase diagram of Glc₁-hex-Sol (the “Sol” represents solanesol as the terpenoid block),⁵⁴ Glc₁-hex-DLToc, Glc₁-hex-Phy, Glc₁-hex-Far, and typical synthetic glycolipids.^{64,67–69} The melting and clearing temperatures are indicated as T_m and T_c , respectively. The vertical axis for the BCOs indicates the annealing temperature.

These promising results inspired the subsequent combination of tocopherol and glucose to construct an ultrafine 3D network morphology. It should be noted here that the Glc₁-hex-DLToc species discussed so far is derived from the synthetic DL- α -tocopherol, and the stereochemistry of the three stereocenters on the hydrocarbon chain is classified as all-racemic. To gain insight into the impact of the chirality of the terpenoid segment on 3D network formation, an optically pure version of Glc₁-hex-DLToc was prepared (i.e., Glc₁-hex-DToc) using natural D- α -tocopherol with an all- $\odot$ configuration (**Scheme 3.1**). Similar to its racemic counterpart, the WAXS results for Glc₁-hex-DToc revealed its completely amorphous nature (**Figures 3.5(b)** and **(d)**). To evaluate the bulk state morphology, SAXS measurements were carried out on the as-synthesized sample and on the specimens annealed at 80, 130, and 160 °C (**Figure 3.5(c)**). The morphology and unit cell parameters under each annealing condition were found to be the same as those

obtained for Glc₁-hex-DLToc, implying that the chirality of the tocopherol segment has little to no impact on the bulk state self-assembly, and that the microphase-separated morphology seems to be mainly determined by the polar–nonpolar repulsion between the Glc₁ and tocopherol blocks. However, the sharpness of the scattering peaks, which is related to the grain size of the ordered structure, was apparently different between the racemic and optically pure BCOs. Thus, to clarify the subtle differences in the nanostructures of Glc₁-hex-DLToc and Glc₁-hex-DToc, the primary scattering peaks of the SAXS profiles recorded for the samples annealed at 130 °C were fitted using the Gaussian function to calculate the full width at half maximum (FWHM) (**Figure S3.15**). As a result, the FWHM values of Glc₁-hex-DLToc and Glc₁-hex-DToc were found to be 0.04044 and 0.03525 nm⁻¹, respectively. According to the Scherrer equation ($\tau = K\lambda/\beta\cos\theta$, where τ is the grain size, K is the shape factor, λ is the X-ray wavelength, β is the FWHM, and θ is the incidence angle), the FWHM is inversely proportional to the grain size, and it can be concluded that the GYR structure of Glc₁-hex-DToc possesses a 1.15 times larger grain size than that of Glc₁-hex-DLToc. Therefore, optically pure tocopherol has an advantage over racemic tocopherol in forming a 3D network morphology with a superior long-range order.

GISAXS experiments were then conducted on thin films of Glc₁-hex-DLToc and Glc₁-hex-DToc to investigate the possibility of constructing 3D network structures, and to further clarify the effect of the tocopherol chirality on self-assembly in the thin film state. As presented in **Figures 3.7(a)** and **(b)**, the 2D GISAXS pattern of the as-cast Glc₁-hex-DLToc thin film shows scattering spots corresponding to the (003), (009), (100), (110), (101), (102), and (108) planes of the HPL_{ABC} structure. The out-of-plane scattering profile extracted from the meridian line at $2\theta_f = 0.24^\circ$ showed two scattering peaks at $\sigma_f = 1.58^\circ$ and 4.79° , corresponding to the (003) and (009) diffractions of the lamellar

stacking of HPL_{ABC} parallel to the Si substrate (**Figure 3.7(c)**). Based on the position of the (003) peak, the d value was calculated to be 5.4 nm. This value correlates to one-third of the repeating length of the ABC lamellar stacking; therefore, c was determined to be 16.2 nm. In addition, the 1D in-plane scattering profile extracted from the equatorial line at $\sigma_f = 0.18^\circ$ showed peaks corresponding to the (100) and (110) planes at $2\theta_f = 1.10$ and 1.92° , respectively (**Figure 3.7(d)**). The positions of these two in-plane peaks led to an a value of 9.0 nm, which represents the distance between the perforations in the HPL_{ABC} structure. Since the GISAXS 2D scattering image recorded for the as-cast $\text{Glc}_1\text{-hex-DToc}$ film showed scattering spots at similar positions to those associated with $\text{Glc}_1\text{-hex-DLToc}$ (**Figures 3.8(a), (c), and (d)**), it was considered that $\text{Glc}_1\text{-hex-DToc}$ also formed the HPL_{ABC} morphology in the thin film state, with $a = 8.8$ nm and $c = 16.2$ nm (**Figure 3.8(b)**). However, the $\text{Glc}_1\text{-hex-DToc}$ thin film exhibited stronger and sharper scattering spots. In addition, higher-order scattering spots, such as those corresponding to the (104), (107), and (113) planes, were clearly observed (**Fig. 3.7(a)**). These results clearly show that the optically pure $\text{Glc}_1\text{-hex-DToc}$ is arranged in a more ordered manner than the racemic $\text{Glc}_1\text{-hex-DLToc}$, even in the thin film state. The HPL_{ABC} structures formed by $\text{Glc}_1\text{-hex-DLToc}$ and $\text{Glc}_1\text{-hex-DToc}$ in the thin film state can be constructed by spin-coating and maintained at a high annealing temperature of up to 180°C (**Figure S3.16**). Meanwhile, the long-term stability of the HPL_{ABC} structures in the thin film state is also important for various applications. Thus, the author performed GISAXS measurement at one-month intervals for the same thin film samples stored at ambient condition. Comparing the GISAXS 2D scattering images, the HPL_{ABC} structures were found to be maintained for over one month, supporting the long-term stability (**Figures S3.16 and S3.17**). Therefore, $\text{Glc}_1\text{-hex-DLToc}$ and $\text{Glc}_1\text{-hex-DToc}$ can be considered good candidates for fabricating templates with ultrasmall 3D structures in their thin films.

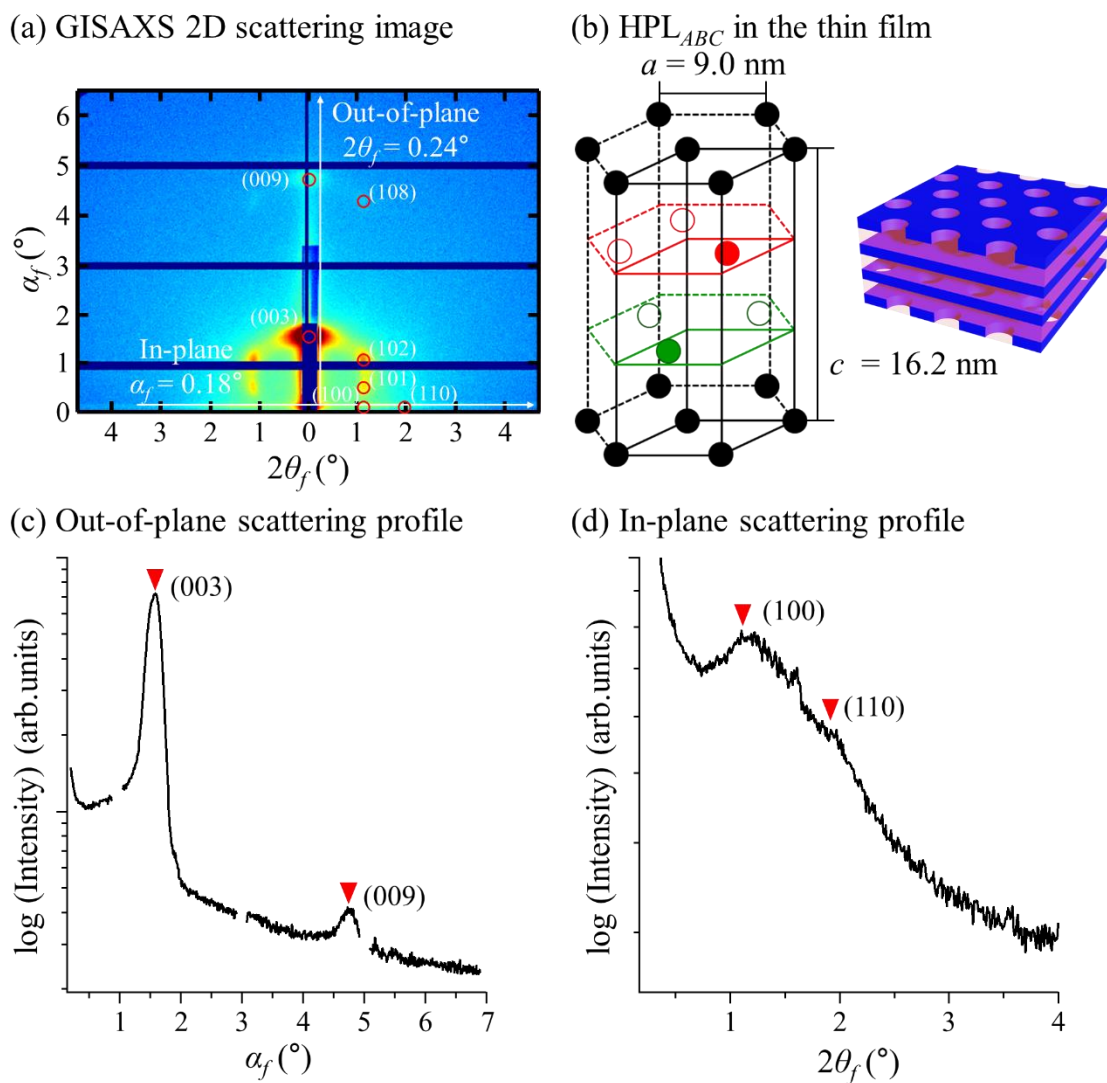


Figure 3.7. (a) Representative GISAXS 2D scattering image of the as-cast nanoscale Glc₁-hex-DLToc film (40–50 nm thick) with $\alpha_i = 0.1803^{\circ}$, SDD = 1024.29 mm, and $\lambda = 1.50$ Å. (b) Schematic illustrations showing the HPL_{ABC} structure. (c) 1D out-of-plane scattering profile along the meridian line at $2\theta_f = 0.24^{\circ}$, as determined from (a). (d) 1D in-plane scattering profile along the equatorial line at $\alpha_f = 0.18^{\circ}$, as determined from (a).

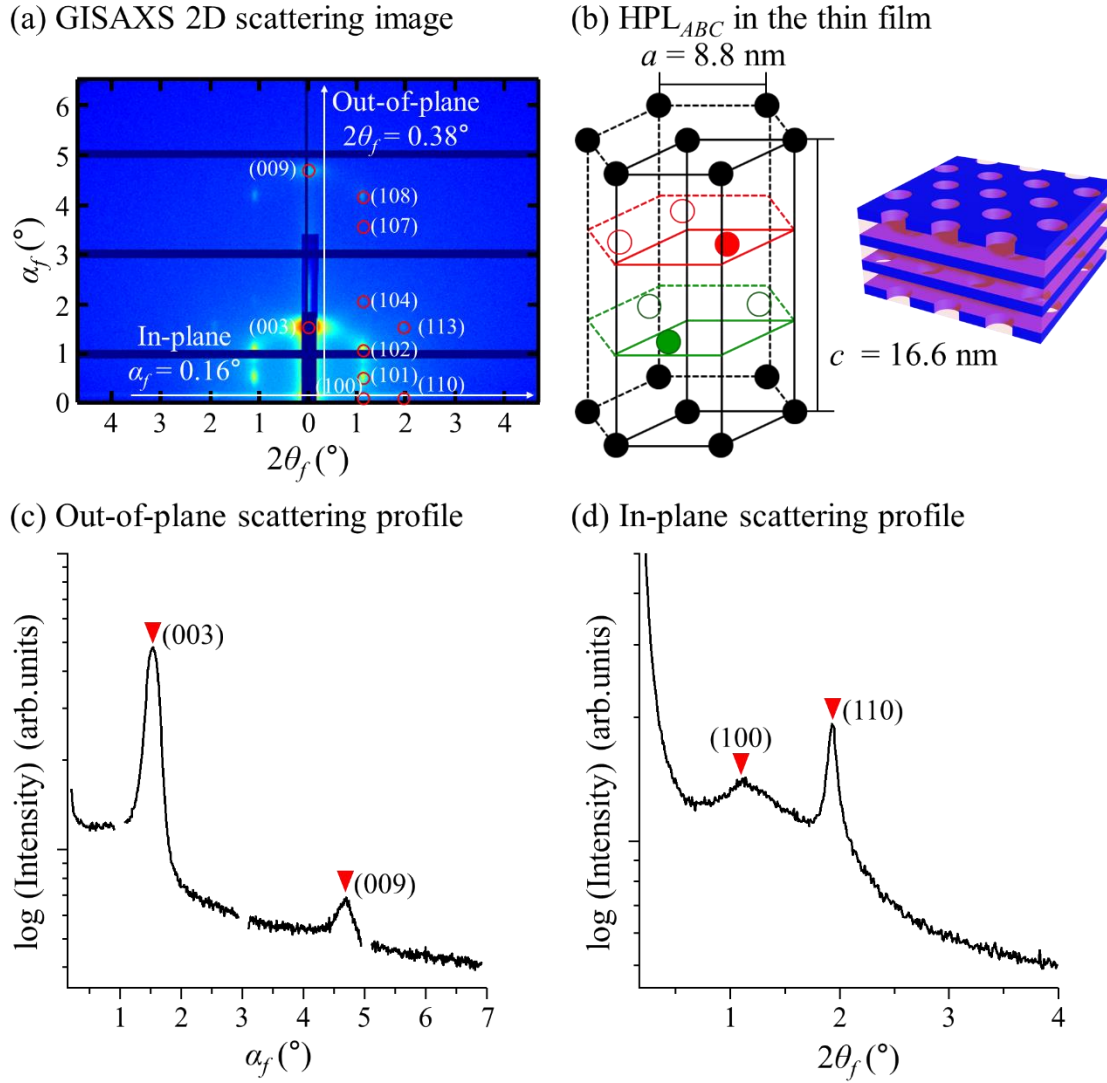


Figure 3.8. (a) Representative GISAXS 2D scattering image of the as-cast nanoscale Glc₁-hex-DToc film (40–50 nm thick) with $\alpha_i = 0.1562^\circ$, SDD = 1024.29 mm, and $\lambda = 1.50$ Å. (b) Schematic illustrations showing the HPL_{ABC} structure. (c) 1D out-of-plane scattering profile along the meridian line at $2\theta_f = 0.38^\circ$, as derived from (a). (d) 1D in-plane scattering profile along the equatorial line at $\alpha_f = 0.16^\circ$, as derived from (a).

3.3.4 Microphase Separated Behavior with Different Linker Structure

Subsequently, to further modulate the self-assembly behavior of the glucose–tocopherol BCO, the impact of the chemical nature of the glucose–tocopherol junction was investigated. For this purpose, 6-azidohexanoic acid was replaced with 4-azidobenzoic acid as a more rigid chemical junction between the constituent blocks of BCO. In this case, 4-azidobenzoic acid was reacted with DL- α -tocopherol and D- α -tocopherol to produce azido-functionalized precursors, which were then subjected to a click reaction with Glc₁-C $\equiv$ CH to produce Glc₁-bz-DLToc and Glc₁-bz-DToc, respectively (**Scheme 3.1**).

No obvious scattering peaks were observed on the WAXS profiles of Glc₁-bz-DLToc, regardless of the annealing conditions employed, thereby confirming its amorphous nature (**Figure 3.9(b)**). In contrast, scattering peaks attributed to various microphase-separated structures were detected in the SAXS profiles (**Figure 3.9(a)**). Interestingly, although both Glc₁-hex-DLToc and Glc₁-hex-DToc formed HPL_{ABC} only at lower temperatures (i.e., in the as-cast sample and the sample annealed at 80 °C) and exhibited GYR structures at higher temperatures (i.e., after annealing at 130 and 160 °C), the HPL_{ABC} structure was observed in Glc₁-bz-DLToc even at elevated temperatures (as-synthesized: $a = 10.6$ and $c = 20.8$ nm; annealed at 80 °C: $a = 10.2$ and $c = 17.2$ nm; annealed at 130 °C: $a = 10.8$ and $c = 17.9$ nm). Furthermore, Glc₁-bz-DLToc exhibited a hexagonally close-packed cylinders (HEX) structure even after annealing at higher temperatures (annealed at 180 °C: cylinder-to-cylinder distance (d_{c-c}) = 7.5 nm; annealed at 210 °C: $d_{c-c} = 7.2$ nm). These results clearly demonstrate the significant impact of the linker structure on microphase separation. More specifically, the effect of the linker structure was clearly manifested by the different morphologies of the samples annealed at 130 °C, wherein Glc₁-hex-DLToc formed a GYR structure, and Glc₁-bz-DLToc formed

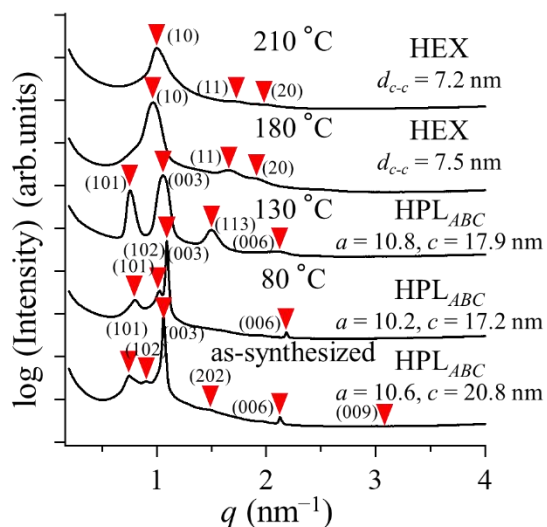
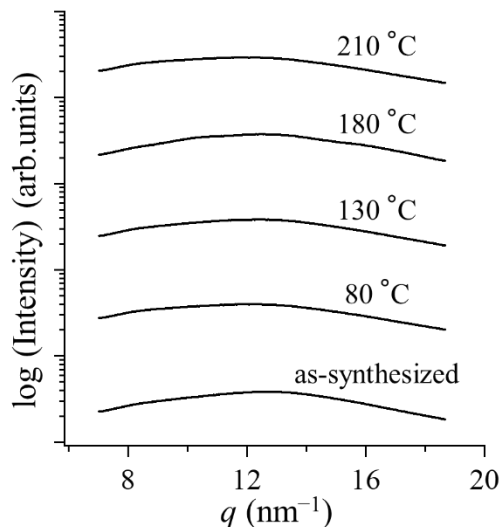
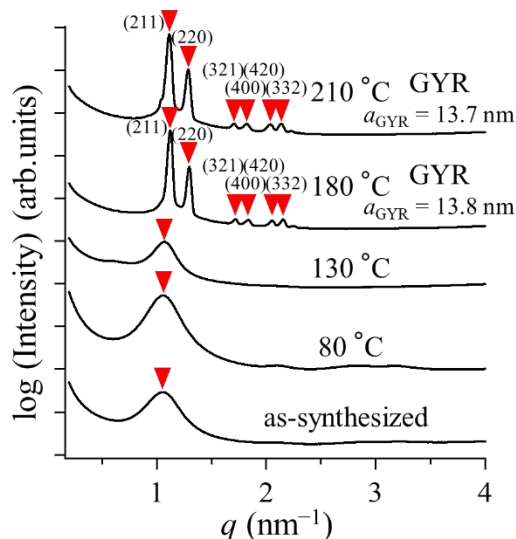
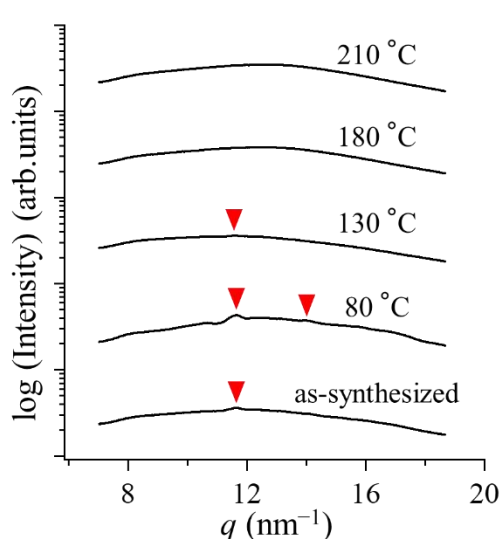
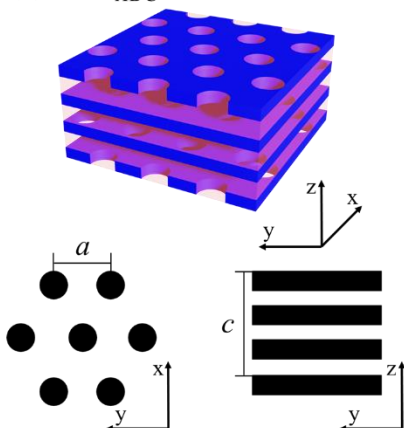
an HPL structure. This result implies that the replacement of hexanoate with a benzoate linker reduced the packing parameter of the BCO, thereby enhancing the stability of the lower-curvature HPL phase relative to that of the GYR phase.

It should be noted here that the hexanoate and benzoate linkers consist of an aliphatic pentyl group and an aromatic phenylene ring, respectively. For the first-order approximation, the contribution of these two groups to the hydrocarbon volume of the hydrophobic block was estimated using the ratio of their mass to the corresponding mass density. Taking the values of the mass density ρ as 0.626 g cm^{-3} for pentane and 0.876 g cm^{-3} for benzene, the volumes of the pentylene and phenylene moieties were estimated to be 0.21 and 0.14 nm^3 , respectively. Consequently, the replacement of hexanoate with benzoate in the linker reduced the hydrocarbon volume and the packing parameter of the hydrophobic block, such that the thermodynamic stability of the HPL phase in Glc₁-bz-DLToc was enhanced over that of the GYR phase.

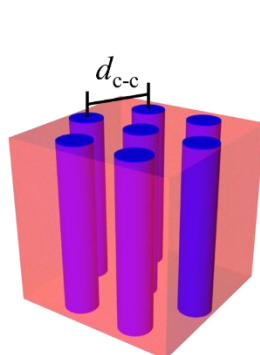
Furthermore, the broad peak observed in the SAXS profiles of the as-synthesized Glc₁-bz-DToc sample and of the samples annealed at 80 and $130 \text{ }^{\circ}\text{C}$ suggested the absence of a periodic ordered structure (**Figure 3.9©**). However, several diffraction peaks were observed in the WAXS profiles of the samples annealed below $130 \text{ }^{\circ}\text{C}$, reflecting the crystallinity of the DToc block (**Figure 3.9(d)**). The results demonstrate that the crystallization of the DToc block has a strong impact on the microphase-separated structure of the BCO. More specifically, at a lower temperature, the driving force for crystallization could outweigh that of microphase separation, such that the crystallization process perturbs or even disrupts the microphase-separated morphology, leading to a rather disordered structure. Upon annealing at a sufficiently high temperature that exceeds the crystal melting point (i.e., 180 or $210 \text{ }^{\circ}\text{C}$), the driving force for the microphase separation of Glc₁-bz-DToc led to the formation of well-ordered GYR structures ($a_{\text{GYR}} =$

13.8 and 13.7 nm for the samples annealed at 180 and 210 °C, respectively) (**Figure 3.9©**).

It is important to note that different morphologies were observed between Glc₁-bz-DLToc and Glc₁-bz-DToc at these two annealing temperatures, wherein the racemic and chiral BCO displayed HEX and GYR structures, respectively, demonstrating that the chirality of tocopherol has a strong influence on the self-assembly behavior in Glc₁-bz-Toc. However, such a significant effect was not observed for the Glc₁-hex-Toc specimen bearing a hexanoate linker. This implies that a rigid benzoate linker may amplify the chirality of the tocopherol block.

(a) SAXS profiles of Glc₁-bz-DLToc(b) WAXS profiles of Glc₁-bz-DLToc(c) SAXS profiles of Glc₁-bz-DToc(d) WAXS profiles of Glc₁-bz-DToc(e) HPL_{ABC} structure

(f) HEX structure



(g) GYR structure

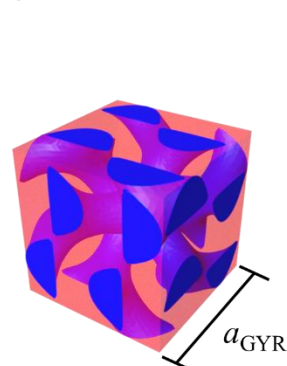


Figure 3.9. (a, c) SAXS and (b, d) WAXS profiles of the as-synthesized and thermally annealed Glc₁-bz-DLToc and Glc₁-bz-DToc specimens. Schematic illustrations for the HPL_{ABC}, (f) HEX, and (g) GYR structures are also provided.

Finally, the author investigated the thin film morphologies of Glc₁-bz-DLToc and Glc₁-bz-DToc using GISAXS measurements. Although Glc₁-bz-DLToc and Glc₁-bz-DToc formed different morphologies in the bulk, both thin films showed a similar self-assembly behavior. More specifically, the as-cast thin films formed horizontally oriented LAM structures ($d = 5.4\text{--}6.2$ nm), while the HPL_{ABC} ($a = 9.0\text{--}13.3$, $c = 17.2\text{--}18.7$ nm) and GYR morphologies ($a_{\text{GYR}} = 13.9\text{--}14.7$ nm) were observed upon the thermal annealing at 130–180 °C for 6 h, respectively (**Figure S3.18** and **S3.19**). Notably, the GYR structure was obtained from both Glc₁-bz-DLToc and Glc₁-bz-DToc thin films even after thermal annealing at 210 °C (**Figure 3.10(a)** and **(b)**), which differs from the results obtained for the bulk sample. Indeed, these results demonstrated that the Glc₁-bz-DLToc species annealed at 210 °C formed a HEX structure in the bulk state. Interestingly, by comparing the GISAXS 2D scattering images of the Glc₁-bz-DLToc and Glc₁-bz-DToc thin films annealed at 210 °C, it was revealed that the optically pure Glc₁-bz-DToc formed more orderly HPL_{ABC} and GYR structures than the Glc₁-bz-DLToc specimen, as evidenced by the presence of higher-order scattering spots (e.g., (332), (420), and (400) peaks). Furthermore, 1D azimuthal scattering profiles, which were extracted from the GISAXS 2D scattering images of Glc₁-bz-DLToc and Glc₁-bz-DToc, gave α_f values of 1.44 and 1.42°, respectively. The peak intensity and sharpness of each Gaussian fit curve demonstrated that Glc₁-bz-DToc exhibited a highly ordered GYR structure (**Figure 3.10(c)** and **(d)**), again confirming the positive effects of the tocopherol chirality on the arrangement of the nanostructure.

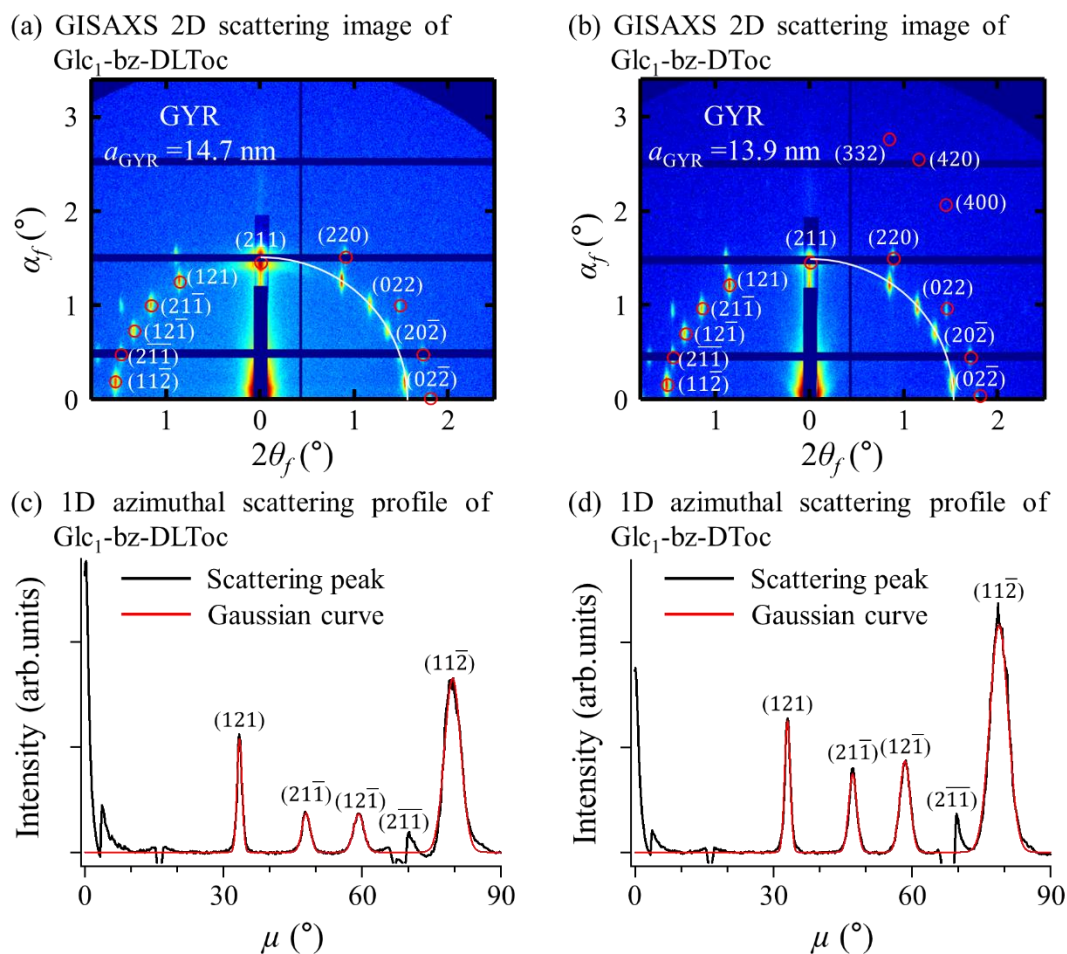


Figure 3.10. Representative GISAXS 2D scattering image of the nanoscale (a) Glc₁-bz-DLToc ($\alpha_i = 0.1062^\circ$) and (b) Glc₁-bz-DToc ($\alpha_i = 0.1013^\circ$) films (40–50 nm thick) annealed at 210 °C, where SDD = 1024.29 mm and $\lambda = 1.50$ Å. (c, d) The 1D azimuthal scattering profiles at $\alpha_f = 1.44$ and 1.42° (black) and their Gaussian fit curves (red), as determined from (a) and (b), respectively.

3.4 Conclusion

Ultrafine three-dimensional (3D) network morphologies (i.e., gyroid (GYR) and ABC -stacked hexagonally perforated lamellae (HPL_{ABC})), were successfully prepared from biobased sugar–terpenoid hybrid block co-oligomers (BCOs) consisting of glucose and tocopherol. After carrying out small-angle X-ray scattering (SAXS) measurements for a series of BCOs possessing different terpenoids, it became apparent that tocopherol is critical for ensuring the formation of a 3D network morphology, while the other terpenoids, namely farnesol and phytol, resulted in the generation of lamellar structures. These differences can be attributed to the molecular shapes of the corresponding tocopherols, along with the different volume fractions when combined with glucose. Importantly, the HPL_{ABC} and GYR structures were successfully obtained from BCOs consisting of glucose and tocopherol, even in the thin film state. The HPL_{ABC} structure, which is otherwise known as a metastable phase in block copolymers, was maintained even after prolonged high-temperature annealing at 180 °C in the thin film state, thereby confirming the utility of this system as a template for fabricating 3D network nanostructures. Furthermore, it was found that the stereochemistry of the tocopherol hydrocarbon chain affects the microphase separation behavior. Finally, the effects of the chemical structure of the bridging linker between the constituent blocks were examined, and it was deduced that a rigid benzoate linker amplified the chirality effect of the hydrocarbon chain, leading to different morphologies. The insights obtained in this study are expected to greatly contribute to the molecular design of precise block copolymers and the construction of intricate nanostructural templates with ultrasmall feature sizes.

3.5 References

1. Stoykovich, M. P.; Nealey P. F. Block Copolymers and Conventional Lithography. *Mater. Today*. **2006**, 9, 20–29.
2. De La Olvera Cruz, M. Theory of Microphase Separation in Block Copolymer Solutions. *J. Chem. Phys.*, **1989**, 90, 1995–2002.
3. Bates, F. S.; Fredrickson, G. H. Block Copolymers-Designer Soft Materials. *Phys. Today*, **1999**, 52, 32–38.
4. Bates, F. S.; Bair, H. E.; Hartney, M. A. Block Copolymers Near the Microphase Separation Transition. 1. Preparation and Physical Characterization of a Model System. *Macromolecules*, **1984**, 17, 1987–1993.
5. Li, X.; Wang, C.; Zhou, J.; Yang, Z.; Zhang, Y.; Deng, H. Ultra-Fast Block Copolymers for Sub-5nm Lithographic Patterning. *J. Photopolym. Sci. Technol.*, **2018**, 31, 483–486.
6. Ji, S.; Wan, L.; Liu, C. C.; Nealey, P. F. Directed Self-Assembly of Block Copolymers on Chemical Patterns: a Platform for Nanofabrication. *Prog. Polym. Sci.*, **2016**, 54–55, 76–127.
7. Shao, Y.; Hou, B.; Li, W.; Yan, X.; Wang, X.; Xu, Y.; Dong, Q.; Li, W.; He, J.; Bin Zhang, W. Three-Component Bolaform Giant Surfactants Forming Lamellar Nanopatterns with Sub-5nm Feature Sizes. *Macromolecules*, **2023**, 56, 1562–1571.
8. Hou, B.; Zhang, W.-B.; Shao, Y. Unconventional 2D Periodic Nanopatterns Based on Block Molecules. *Chinese J. Polym. Sci.*, **2023**, 41, 1508–1524.

9. Oh, J.; Suh, H. S.; Ko, Y.; Nah, Y.; Lee, J. C.; Yeom, B.; Char, K.; Ross C. A.; Son, J. G. Universal Perpendicular Orientation of Block Copolymer Microdomains Using a Filtered Plasma. *Nat. Commun.*, **2019**, *10*, 2912.
10. Phillip, W. A.; O'Neill, B.; Rodwogin, M.; Hillmyer, M. A.; Cussler, E. L. Self-Assembled Block Copolymer Thin Films as Water Filtration Membranes. *ACS Appl. Mater. Interfaces*, **2010**, *2*, 847–853.
11. Cochran, E. W.; Garcia-Cervera, C. J.; Fredrickson, G. H. Stability of The Gyroid Phase in Diblock Copolymers at Strong Segregation. *Macromolecules*, **2006**, *39*, 4264–4264.
12. Hajduk, D. A.; Harper, P. E.; Gruner, S. M.; Honeker, C. C.; Kim, G.; Thomas, E. L.; Fetters, L. J. The Gyroid: a New Equilibrium Morphology in Weakly Segregated Diblock Copolymers. *Macromolecules*, **2002**, *27*, 4063–4075.
13. Wu, H.; Huang, H.; Zhang, Y.; Lu, X.; Majewski, P. W.; Feng, X. Stabilizing Differential Interfacial Curvatures by Mismatched Molecular Geometries: Toward Polymers with Percolating 1 nm Channels of Gyroid Minimal Surfaces. *ACS Nano*, **2022**, *16*, 21139–21151.
14. Hsu, C. H.; Yue, K.; Wang, J.; Dong, X. H.; Xia, Y.; Jiang, Z.; Thomas, E. L.; Cheng, S. Z. D. Thickness-Dependent Order-to-Order Transitions of Bolaform-Like Giant Surfactant in Thin Films. *Macromolecules*, **2017**, *50*, 7282–7290.
15. Shan, W.; Zhang, W.; Huang, M.; Ji, Y.; Zhang, R.; Zhang, R.; Su, Z.; Liu, H.; Feng, X.; Guo, D.; Huang, J.; Liu, T.; Li, T.; Mao, J.; Wesdemiotis, C.; Shi, A. C.; Cheng, S. Z. D. Fine-Tuned Order-Order Phase Transitions in Giant Surfactants via Interfacial Engineering, *Giant*, **2020**, *1*, 100002.

16. Khalatur P. G.; Khokhlov, A. R. Nonconventional Scenarios of Polymer Self-Assembly *Soft Matter*, **2013**, 9, 10943–10954.
17. Thomas, E. L.; Alward, D. B.; Kinning, D. J.; Martin, D. C.; Handlin Jr., D. L.; Fetters, L. J. Ordered bicontinuous double-diamond structure of star block copolymers: a new equilibrium microdomain morphology. *Macromolecules*, **2002**, 19, 2197–2202.
18. Likhtman, A. E.; Semenov, A. N. Stability of The OBDD Structure for Diblock Copolymer Melts in The Strong Segregation Limit. *Macromolecules*, **2002**, 27, 3103–3106.
19. Takagi, W.; Suzuki, J.; Aoyama, Y.; Mihira, T.; Takano, A.; Matsushita, Y. Bicontinuous Double-Diamond Structures Formed in Ternary Blends of AB Diblock Copolymers with Block Chains of Different Lengths. *Macromolecules*, **2019**, 52, 6633–6640.
20. Chu, C. Y.; Jiang, X.; Jinnai, H.; Pei, R. Y.; Lin, W. F.; Tsai, J. C.; Chen, H. L. Real-Space Evidence of The Equilibrium Ordered Bicontinuous Double Diamond Structure of a Diblock Copolymer. *Soft Matter*, **2015**, 11, 1871–1876.
21. Vukovic, I.; Ten Brinke, G.; Loos, K. Hexagonally Perforated Layer Morphology in PS-*b*-P4VP(PDP) Supramolecules. *Macromolecules*, **2012**, 45, 9409–9418.
22. Wen, T.; Wang, H. F.; Georgopoulos, P.; Avgeropoulos, A.; Ho, R.-M. Three-Dimensional Visualization of Phase Transition in Polystyrene-block-Polydimethylsiloxane Thin Film. *Polymer*, **2019**, 167, 209–214.
23. Matsen, M. W.; Bates, F. S. Unifying Weak- and Strong-Segregation Block Copolymer Theories. *Macromolecules*, **1996**, 29, 1091–1098.

24. Matsen, M. W.; Bates, F. S. Origins of Complex Self-Assembly in Block Copolymers. *Macromolecules*, **1996**, 29, 7641–7644.
25. Mukherjee, A.; Ankit, K.; Reiter, A.; Selzer, M.; Nestler, B. Electric-Field-Induced Lamellar to Hexagonally Perforated Lamellar Transition in Diblock Copolymer Thin Films: Kinetic Pathways. *Phys. Chem. Chem. Phys.*, 2016, **18**, 25609–25620.
26. Jung, J.; Park, H. W.; Lee, J.; Huang, H.; Chang, T.; Rho, Y.; Ree, M.; Sugimori, H.; Jinnai, H. Structural Characterization of The Fddd Phase in a Diblock Copolymer Thin Film by Electron Microtomography. *Soft Matter*, **2011**, 7, 10424–10428.
27. Wang, Y.-C.; Kim, M. I.; Akasaka, S.; Saijo, K.; Hasegawa, H.; Hikima, T.; Takenaka, M. Fddd Structure in Polystyrene-block-Polyisoprene Diblock Copolymer/Polystyrene Homopolymer Blends. *Macromolecules*, **2016**, 49, 2257–2261.
28. Urade, V. N.; Wei, T.-C.; Tate, M. P.; Kowalski, J. D.; Hillhouse, H. W. Nanofabrication of Double-Gyroid Thin Films. *Chem. Mater.*, **2007**, 19, 768–777.
29. Yamada, K.; Nonomura, M.; Ohta, T. Fddd Structure in AB-Type Diblock Copolymers. *J. Phys. Condens. Matter*, **2006**, 18, L421–L427.
30. Yang, K. C.; Yao, C. T.; Huang, L. Y.; Tsai, J. C.; Hung, W. S.; Hsueh, H. Y.; Ho, R. M. Single Gyroid-Structured Metallic Nanoporous Spheres Fabricated from Double Gyroid-Forming Block Copolymers via Templated Electroless Plating. *NPG Asia Mater.*, **2019**, 11, 9.
31. González-Castaño, M.; Baena-Moreno, F.; Carlos Navarro de Miguel, J.; Miah, K. U. M.; Arroyo-Torralvo, F.; Ossenbrink, R.; Odriozola, J. A.; Benzinger, W.; Hensel, A.; Wenka, A.; Arellano-García, H. 3D-Printed Structured Catalysts for CO₂

- Methanation Reaction: Advancing of Gyroid-Based Geometries. *Energy Convers. Manag.*, **2022**, 258, 115464.
32. Li, L.; Schulte, L.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S. Gyroid Nanoporous Membranes with Tunable Permeability. *ACS Nano*, **2011**, 5, 7754–7766.
33. Li, L.; Szewczykowski, P.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S. Ultrafiltration by Gyroid Nanoporous Polymer Membranes *J. Memb. Sci.*, **2011**, 384, 126–135.
34. Zheng, S.; Hoang, M. C.; Du Nguyen, V.; Go, G.; Nan, M.; Darmawan, B. A.; Kim, S.; Im, S. H.; Lee, T.; Bang, D.; Park, J. O.; Choi, E. Microrobot with Gyroid Surface and Gold Nanostar for High Drug Loading and Near-Infrared-Triggered Chemo-Photothermal Therapy. *Pharmaceutics*, **2022**, 14(11), 2393.
35. Lee, H. C.; Hsueh, H. Y.; Jeng, U. S.; Ho, R. M. Functionalized Nanoporous Gyroid SiO₂ with Double-Stimuli-Responsive Properties as Environment-Selective Delivery Systems, *Macromolecules*, **2014**, 47, 3041–3051.
36. Tella, J. O.; Adekoya, J. A.; Ajanaku, K. O. Mesoporous Silica Nanocarriers as Drug Delivery Systems for Anti-Tubercular Agents: a Review. *R. Soc. Open Sci.*, **2022**, 9, 6.
37. Urbas, A. M.; Maldovan, M.; DeRege, P.; Thomas, E. L. Bicontinuous Cubic Block Copolymer Photonic Crystals. *Adv. Mater.*, **2002**, 14, 1850–1853.
38. Peng, S.; Zhang, R.; Chen, V. H.; Khabiboulline, E. T.; Braun, P.; Atwater, H. A. Three-Dimensional Single Gyroid Photonic Crystals with a Mid-Infrared Bandgap. *ACS Photonics*, **2016**, 3, 1131–1137.

39. Fruchart, M.; Jeon, S. Y.; Hur, K.; Cheianov, V.; Wiesner, U.; Vitelli, V. Soft Self-Assembly of Weyl Materials for Light and Sound. *Proc. Natl. Acad. Sci. U. S. A.*, **2018**, *115*, E3655–E3664.
40. Crossland, E. J. W.; Kamperman, M.; Nedelcu, M.; Ducati, C.; Wiesner, U.; Smilgies, D. -M.; Toombes, G. E. S.; Hillmyer, M. A.; Ludwigs, S.; Steiner, U.; Snaith, H. J. A Bicontinuous Double Gyroid Hybrid Solar Cell. *Nano Lett.*, **2008**, *9*, 2807–2812.
41. Zalusky, A. S.; Olayo-Valles, R.; Taylor, C. J.; Hillmyer, M. A. Mesoporous Polystyrene Monoliths. *J. Am. Chem. Soc.*, **2001**, *123*, 1519–1520.
42. Wang, X.-B.; Lo, T.-Y.; Hsueh H.-Y.; Ho, R.-M. Double and Single Network Phases in Polystyrene-block-Poly(L-lactide) Diblock Copolymers. *Macromolecules*, **2013**, *46*, 2997–3004.
43. Barriga, H. M. G.; Holme, M. N.; Stevens, M. M. Cubosomes: the Next Generation of Dmart Lipid Nanoparticles?. *Angew. Chemie. Int. Ed.*, **2019**, *58*, 2958–2978.
44. Park, W. I.; Kim, Y.; Jeong, J. W.; Kim, K.; Yoo, J. K.; Hur, Y. H.; Kim, J. M.; Thomas, E. L.; Alexander-Katz, A.; Jung, Y. S. Host-Guest Self-Assembly in Block Copolymer Blends. *Sci. Rep.*, **2013**, *3*, 1–10.
45. Khandpur, A. K.; Förster, S.; Bates, F. S.; Hamley, I. W.; Ryan, A. J.; Bras, W.; Almdal, K.; Mortensen, K. Polyisoprene-Polystyrene Diblock Copolymer Phase Diagram Near the Order-Disorder Transition. *Macromolecules*, **1995**, *28*, 8796–8806.
46. Lin, C.-H.; Higuchi, T.; Chen, H.-L.; Tsai, J.-C.; Jinnai, H.; Hashimoto, T. Stabilizing the Ordered Bicontinuous Double Diamond Structure of Diblock Copolymer by Configurational Regularity. *Macromolecules*, **2018**, *51*, 4049–4058.

47. Ding, S.-P.; Zhang, Z.-K.; Ye, Z.; Du, B.-Y.; Xu, J.-T. Fabrication of High χ -Low N Block Copolymers with Thermally Stable Sub-5 nm Microdomains Using Polyzwitterion as a Constituent Block. *ACS Macro Lett.*, **2021**, *10*, 1321–1325.
48. Park, S. M.; Liang, X.; Harteneck, B. D.; Pick, T. E.; Hiroshiba, N.; Wu, Y.; Helms, B. A.; Olynick, D. L. Sub-10 nm Nanofabrication via Nanoimprint Directed Self-Assembly of Block Copolymers. *ACS Nano*, **2011**, *5*, 8523–8531.
49. Sinturel, C.; Bates, F. S.; Hillmyer, M. A. High χ -Low N Block Polymers: How Far Can We Go?. *ACS Macro Lett.*, **2015**, *4*, 1044–1050.
50. Shen, Z.; Luo, K.; Park, S. J.; Li, D.; Mahanthappa, M. K.; Bates, F. S.; Dorfman, K. D.; Lodge, T. P.; Ilja Siepmann, J. Stabilizing a Double Gyroid Network Phase with 2 nm Feature Size by Blending of Lamellar and Cylindrical Forming Block Oligomers. *JACS Au*, **2022**, *2*, 1405–1416.
51. Nowak, S. R.; Lachmayr, K. K.; Yager, K. G.; Sita, L. R. Stable Thermotropic 3D and 2D Double Gyroid Nanostructures with Sub-2-nm Feature Size from Scalable Sugar-Polyolefin Conjugates. *Angew. Chemie. Int. Ed.*, **2021**, *60*, 8710–8716.
52. Yu, X.; Yue, K.; Hsieh, F.; Li, Y.; Dong, X. H.; Liu, C.; Xin, Y.; Wang, H. F.; Shi, A. C.; Newkome, G. R.; Ho, R. M.; Chen, E. Q.; Bin Zhang, W.; Cheng, S. Z. D. Giant Surfactants Provide a Versatile Platform for Sub-10-nm Nanostructure Engineering. *Proc. Natl. Acad. Sci. U. S. A.*, **2013**, *110*, 10078–10083.
53. Cai, X.; Hauche, S.; Poppe, S.; Cao, Y.; Zhang, L.; Huang, C.; Tschierske, C.; Liu, F. Network Phases with Multiple-Junction Geometries at the Gyroid-Diamond Transition. *J. Am. Chem. Soc.*, **2023**, *145*, 1000–1010.

54. Isono, T.; Komaki, R.; Lee, C.; Kawakami, N.; Ree, B. J.; Watanabe, K.; Yoshida, K.; Mamiya, H.; Yamamoto, T.; Borsali, R.; Tajima, K.; Satoh, T. Rapid Access to Discrete and Monodisperse Block Co-oligomers from Sugar and Terpenoid toward Ultrasmall Periodic Nanostructures. *Commun. Chem.*, **2020**, *3*, 135.
55. Hashim, R.; Zahid, N. I.; Velayutham, T. S.; Aripin, N. F. K.; Ogawa, S.; Sugimura, A. Dry Thermotropic Glycolipid Self-Assembly: a Review. *J. Oleo Sci.*, **2018**, *67*, 651–668.
56. Von Minden, H. M.; Brandenburg, K.; Seydel, U.; Koch, M. H. J.; Garamus, V.; Willumeit, R.; Vill, V. Thermotropic and Lyotropic Properties of Long Chain Alkyl Glycopyranosides. Part II. Disaccharide Headgroups. *Chem. Phys. Lipids*, **2000**, *106*, 157–179.
57. Isono, T.; Komaki, R.; Kawakami, N.; Chen, K.; Chen, H.-L.; Lee, C.; Suzuki, K.; Ree, B. J.; Mamiya, H.; Yamamoto, T.; Borsali, R.; Tajima, K.; Satoh, T. Tailored Solid-State Carbohydrate Nanostructures Based on Star-Shaped Discrete Block Co-oligomers. *Biomacromolecules*, **2022**, *23*, 3978–3989.
58. Israelachvili, J. N. *Intermolecular and Surface Forces: Third Edition*, Elsevier Inc., 2011.
59. Grandjean, C.; Boutonnier, A.; Guerreiro, C.; Fournier, J.-M.; Mulard, L. A. On the Preparation of Carbohydrate–Protein Conjugates Using the Traceless Staudinger Ligation. *J. Org. Chem.*, **2005**, *70*, 7123–7132.
60. Daly, R.; Vaz, G.; Davies, A. M.; Senge, M. O.; Scanlan, E. M. Synthesis and Biological Evaluation of a Library of Glycoporphyrin Compounds. *Chem. Eur. J.*, **2012**, *18*, 14671–14679.

61. Ogawa, S.; Asakura K.; Osanai, S. Lyotropic Behavior of a Mono-Tailed Glycolipid Assembly During Solidification and Melting of Electrolyte/Ice Eutectic Systems. *Chem. Pharm. Bull.*, 2014, **62**, 1180–1184.
62. Misran, O.; Timimi, B. A.; Heidelberg, T.; Sugimura, A.; Hashim, R.; Deuterium NMR Investigation of the Lyotropic Phases of Alkyl β -glycoside/D₂O Systems. *J. Phys. Chem. B*, **2013**, *117*, 7355–7344.
63. Seddon, J. M.; Zeb, N.; Templer, R. H.; McElhaney, R. N.; Mannock, D. A. An *Fd3m* Lyotropic Cubic Phase in a Binary Glycolipid/Water System. *Langmuir*, **1996**, *12*, 5250–5253.
64. Garidel, P.; Kaconis, Y.; Heinbockel, L.; Wulf, M.; Gerber, S.; Munk, A.; Vill, V. , Brandenburg, K. Self-Organisation, Thermotropic and Lyotropic Properties of Glycolipids Related to their Biological Implications. *Open Biochem. J.*, **2015**, *9*, 49–72.
65. Mannock, D. A.; McElhaney, R. N. Thermotropic and Lyotropic Phase Properties of Glycolipid Diastereomers: Role of Headgroup and Interfacial Interactions in Determining Phase Behaviour. *Curr. Opin. Colloid Interface Sci.*, **2004**, *8*, 426–447.
66. Zha, R. H.; De Waal, B. F. M.; Lutz, M.; Teunissen, A. J. P.; Meijer, E. W. End Groups of Functionalized Siloxane Oligomers Direct Block-Copolymeric or Liquid-Crystalline Self-Assembly Behavior. *J. Am. Chem. Soc.*, **2016**, *138*, 5693–5698.
67. Vill, V.; Minden, H. M. von; Koch, M. H. J.; Seydel, U.; Brandenburg, K. Thermotropic and Lyotropic Properties of Long Chain Alkyl Glycopyranosides: Part I: Monosaccharide Headgroups. *Chem. Phys. Lipids*, **2000**, *104*, 75–91.

68. Vill, V.; Böcker, T.; Thiem, J.; Fischer, F. Studies on Liquid-Crystalline Glycosides. *Liq. Cryst.*, **1989**, *6*, 349–356.
69. Boydirc, B. J.; Drummond, C. J.; Krodkiewska, I.; Grieser, F. How Chain Length, Headgroup Polymerization, and Anomeric Configuration Govern the Thermotropic and Lyotropic Liquid Crystalline Phase Behavior and the Air-Water Interfacial Adsorption of Glucose-based. *Langmuir*, **2000**, *16*, 7359–7367.

3.6 Supporting Information

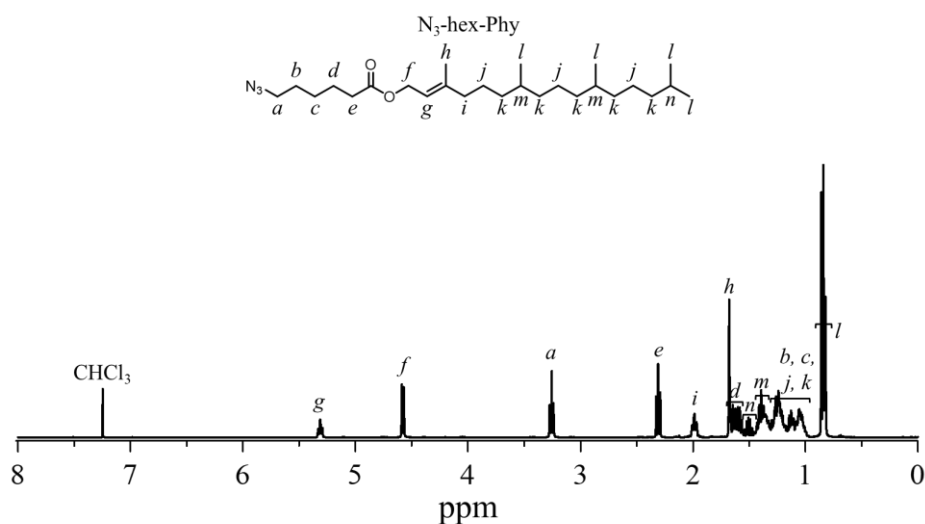
Synthesis of Glc₁-hex-Phy

Figure S3.1. ¹H NMR spectrum of N₃-hex-Phy (CDCl₃, 400 MHz).

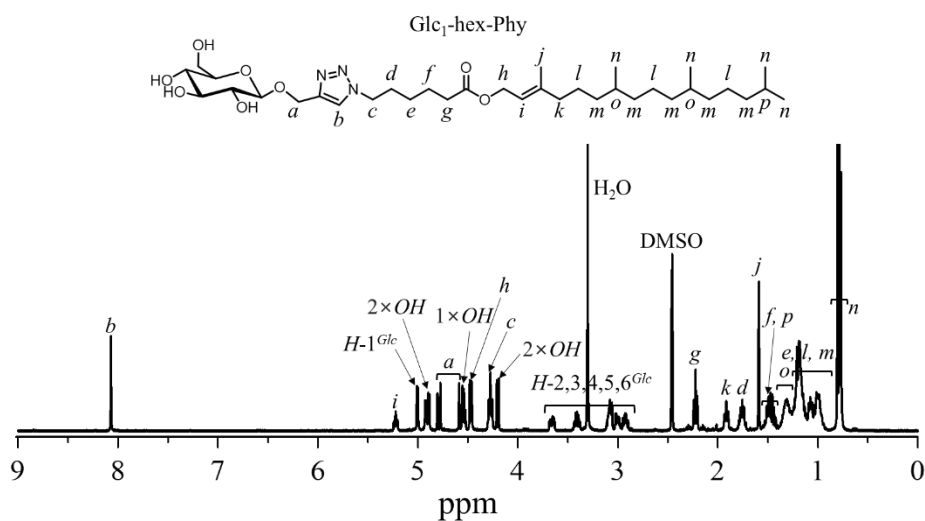


Figure S3.2. ¹H NMR spectrum of Glc₁-hex-Phy (DMSO-*d*₆, 400 MHz).

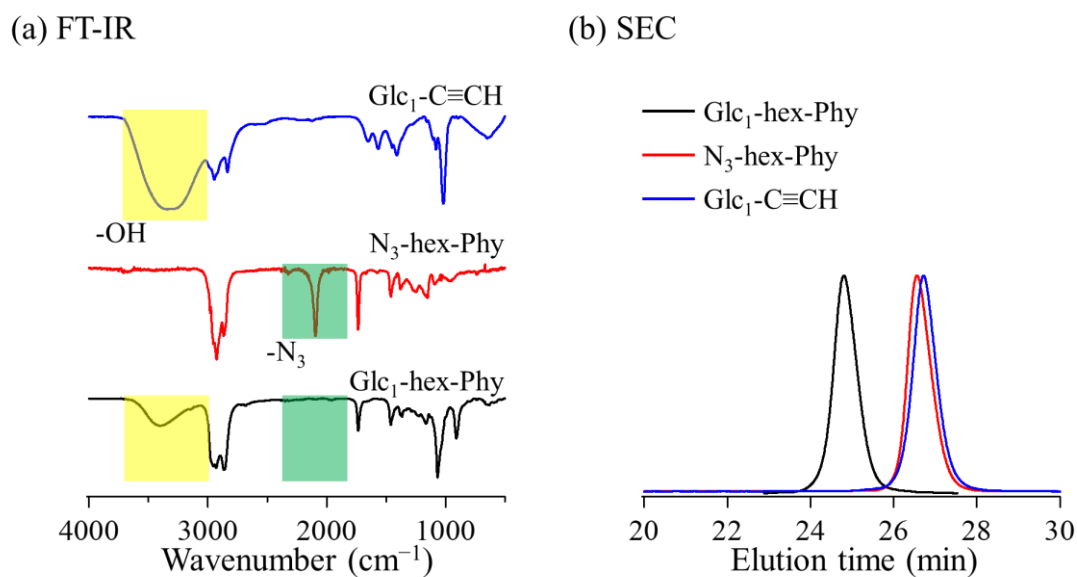


Figure S3.3. (a) FT-IR spectra of Glc₁-C≡CH (blue), N₃-hex-Phy (red), and Glc₁-hex-Phy (black). (b) SEC traces of Glc₁-C≡CH (blue), N₃-hex-Phy (red), and Glc₁-hex-Phy (black) (eluent, DMF containing 0.01 mol L⁻¹ LiCl; flow rate, 0.6 mL min⁻¹).

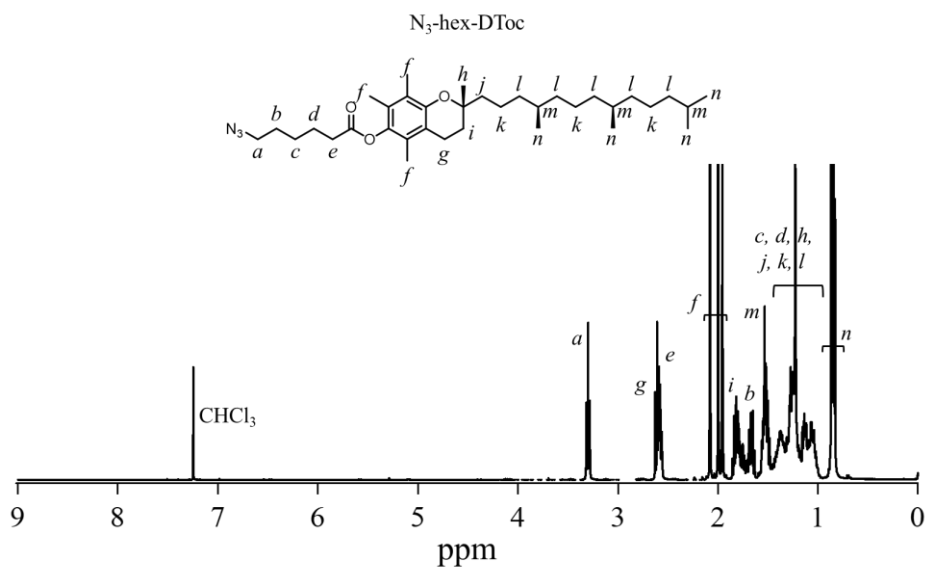
Synthesis of Glc₁-hex-Phy

Figure S3.4. ¹H NMR spectrum of N₃-hex-DToc (CDCl₃, 400 MHz).

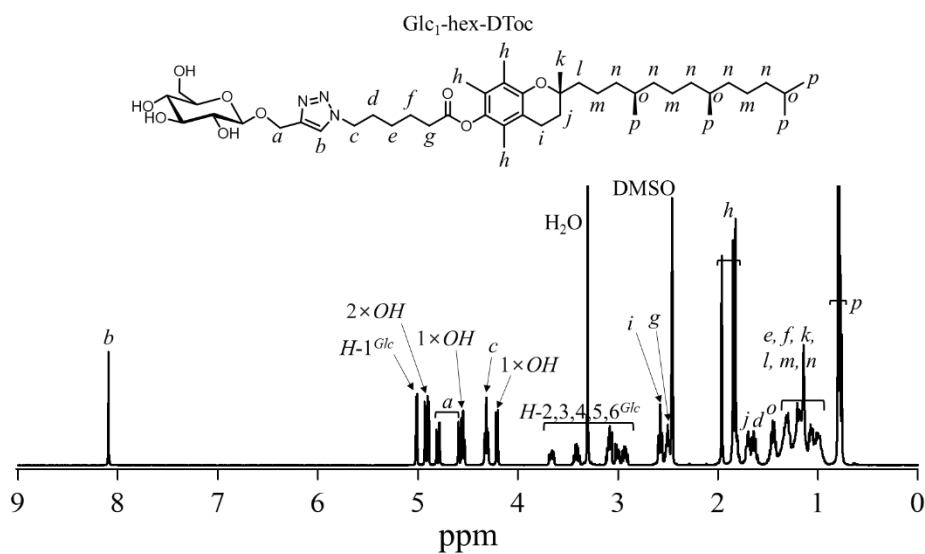


Figure S3.5. ¹H NMR spectrum of Glc₁-hex-DToc (DMSO-*d*₆, 400 MHz).

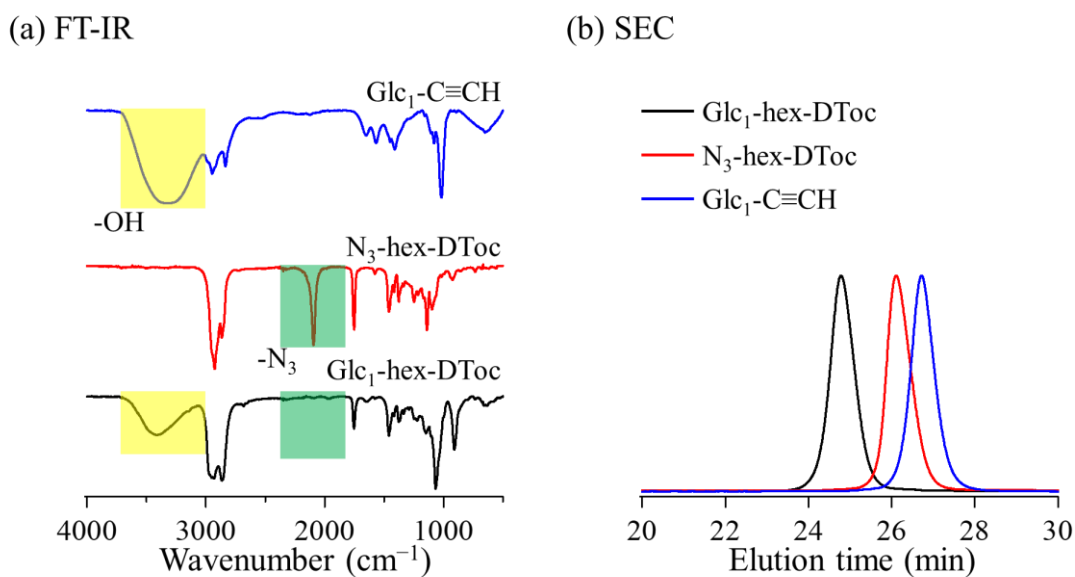


Figure S3.6. (a) FT-IR spectra of Glc₁-C≡CH (blue), N₃-hex-DToc (red), and Glc₁-hex-DToc (black). (b) SEC traces of Glc₁-C≡CH (blue), N₃-hex-DToc (red), and Glc₁-hex-DToc (black) (eluent, DMF containing 0.01 mol L⁻¹ LiCl; flow rate, 0.6 mL min⁻¹).

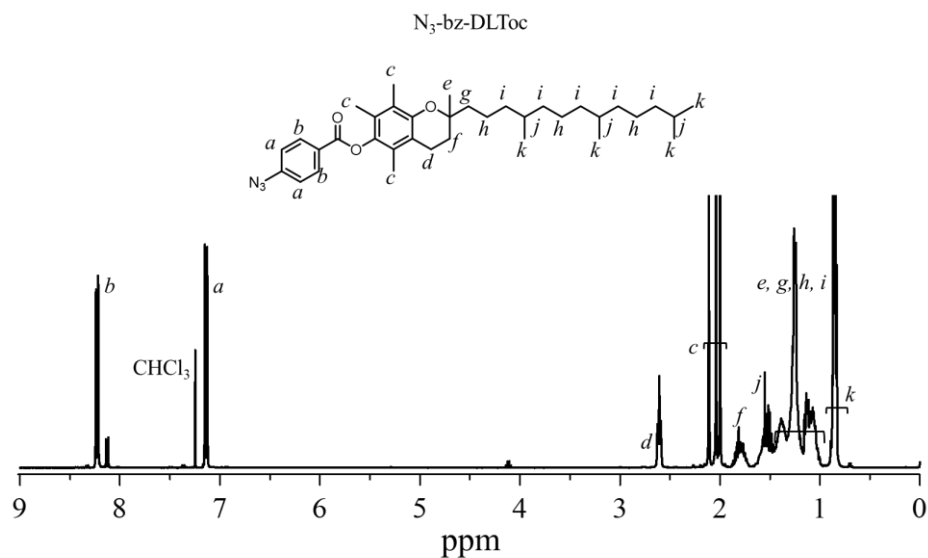
Synthesis of Glc₁-bz-DLToc

Figure S3.7. ¹H NMR spectrum of N₃-bz-DLToc (CDCl₃, 400 MHz).

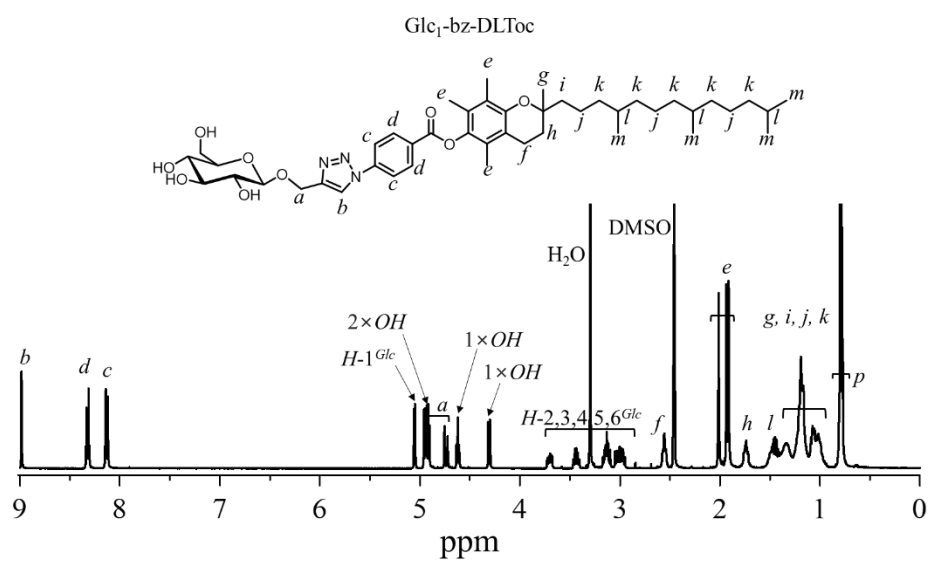


Figure S3.8. ¹H NMR spectrum of Glc₁-bz-DLToc (DMSO-*d*₆, 400 MHz).

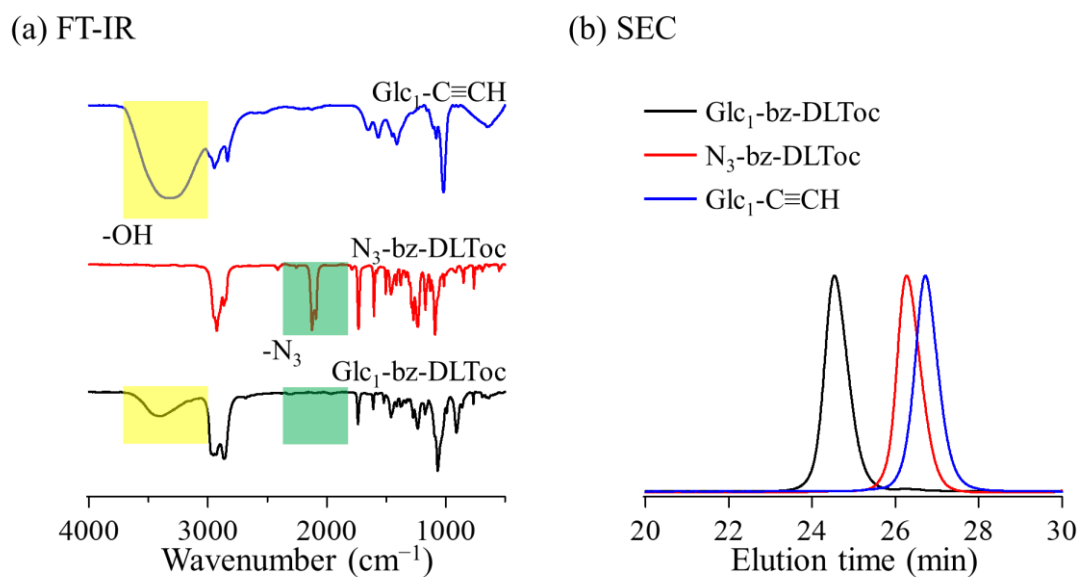


Figure S3.9. (a) FT-IR spectra of Glc₁-C≡CH (blue), N₃-bz-DLToc (red), and Glc₁-bz-DLToc (black). (b) SEC traces of Glc₁-C≡CH (blue), N₃-bz-DLToc (red), and Glc₁-bz-DLToc (black) (eluent, DMF containing 0.01 mol L⁻¹ LiCl; flow rate, 0.6 mL min⁻¹).

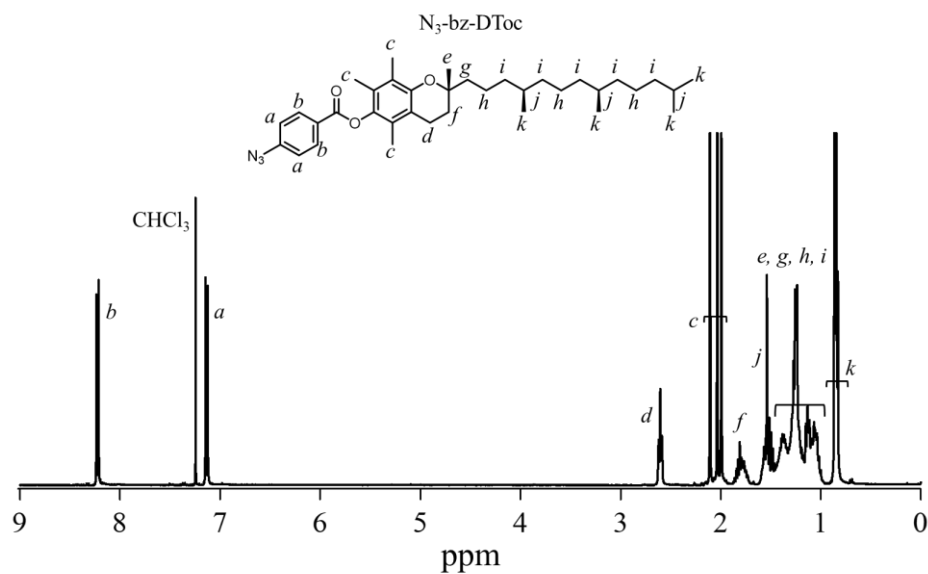
Synthesis of Glc₁-bz-DToc

Figure S3.10. ¹H NMR spectrum of N₃-bz-DToc (CDCl₃, 400 MHz).

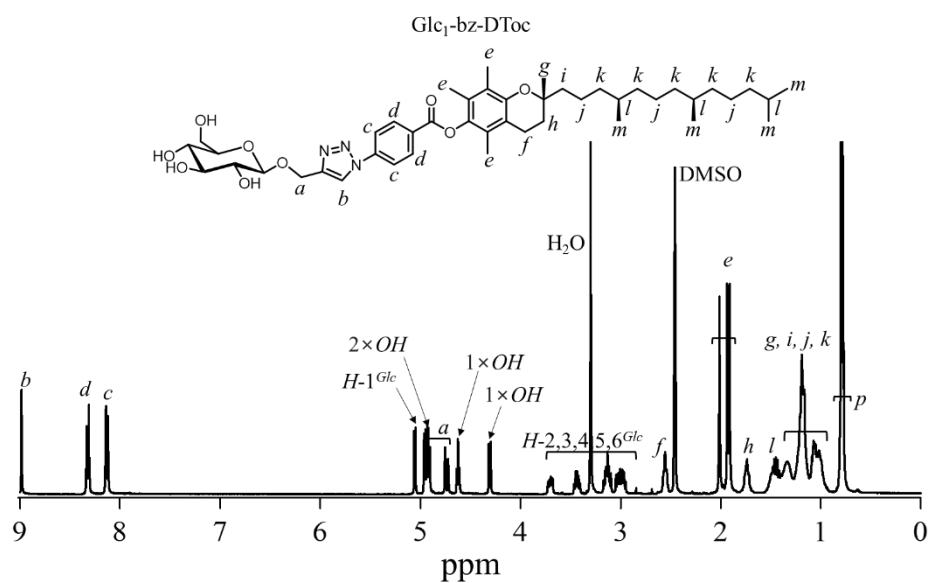


Figure S3.11. ¹H NMR spectrum of Glc₁-bz-DToc (DMSO-*d*₆, 400 MHz).

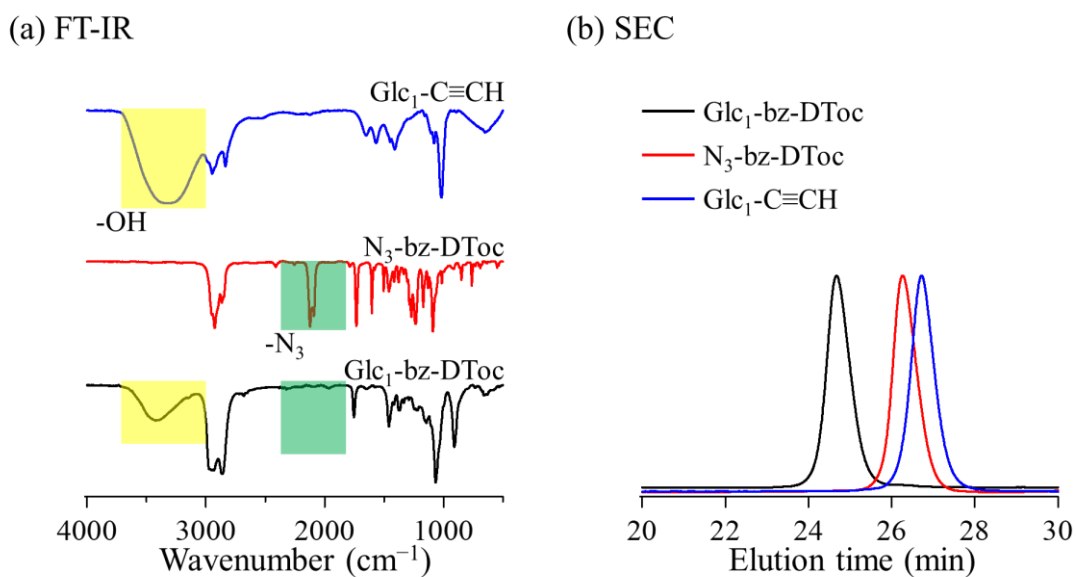


Figure S3.12. (a) FT-IR spectra of Glc₁-C≡CH (blue), N₃-bz-DToc (red), and Glc₁-bz-DToc (black). (b) SEC traces of Glc₁-C≡CH (blue), N₃-bz-DToc (red) and Glc₁-bz-DToc (black) (eluent, DMF containing 0.01 mol L⁻¹ LiCl; flow rate, 0.6 mL min⁻¹).

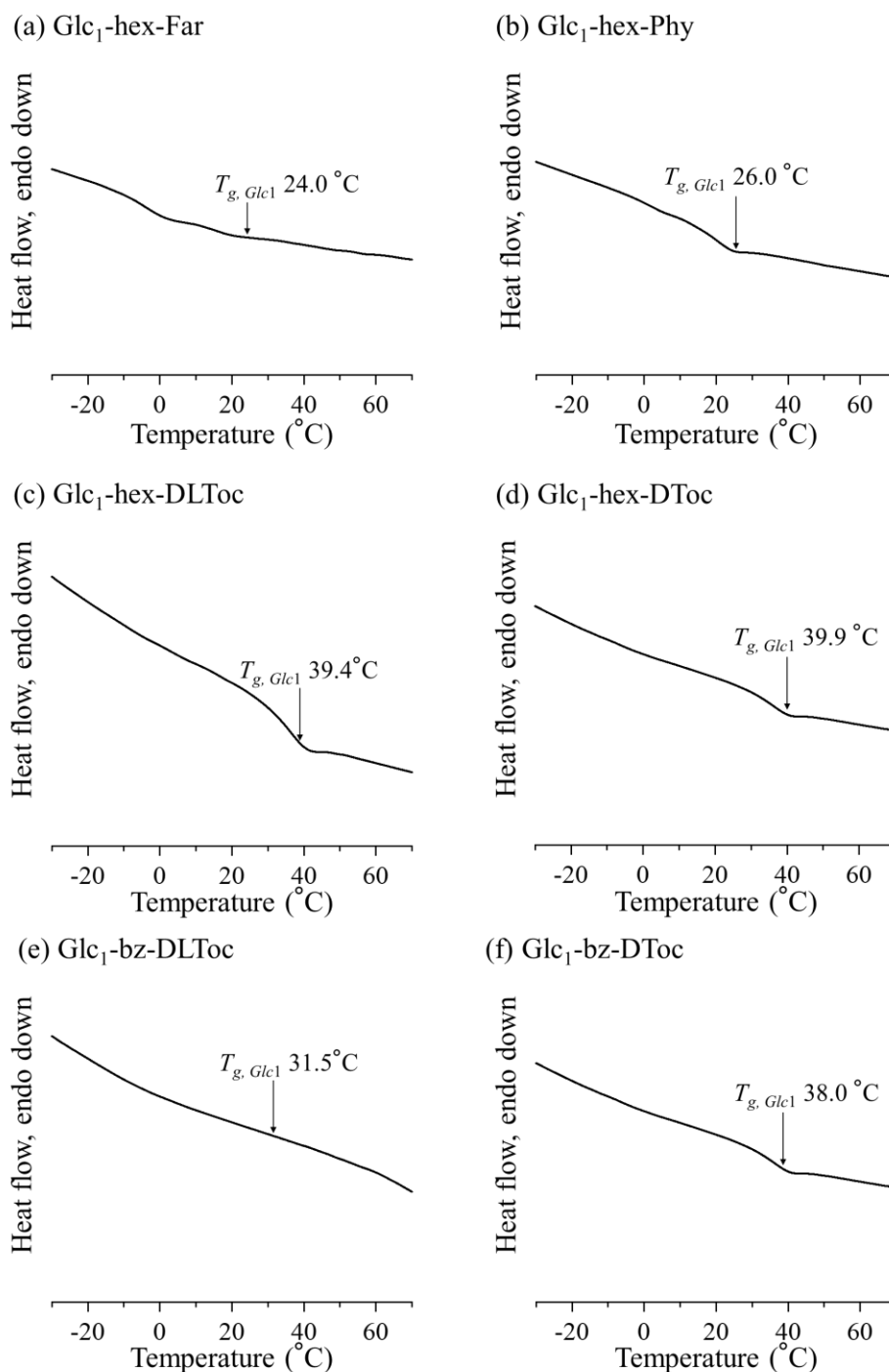
DSC measurement of BCOs

Figure S3.13. DSC traces of (a) Glc₁-hex-Far, (b) Glc₁-hex-Phy, (c) Glc₁-hex-DLToc, (d) Glc₁-hex-DToc, (e) Glc₁-bz-DLToc, and (f) Glc₁-bz-DToc during the second heating run (heating and cooling rate, $10\text{ }^{\circ}\text{C min}^{-1}$).

TGA measurement of BCOs

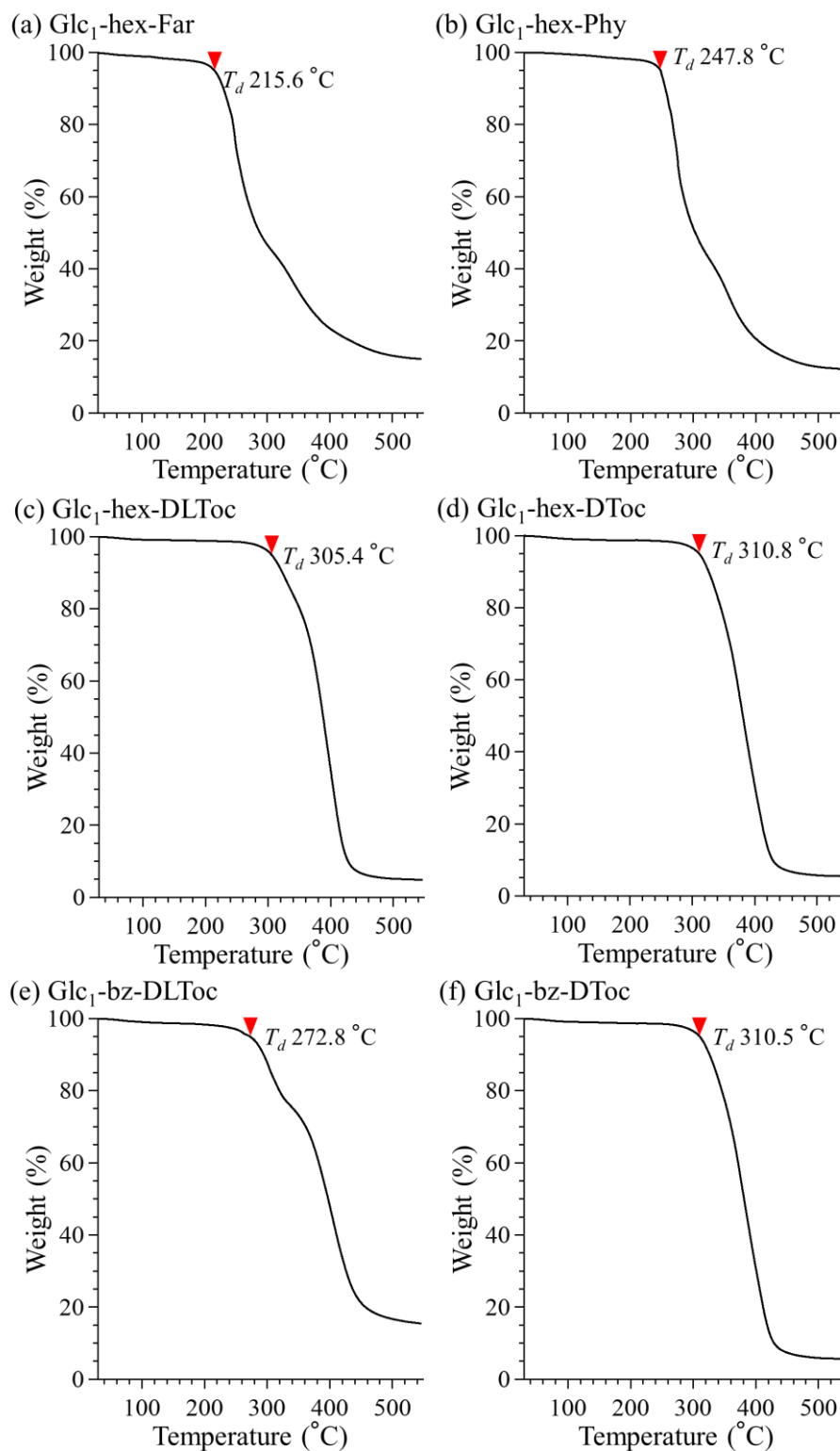


Figure S3.14. TGA traces of (a) Glc₁-hex-Far, (b) Glc₁-hex-Phy, (c) Glc₁-hex-DLToc, (d) Glc₁-hex-DToc, (e) Glc₁-bz-DLToc, and (f) Glc₁-bz-DToc with a heating rate of 10 °C min⁻¹ from 30 °C to 550 °C.

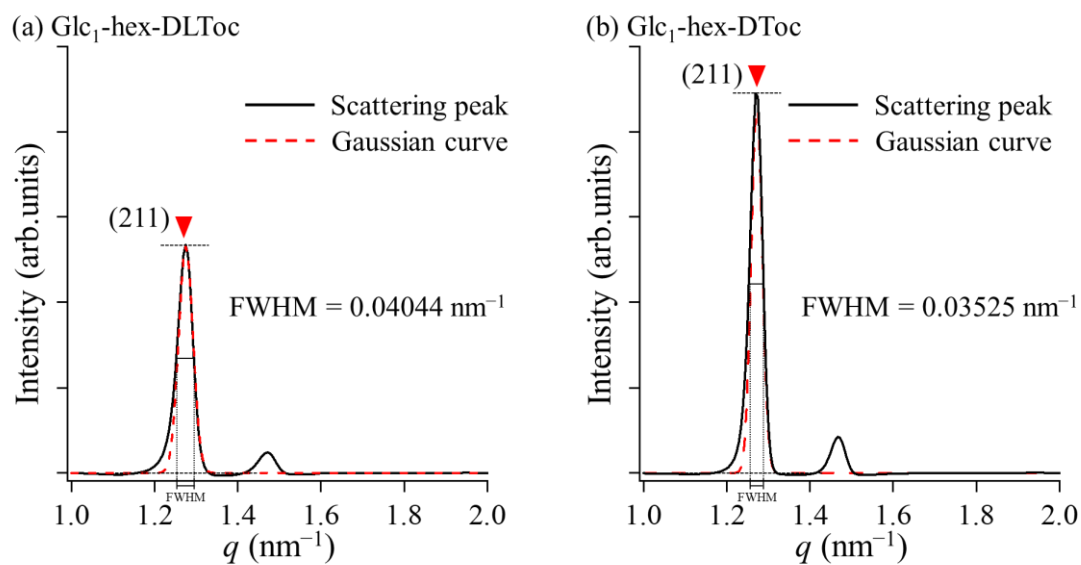
Gaussian fitting of scattering peaks derived from gyroid morphology

Figure S3.15. Gaussian fitting results for the SAXS profiles of (a) Glc₁-hex-DLToc and (b) Glc₁-hex-DToc which were annealed at 130 °C for 6 h.

GISAXS 2D scattering images of Glc₁-hex-DLToc and Glc₁-hex-DToc films

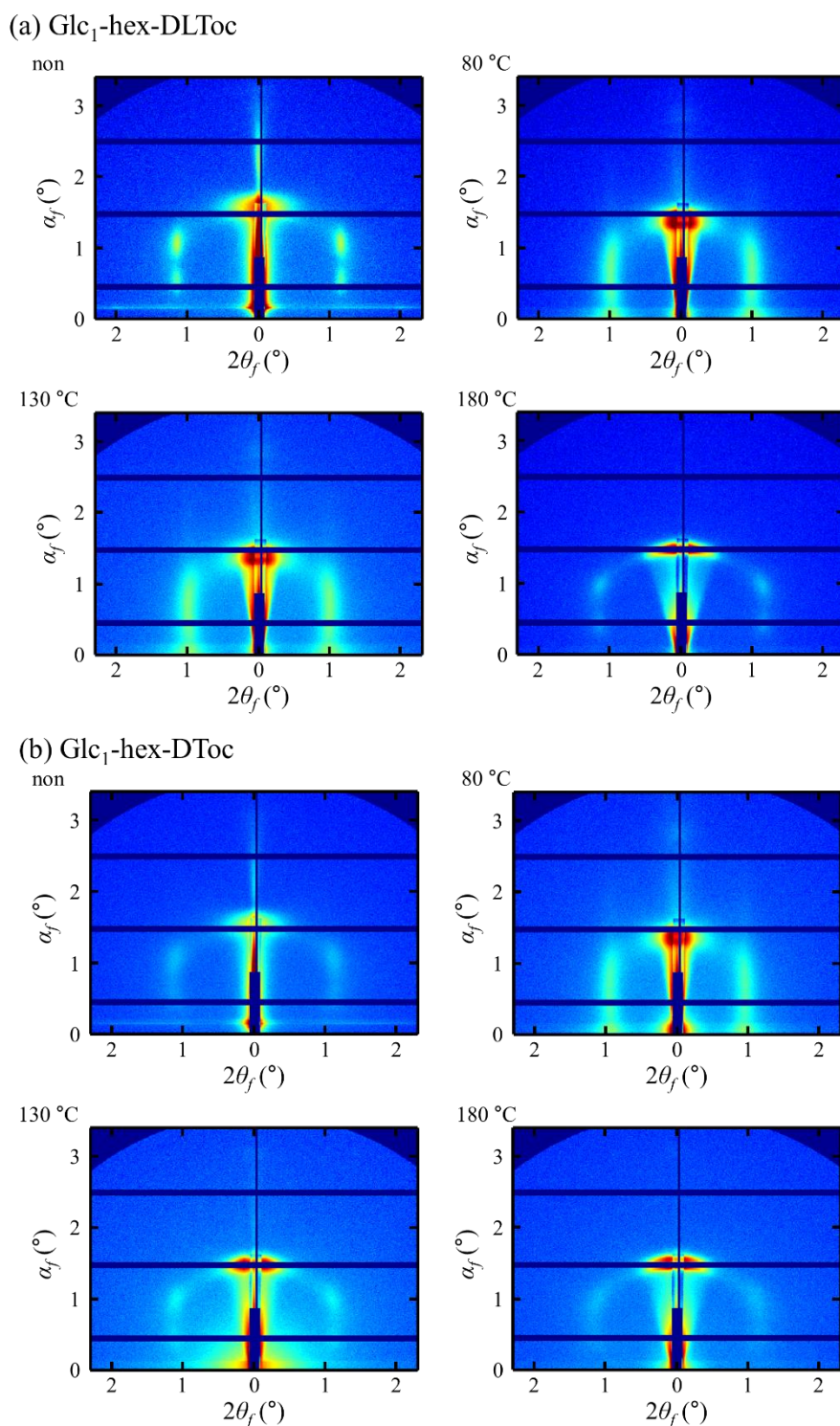


Figure S3.16. Representative GISAXS 2D scattering images with SDD = 2039.51 mm, and $\lambda = 1.50$ Å of (a) Glc₁-hex-DLToc and (b) Glc₁-hex-DToc film (40–50 nm thick) before and after thermal annealing at 80, 130, or 180 °C for 6 h.

GISAXS 2D scattering images of Glc₁-hex-DLToc and Glc₁-hex-DToc films after one month

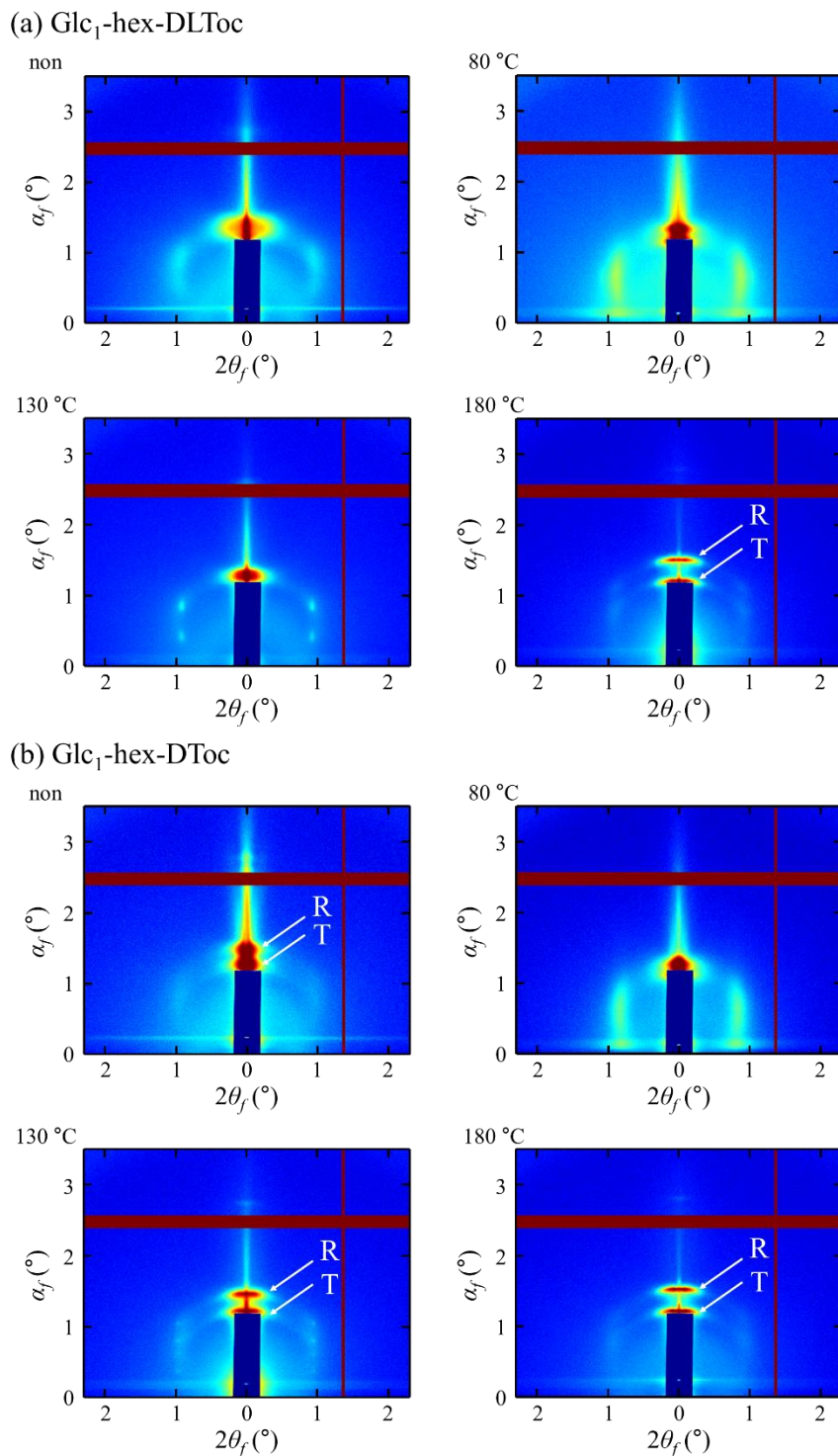


Figure S3.17. Representative GISAXS 2D scattering images with SDD = 859.77 mm, and $\lambda = 1.24 \text{ \AA}$ of same (a) Glc₁-hex-DLToc and (b) Glc₁-hex-DToc film samples at Figure S3.6.16 after one month. The scattering peaks generated by the reflected and transmitted X-ray beam are indicated as R and T, respectively.

GISAXS 2D scattering images of Glc₁-bz-DLToc films

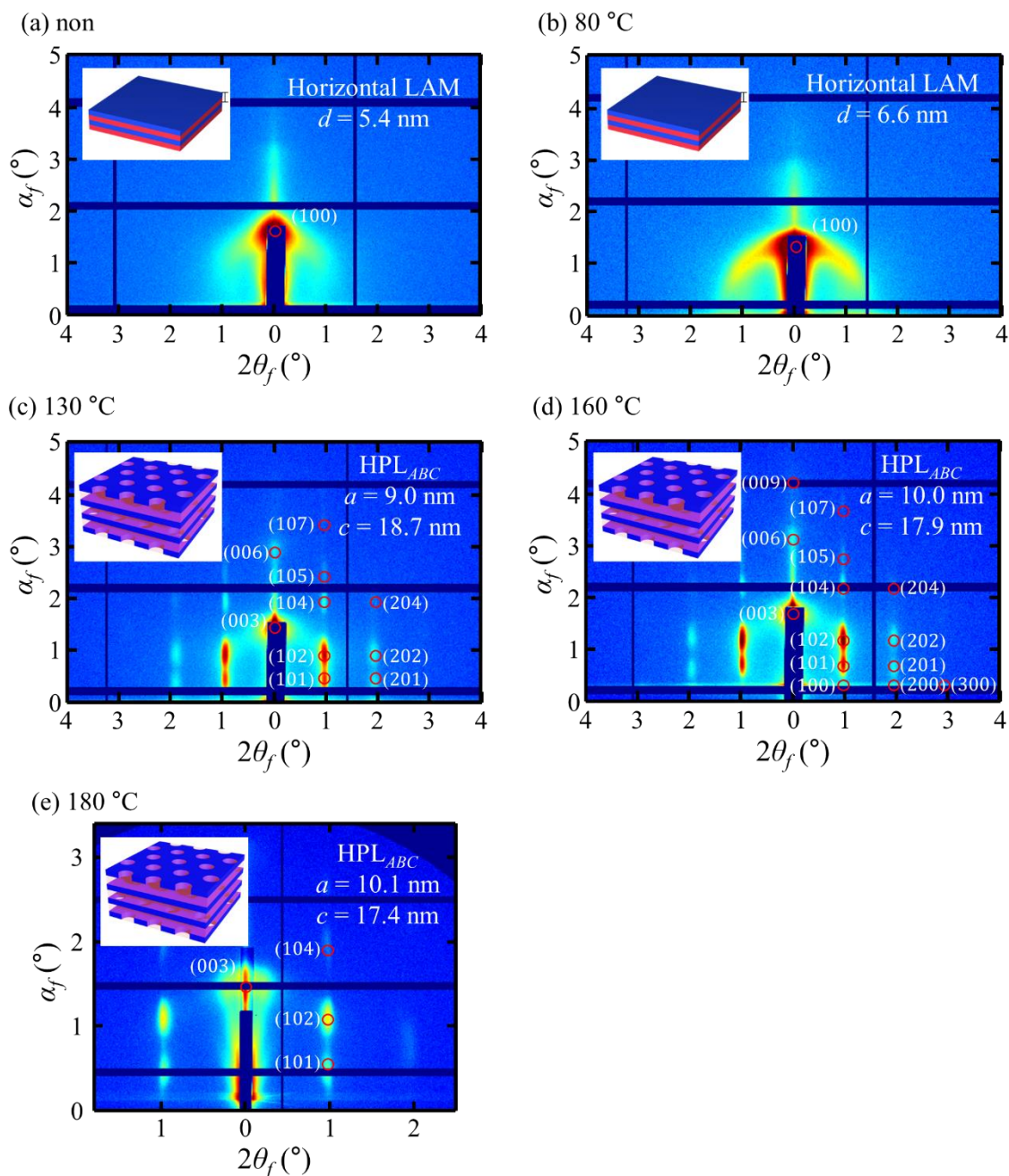


Figure S3.18. Representative GISAXS 2D scattering images of the (a) as-cast, (b) 80 °C, (c) 130 °C, (d) 160 °C (SDD = 2039.51 mm), and 180 °C-annealed (SDD = 2036.98 mm) nanoscale Glc₁-bz-DLToc film (40–50 nm thick) with $\lambda = 1.50$ Å.

GISAXS 2D scattering images of Glc₁-bz-DToc films

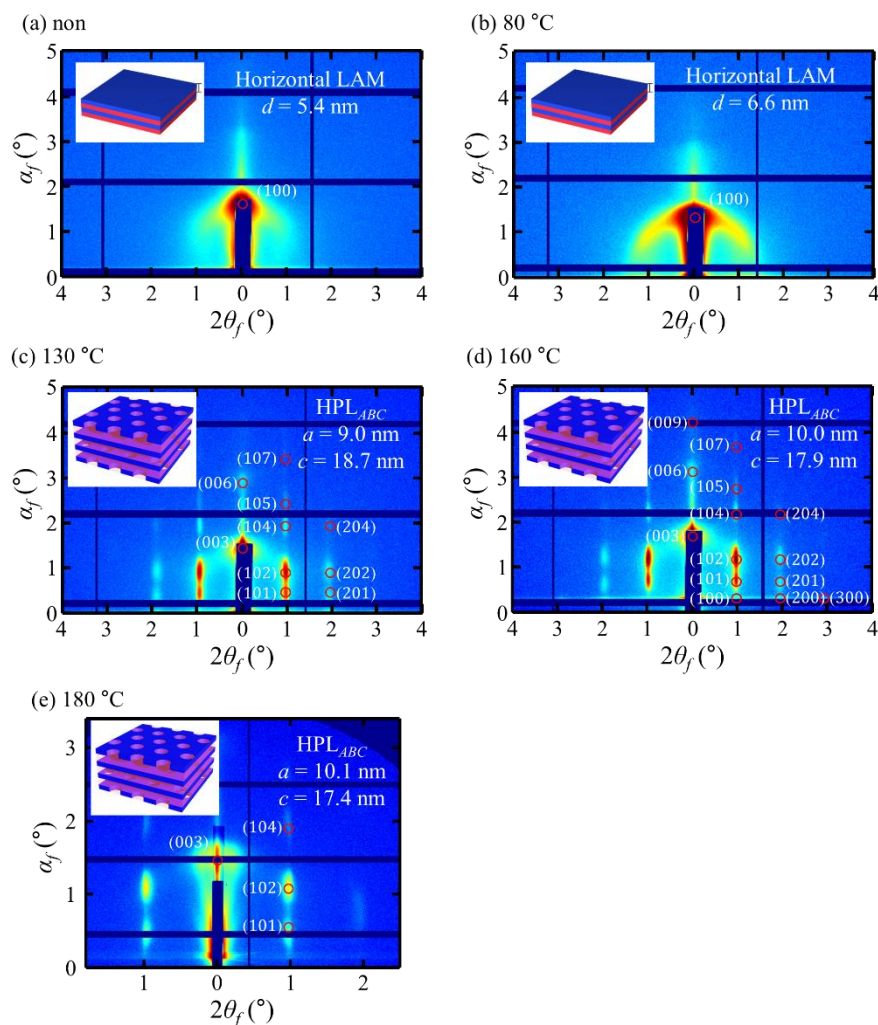


Figure S3.19. Representative GISAXS 2D scattering image of the (a) as-cast, (b) 80 °C, (c) 130 °C, (d) 160 °C (SDD = 1043.04 mm), and 180 °C-annealed (SDD = 2036.98 mm) nanoscale Glc₁-bz-DToc film (40–50 nm thick) with $\lambda = 1.50$ Å.

Chapter 4

Sugar-Rich

*Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers*

4.1 Introduction

Block copolymers (BCPs) self-assemble into microphase-separated structures due to the incompatibility between the constitutional chemically different polymer blocks and the constraints imposed by their covalent linkage. This unique phenomenon drives the formation of nanoscale morphologies, such as lamellae (LAM), gyroid (GYR), hexagonally packed cylinders (HEX), and body-centered cubic (BCC) spheres. These ordered morphologies are highly tunable based on the BCP molecular design, including the monomer selection, molecular weight, and volume fractions.¹⁻⁵

The BCP microphase separation to form various nanostructures has led to their extensive exploration in a wide range of nanotechnological applications.⁶⁻⁹ In lithographic application, microphase-separated BCPs serve as templates for creating nanopatterns with domain spacing below 20 nm, enabling advancements in semiconductor fabrication.¹⁰⁻¹³ Additionally, BCP-derived structures are leveraged in the preparation of filtration membranes with precise pore sizes, ideal for gas separation and water purification.^{6,14-22} Their optical properties also make them promising candidates for photonic devices, where the arrangement of microphase-separated domains can manipulate light at the nanoscale.²³ These versatile applications underscore the transformative potential of BCPs in addressing the challenges of next-generation nanomaterial design. In this field, the demand for materials capable of constructing ultrasmall structures, particularly those below 10 nm of domain spacing, continues to grow due to their critical role in applications. For instance, reducing the feature size of patterns is essential for the miniaturization of semiconductor devices, enabling higher-density integration and improved device performance. Similarly, nanoporous materials with sub-10 nm pores are essential for applications in molecular sieving, gas separation,

and catalysis, where precise control over pore size can significantly enhance efficiency and selectivity.

Achieving these ultrasmall structures requires the development of materials that can reliably self-assemble into highly ordered morphologies with sub-10 nm scale domain spacing. One promising approach to achieving such fine structures is reducing the degree of polymerization (N) while increasing the Flory-Huggins interaction parameter (χ) between the blocks.^{24–30} This approach enhances the segregation strength, allowing for well-defined morphologies even at low molecular weights. Nevertheless, conventional BCPs synthesized via polymerization reactions inherently exhibit molecular weight dispersity, which becomes particularly detrimental in the low-molecular-weight regime in terms of self-assembly. In this regime, even minor variations in chain length can disrupt microphase separation and lead to defects or loss of order in the resulting nanostructures. Furthermore, the reproducibility of these systems is often limited by batch-dependent variations in molecular weight and composition, hindering their application in precisely engineered nanostructures.

In *Chapter 2 and 3*, sugar–terpenoid block co-oligomers (BCOs) have been demonstrated as a powerful alternative to address these limitations.^{31–33} BCOs, characterized by their monodisperse and discrete degrees of polymerization for both constitutional blocks, offer precise control over molecular self-assembly. Their ability to form various microphase-separated structures with ultrasmall domain spacing, including LAM, GYR, and HEX morphologies, has been demonstrated. In particular, the BCOs consisting of tocopherol have shown remarkable diversity in their morphologies, achieving complex structures including GYR and hexagonally perforated lamellae (HPL_{ABC}) through systematic variation in molecular parameters. Despite these advancements, such BCOs predominantly feature a small sugar volume fraction (< 0.3),

resulting in microphase-separated structures dominated by hydrophobic segments. This tendency is attributed to the larger volume occupied by hydrophobic terpenoid blocks, which drive the self-assembly toward hydrophobic segment-rich morphologies. Current studies, including those on glycolipid-based systems, predominantly report LAM morphologies, indicating a gap in the development of sugar-rich systems capable of forming more intricate microphase-separated structures.

Sugars, as hydrophilic blocks in BCOs, offer unique opportunities for material design due to their rich chemical functionality. The multiple hydroxyl groups in sugar molecules enable extensive hydrogen-bonding interactions, contributing to strong segregation from hydrophobic segments and facilitating microphase separation.^{28–36} Additionally, these hydroxyl groups offer a versatile platform for chemical modification, allowing for the introduction of functional groups.^{37–39} This chemical versatility not only broadens the range of achievable morphologies but also offers potential for post-formation modifications tailored to various applications. These capabilities enable the development of functional nanostructures suited for advanced uses such as biocompatible surface,^{40,41} sensing,^{42–44} drug delivery,^{45,46} and membrane technologies.^{47,48} Despite their potential, sugar-rich BCO systems face significant challenges in achieving diverse morphologies. The strong hydrophilicity and large sugar volume fraction often favor simple LAM structures, limiting their morphological diversity.^{49,50} Among the known research, there is a rare case where a BCO containing maltoheptaose forms HEX structure, indicating that specific molecular configurations can lead to increased structural variety.⁵¹ Moreover, the formation of well-ordered microphase-separated structures is challenging for longer sugar chains due to their inherent polydispersity. In practice, most studies focus on micellar behavior in solution rather than in bulk state microphase separation.

***Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers***

In this study, the author aims to advance the development of diverse sugar-rich microphase-separated structures by synthesizing sugar-rich BCOs and exploring their self-assembly behavior. By selecting structurally defined oligosaccharide blocks (maltotriose, maltopentaose, and maltoheptaose) with inherent monodispersity, the author circumvented the challenges posed by the dispersity of longer sugar chains. This strategic choice allowed for the construction of microphase-separated structures in the bulk state, as the uniformity of the selected sugar chains was expected to promote well-ordered sugar-rich nanostructures with ultrasmall domain spacings. This systematic study will provide a foundation for the rational design of sugar-rich BCOs, contributing to the development of advanced nanostructured materials with tailored properties and functionalities. Furthermore, with a series of sugar–terpenoid BCOs with a wide range of sugar volume fraction, the author summarized their phase behavior as phase diagrams based on the chain lengths or annealing temperature versus sugar volume fraction.

4.2 Experimental Section

4.2.1 Materials

Copper(I) bromide (CuBr; Sigma-Aldrich >99.995%), methanol (Sigma-Aldrich >99.8%), *N,N,N',N'',N'''*-pentamethyldiethylenetriamine (PMDETA; Tokyo Chemical Industry Co., Ltd. (TCI), >98.0%), farnesol (Far; TCI, >95.0%), DL- α -tocopherol (DLToc; TCI, >96.0%), 1-(3-dimethylaminopropyl)-3-ethylcarbodiimide hydrochloride (EDC·HCl; TCI, >98.0%), 4-dimethylaminopyridine (DMAP; TCI, >99.0%), sodium sulfate anhydrous (Na₂SO₄; TCI >99.0%), phytol (Phy; Wako Pure Chemical Co., =>100%), dichloromethane (CH₂Cl₂; Junsei Chemical Chemical Co., Ltd, >98.0%), anhydrous tetrahydrofuran (dry-THF, Kanto Chemical Co., Inc (Kanto), >99.5%; water content, <0.001%), anhydrous dimethylformamide (dry-DMF; Kanto, >99.5%; water content, <0.001%), and anhydrous CH₂Cl₂ (dry-CH₂Cl₂; Kanto, >99.5%; water content, <0.001%), *n*-hexane (Kanto, >95.0%), 2-propanol (Kanto, >99.7%), ethyl acetate (Kanto, >99.3%), and silica gel 60N (Kanto, spherical neutral., particle size 63-210 μ m were used as received. Hydrochloric acid (HCl; Kanto, 35.0–37.0%) was diluted to 1 N, and Dowex® 50WX2 hydrogen form (Sigma-Aldrich) was washed with MeOH before use. The preparations of azido-functionalized terpenoids (N₃-hex-Far, N₃-hex-DLToc, and N₃-hex-Phy) were explained in *Chapter 2* and *Chapter 3*.

4.2.2 Instruments

The size exclusion chromatography (SEC) in DMF (containing 0.01 M LiCl) was performed at 40 °C using a Jasco high performance liquid chromatography system (PU-980 Intelligent HPLC pump, CO-965 Column oven, RI-930 Intelligent RI detector, and Shodex DEGAS KT-16) equipped with a Shodex Asahipak GF-310 HQ column (linear, 7.6 mm × 300 mm; pore size, 20 nm; bead size, 5 µm; exclusion limit, 4×10^4) and a Shodex Asahipak GF-7 M HQ column (linear, 7.6 mm × 300 mm; pore size, 20 nm; bead size, 9 µm; exclusion limit, 4×10^7) at a flow rate of 0.6 mL min⁻¹. The number-average molecular weight ($M_{n,SEC}$) and dispersity (D_{SEC}) of the sample were calculated on the basis of a polystyrene (PSt) calibration. The ¹H (400 MHz) nuclear magnetic resonance (NMR) spectra were recorded using a JEOL JNM-ECS400 instrument. The Fourier transform infrared spectroscopy (FT-IR) analysis was carried out using a PerkinElmer Frontier MIR spectrometer equipped with a single reflection diamond universal attenuated total reflection (ATR) accessory. The differential scanning calorimetry (DSC) analysis was measured under a nitrogen atmosphere by Hitachi DSC 7000X (Hitachi High-Tech Science Co., Ltd., Tokyo, Japan). All analyses were performed by utilizing 4–10 mg of samples in hermetically sealed aluminum pans with a heating/cooling rate of 10 °C min⁻¹ from room temperature to 50 °C for first heating, followed by cooling to -50 °C. The samples were then heated again to 300 °C for second heating. The thermogravimetric analysis (TGA) was measured under a nitrogen atmosphere by Hitachi TGA NEXTA STA 200 (Hitachi High-Tech Science Co., Ltd., Tokyo, Japan) with a heating rate of 10 °C min⁻¹ from 30 °C to 500 °C. Bulk sample preparation for Small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) measurements were as follows. The as-synthesized samples were annealed for 6 hours at 80, 130, 160, 180, or 210 °C under vacuum and quenched to room temperature. SAXS experiments for

bulk samples were performed at BL-6A and BL-10C of the Photon Factory (PF, Japan). At the PF, the X-ray wavelength and exposure time were 1.50 Å and 60 s, respectively. A PILATUS3 1M detector (Dectris Ltd., Switzerland, 981×1043 pixels, 172×172 µm pixel size) and a PILATUS3 2M detector (Dectris Ltd., Switzerland, 1475×1679 pixels, 172×172 µm pixel size) were used at BL-6A and BL-10C, respectively, for data acquisition. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate. WAXS experiments for bulk samples were performed at BL-6A and BL-10C. The X-ray wavelength and exposure time were 1.50 Å and 60 s, respectively. A PILATUS3 100K (Dectris Ltd., Switzerland, 487×195 pixels, 172×172 µm pixel size) detector and a PILATUS3 2M were used at BL-6A and BL-10C, respectively, for data acquisition. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate. Thin film sample preparation for grazing incidence small-angle X-ray scattering measurement was as follows. The silicon wafer substrates ($1.3 \text{ cm} \times 1.3 \text{ cm}$) were cleaned by sonication in CH_2Cl_2 for 0.5 h and isopropanol/deionized H_2O 1/1 (v/v) for 0.5 h. Each BCO was dissolved in HFIP at a concentration of 1wt%, and this solution (75 µL) was spin-coated onto the cleaned silicon wafer at 3000 rpm for 1 min to produce nanoscale thin films (film thickness was determined to be 40–50 nm by reflectometry (Filmetrics F-Series model 205-0263, reflectance standard with Si, Filmetrics – A KLA Company). Grazing incidence small-angle X-ray scattering (GISAXS) experiments for thin film samples were performed at BL-6A and BL10C beamline of the Photon Factory (PF, Japan). At the PF, the X-ray wavelength and exposure time were 1.50 Å and 60 s, respectively. A PILATUS3 1M detector (Dectris Ltd., Switzerland, 981×1043 pixels, 172×172 µm pixel size) and a PILATUS3 2M detector (Dectris Ltd., Switzerland, 1475×1679 pixels, 172×172 µm pixel size) were used at BL-6A and BL-10C, respectively.

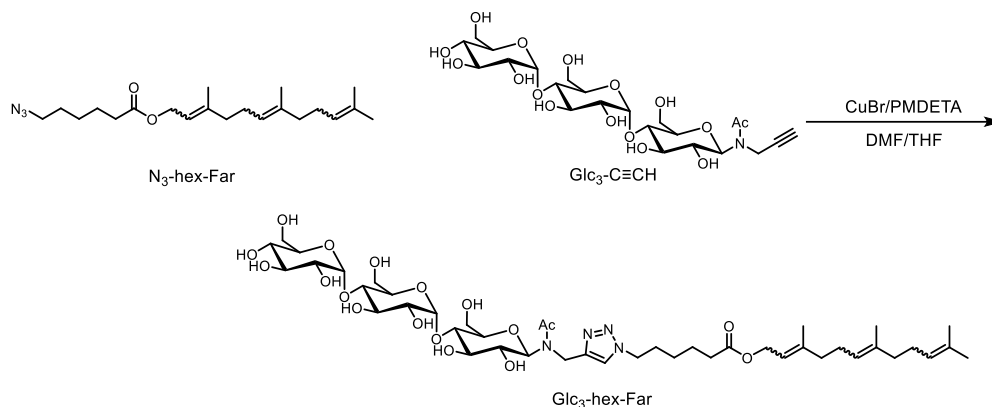
***Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers***

Each scattering image was normally collected for 60 s. The sample-to-detector distance was calibrated using the scattering patterns of silver behenate.

4.2.3 Synthesis of Block Co-oligomers

Synthesis of Glc₃-hex-Far by click reaction

Scheme 4.1. Synthesis of Glc₃-hex-Far



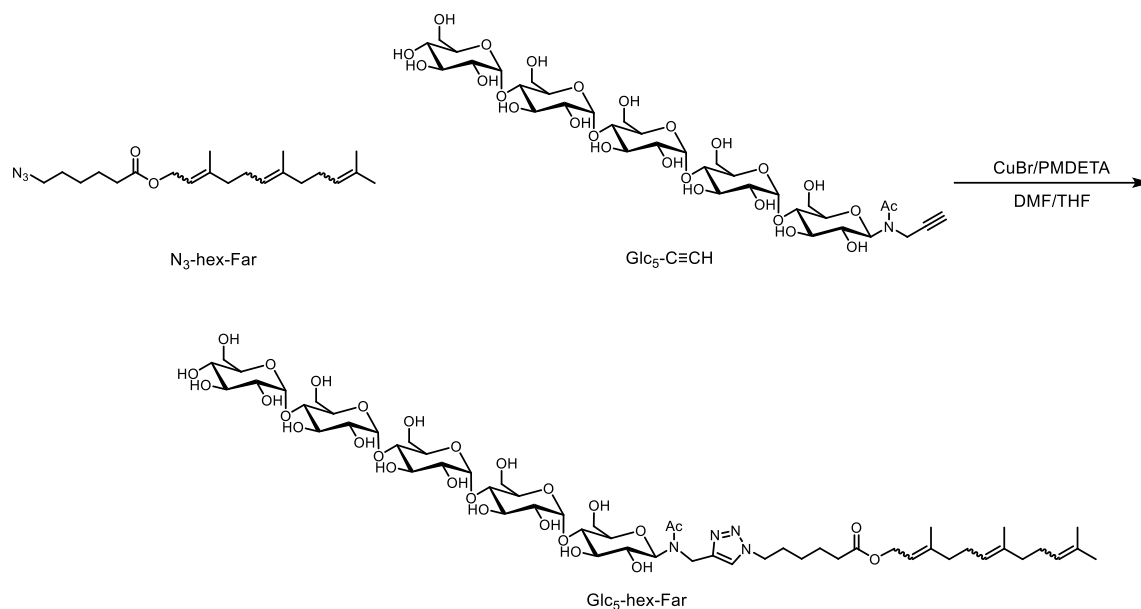
A typical procedure for the click reaction (Cu(I)-catalyzed azido-alkyne cycloaddition) is as follows (method A): N₃-hex-Far (300 mg, 830 μ mol), Glc₃-C≡CH (581 mg, 996 μ mol), and CuBr (35.7 mg, 249 μ mol) were placed in a Schlenk flask, which was evacuated and back-filled with argon three times. PMDETA (43.1 mg, 249 μ mol) solution in a mixed solvent of anhydrous THF (15 mL) and DMF (15 mL) was transferred into the Schlenk flask under an argon atmosphere after degassing by argon bubbling. The reaction mixture was stirred at 60 °C for 72 h and quenched by adding Dowex® 50WX2 hydrogen and H₂O to remove the copper catalyst. After removing the Dowex® 50WX2 hydrogen by filtration, the mixture was concentrated by rotary evaporator and purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₃-hex-Far as a white solid (420.5 mg, yield 53.6%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.1**.

HRMS (ESI): Calcd. For C₄₄H₇₂O₁₈N₄Na⁺ [M + H]⁺ 967.47048, found 967.47338.

Synthesis of Glc₅-hex-Far by click reaction

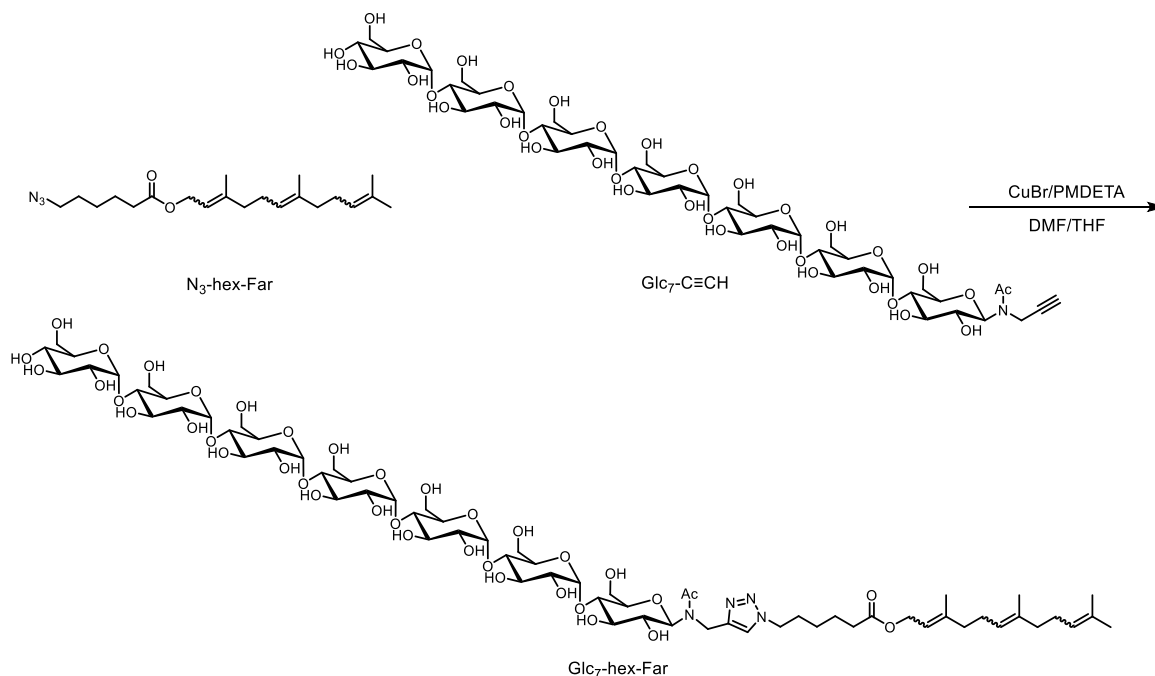
Scheme 4.2. Synthesis of Glc₅-hex-Far



Method A was used for the Click reaction of N₃-hex-Far (130 mg, 360 μmol) and Glc₅-C≡CH (392 mg, 432 μmol) with CuBr (15.5 mg, 108 μmol) and PMDETA (18.7 mg, 108 μmol) in a mixed solvent of dry-THF (10 mL) and dry-DMF (10 mL). The mixture was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₅-hex-Far as a white solid (329.9 mg, yield 72.3%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.2**.

HRMS (ESI): Calcd. For C₅₆H₉₂O₂₈N₄H⁺ [M + H]⁺ 1269.59636, found 1269.59708.

*Synthesis of Glc7-hex-Far by click reaction***Scheme 4.3.** Synthesis of Glc7-hex-Far

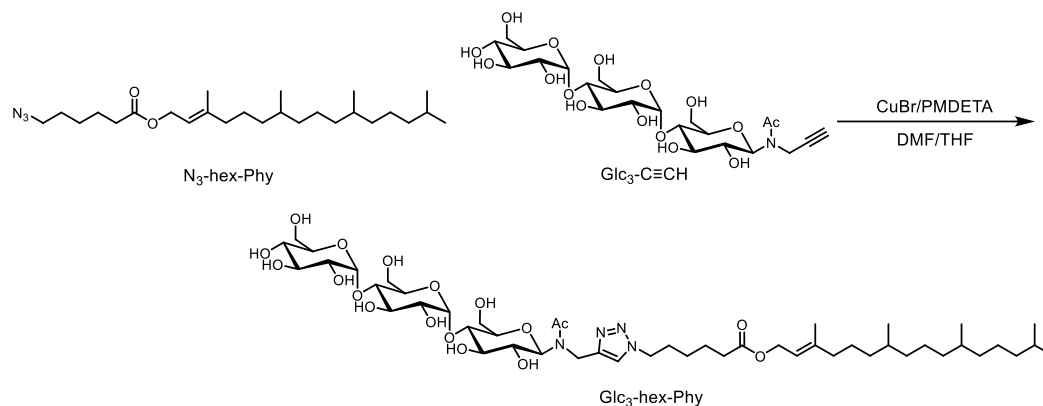
Method A was used for the Click reaction of N₃-hex-Far (31.4 mg, 86.9 μ mol) and Glc₇-C≡CH (129 mg, 104 μ mol) with CuBr (3.74 mg, 26.1 μ mol) and PMDETA (4.52 mg, 26.1 μ mol) in a mixed solvent of dry-THF (10 mL) and dry-DMF (10 mL). The mixture was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₇-hex-Far as a white solid (90.66 mg, yield 65.5%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.3**.

HRMS (ESI): Calcd. For C₆₈H₁₁₂O₃₈N₄Na⁺ [M + Na]⁺ 1615.68334, found 1615.68468.

Synthesis of Glc₃-hex-Phy by click reaction

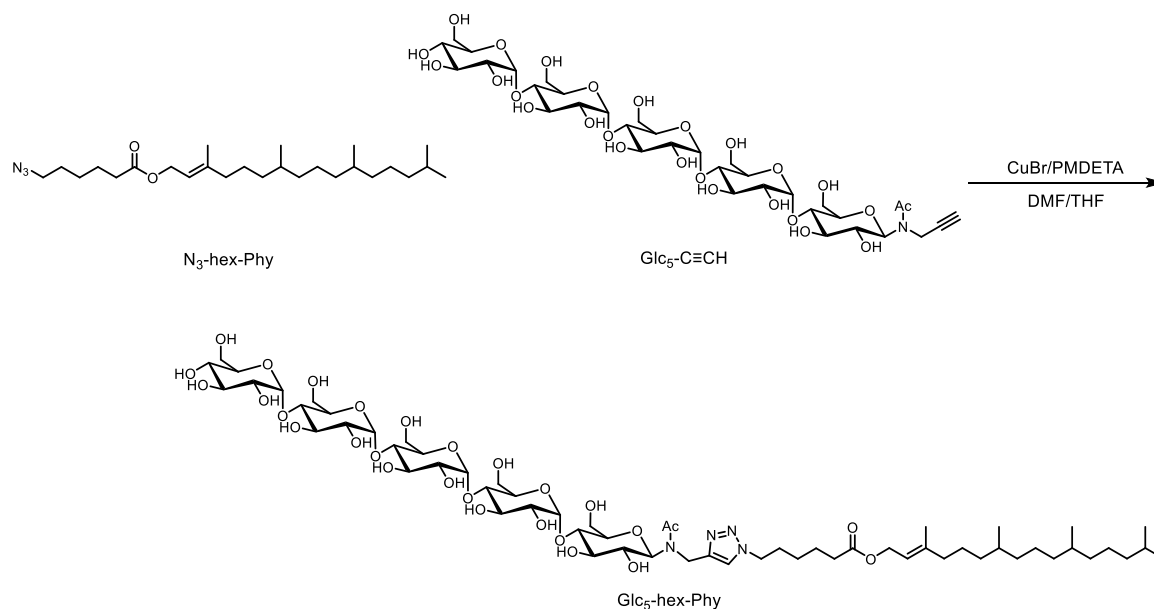
Scheme 4.4. Synthesis of Glc₃-hex-Phy



Method A was used for the Click reaction of N₃-hex-Phy (100 mg, 230 μmol) and Glc₃-C≡CH (174 mg, 298 μmol) with CuBr (9.88 mg, 68.9 μmol) and PMDETA (11.9 mg, 68.9 μmol) in a mixed solvent of dry-THF (10 mL) and dry-DMF (10 mL). The mixture was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₃-hex-Phy as a white solid (173.2 mg, yield 74.0%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.6**.

HRMS (ESI): Calcd. For C₄₉H₈₆O₁₈N₄H⁺ [M + H]⁺, 1019.59883, found 1019.60099.

*Synthesis of Glc₅-hex-Phy by click reaction***Scheme 4.5.** Synthesis of Glc₅-hex-Phy

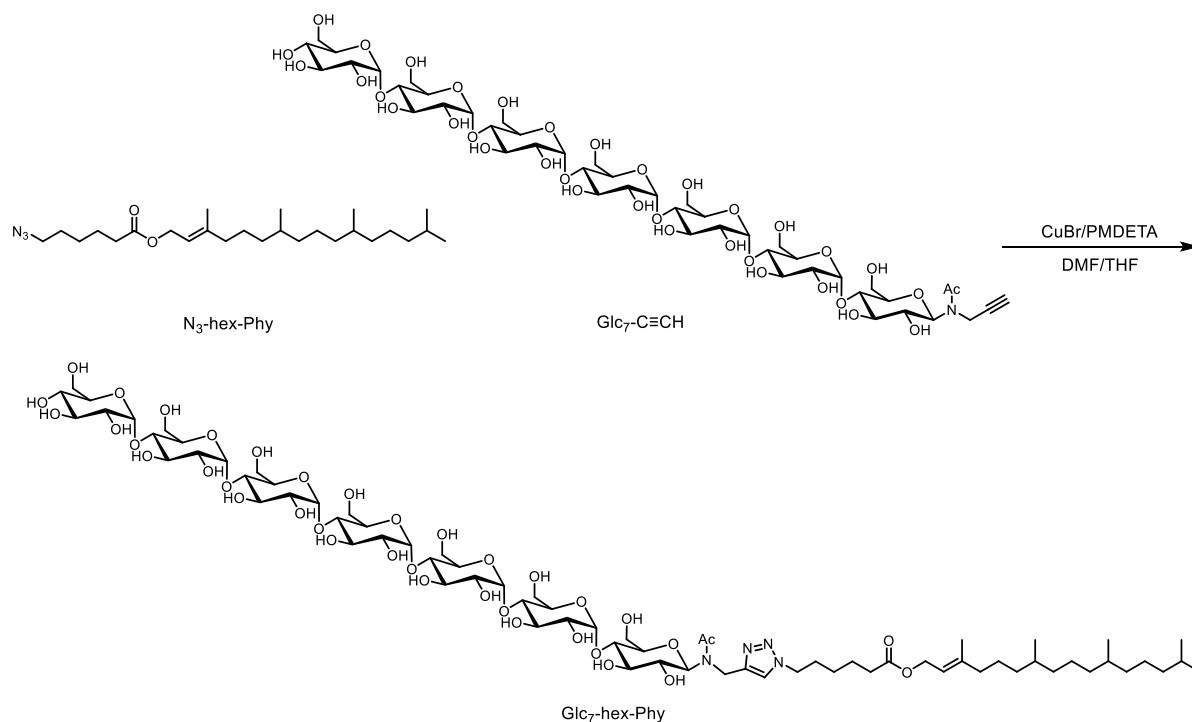
Method A was used for the click reaction of N₃-hex-Phy (100 mg, 230 μ mol) and Glc₅-C≡CH (250 mg, 275 μ mol) with CuBr (9.88 mg, 68.9 μ mol) and PMDETA (11.9 mg, 68.9 μ mol) in a mixed solvent of dry-THF (10 mL) and dry-DMF (10 mL). The mixture was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₅-hex-Phy as a white solid (211.3 mg, yield 68.5%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.7**.

HRMS (ESI): Calcd. For C₆₁H₁₀₆O₂₈N₄Na⁺ [M + Na]⁺ 1365.68744, found 1365.68858.

Synthesis of Glc₇-hex-Phy by click reaction

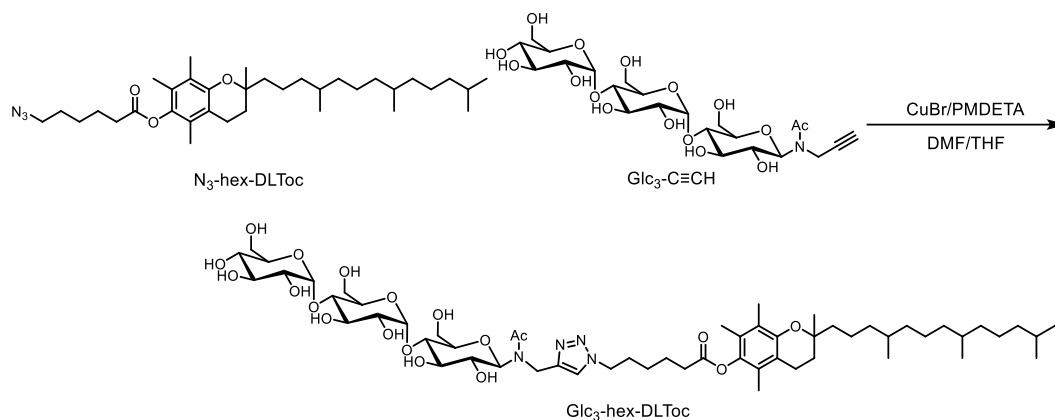
Scheme 4.6. Synthesis of Glc₇-hex-Phy



Method A was used for the click reaction of N₃-hex-Phy (70.0 mg, 161 μmol) and Glc₇-C≡CH (238 mg, 193 μmol) with CuBr (6.91 mg, 48.2 μmol) and PMDETA (8.35 mg, 48.2 μmol) in a mixed solvent of dry-THF (10 mL) and dry-DMF (10 mL). The mixture was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₅-hex-Phy as a white solid (149.2 mg, yield 55.7%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.8**.

HRMS (ESI): Calcd. For C₇₃H₁₂₆O₃₈N₄Na⁺ [M + Na]⁺ 1689.79788, found 1689.79797.

Synthesis of Glc₃-hex-DLToc by click reaction**Scheme 4.7.** Synthesis of Glc₃-hex-DLToc

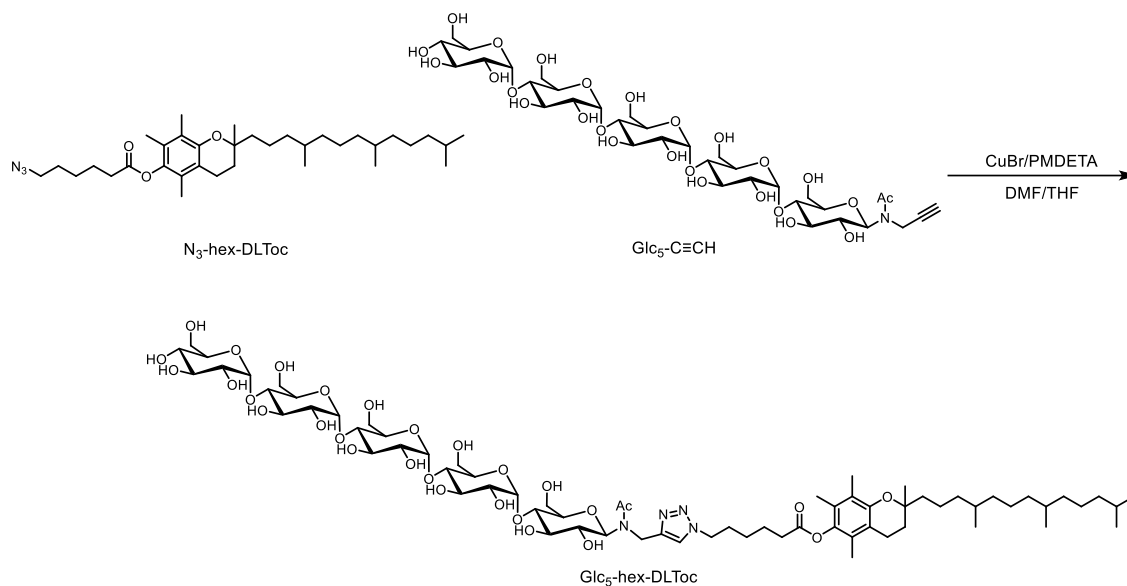
Method A was used for the click reaction of N₃-hex-DLToc (700 mg, 123 μ mol) and Glc₅-C≡CH (597 mg, 102 μ mol) with CuBr (44.1 mg, 307 μ mol) and PMDETA (53.1 mg, 307 μ mol) in a mixed solvent of dry-THF (15 mL) and dry-DMF (15 mL). The crude product was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₃-hex-DLToc as a white solid (304.0 mg, yield 32.0%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.11**.

HRMS (ESI): Calcd. For C₅₈H₉₆O₁₉N₃H⁺ [M + H]⁺ 1153.67741, found 1153.67595.

Synthesis of Glc₅-hex-DLToc by click reaction

Scheme 4.8. Synthesis of Glc₅-hex-DLToc



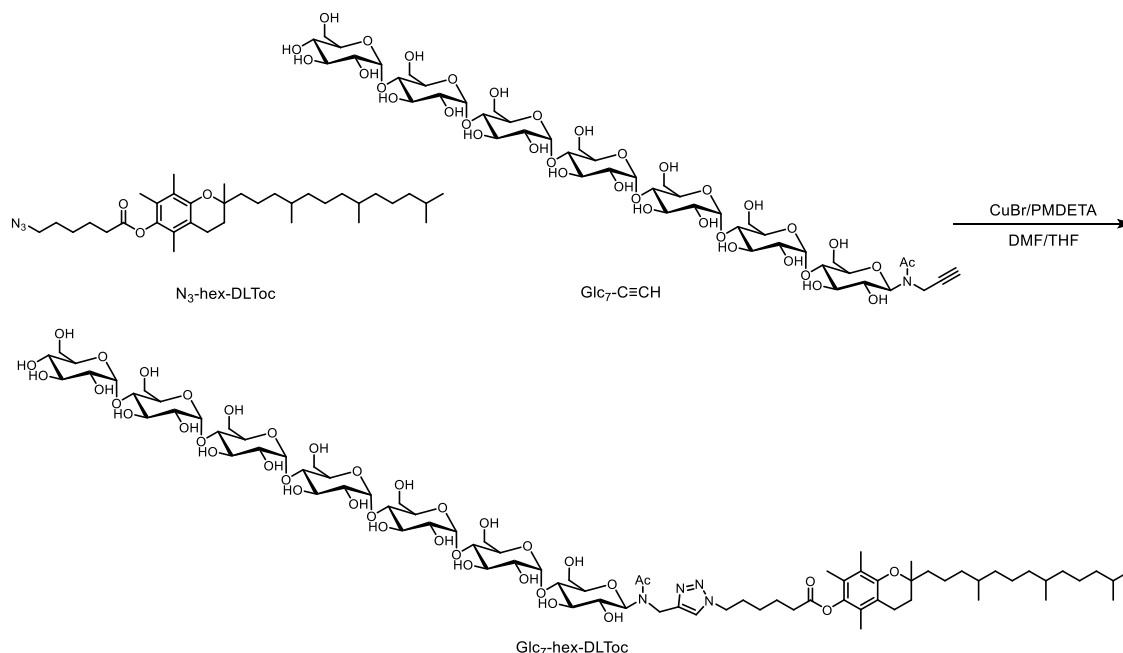
Method A was used for the click reaction of N₃-hex-DLToc (100 mg, 175 μ mol) and Glc₅-C≡CH (191 mg, 211 μ mol) with CuBr (25.2 mg, 175 μ mol) and PMDETA (30.4 mg, 175 μ mol) in a mixed solvent of dry-THF (15 mL) and dry-DMF (15 mL). The crude product was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₅-hex-DLToc as a white solid (190.0 mg, yield 73.3%).

¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.12**.

HRMS (ESI): Calcd. For C₇₀H₁₁₆O₂₉N₄Na⁺ [M + Na]⁺ 1499.75795, found 1499.76174.

Synthesis of Glc₇-hex-DLToc by click reaction

Scheme 4.9. Synthesis of Glc₇-hex-DLToc



Method A was used for the click reaction of N₃-hex-DLToc (100 mg, 175 μ mol) and Glc₇-C≡CH (259 mg, 211 μ mol) with CuBr (25.2 mg, 175 μ mol) and PMDETA (30.4 mg, 175 μ mol) in a mixed solvent of dry-THF (15 mL) and dry-DMF (15 mL). The crude product was purified by reprecipitation of the DMF/THF = 1/1 (v/v) to acetonitrile/H₂O = 9/1 (v/v) solution to give Glc₇-hex-DLToc as a white solid (182.1 mg, yield 57.6%).

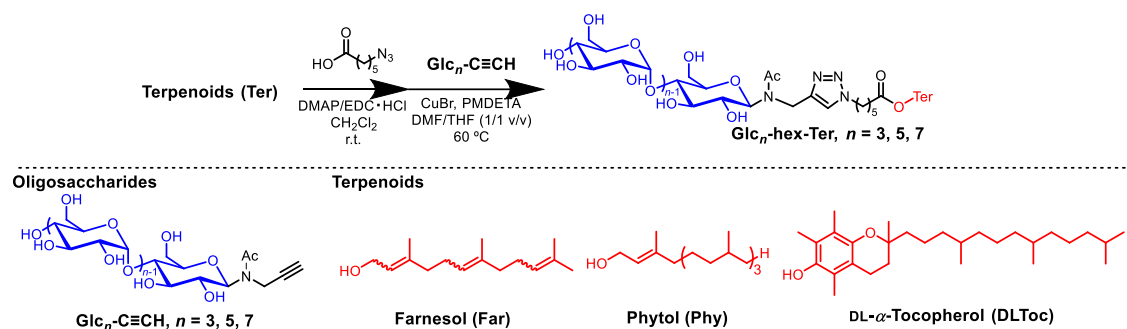
¹H NMR (400 MHz, DMSO-*d*₆): See **Figure S4.13**.

HRMS (ESI): Calcd. For C₈₂H₁₃₆O₃₉N₄Na⁺ [M + Na]⁺ 1823.86457, found 1823.86739.

4.3 Result and Discussion

4.3.1 Synthesis of Block Co-oligomers (BCOs)

To obtain the sugar-rich microphase-separated structure, in this study, the author aimed to synthesize sugar-rich BCOs by combining the relatively longer oligosaccharides, such as maltotriose (Glc₃), maltopentaose (Glc₅), and maltoheptaose (Glc₇), with relatively short terpenoid chains, such as farnesol (Far), phytol (Phy), and DL- α -tocopherol (DLToc). According to the previous chapters, the author first prepared the azido-functionalized terpenoids (N₃-hex-Far, N₃-hex-Phy, and N₃-hex-DLToc) by the condensation reaction of 6-azido-1-hexanoic acid with the corresponding terpenoids. Subsequently, Glc₃-hex-Far, Glc₅-hex-Far, Glc₇-hex-Far, Glc₃-hex-Phy, Glc₅-hex-Phy, Glc₇-hex-Phy, Glc₃-hex-DLToc, Glc₅-hex-DLToc, and Glc₇-hex-DLToc BCOs were obtained through the click reaction with the propargyl-functionalized maltooligosaccharides (Glc₃-C $\equiv$ CH, Glc₅-C $\equiv$ CH, and Glc₇-C $\equiv$ CH) and azido-functionalized terpenoids (**Scheme 4.10**). The progress of the click reactions was monitored via size-exclusion chromatography (SEC) measurements. All the obtained BCOs were characterized by proton nuclear magnetic resonance (¹H NMR) spectroscopy, Fourier-transform infrared (FT-IR) spectroscopy, SEC, and electrospray ionization mass spectrometry (ESI-MS) (**Figures S4.1–S4.15**). The volume fractions (f_v) of each BCOs were calculated using the known molecular weights and densities of the sugar and terpenoid segments, using the formula: $(M.W._{\text{sugar segment}}/\text{density}_{\text{sugar segment}})/((M.W._{\text{sugar segment}}/\text{density}_{\text{sugar segment}}) + (M.W._{\text{terpenoid segment}}/\text{density}_{\text{terpenoid segment}}))$. The calculated f_v values, summarized in **Table 4.1**, reveal that all BCOs have sugar volume fractions of 0.42 or higher, ensuring compatibility with the desired experimental design and structural analyses.

Scheme 4.10. Synthesis of sugar-rich BCOs.**Table 4.1.** Molecular characteristics of BCOs.

BCP name	Sugar M.W.	Hydrophobic M.W.	Total M.W.	f_{sugar}^a
Glc ₃ -hex-Far	583.5	361.5	945.1	0.51
Glc ₅ -hex-Far	907.8	361.5	1269.4	0.62
Glc ₇ -hex-Far	1232.1	361.5	1593.6	0.69
Glc ₃ -hex-Phy	583.5	435.7	1019.2	0.46
Glc ₅ -hex-Phy	907.8	435.7	1343.5	0.57
Glc ₇ -hex-Phy	1232.1	435.7	1667.8	0.64
Glc ₃ -hex-DLToc	583.5	569.9	1153.4	0.42
Glc ₅ -hex-DLToc	907.8	569.9	1477.7	0.53
Glc ₇ -hex-DLToc	1232.1	569.9	1802.0	0.60

^aSugar volume fraction (f_{sugar}) calculated based on the known density values of saccharide (1.36 g cm⁻³), farnesol (0.887 g cm⁻³), phytol (0.850 g cm⁻³), and tocopherol (0.950 g cm⁻³).

4.3.2 Construction of Sugar-Rich Microphase-Separated Structure

To conduct detailed analysis of the microphase-separated morphologies of the obtained BCOs, small-angle X-ray scattering (SAXS) and wide-angle X-ray scattering (WAXS) measurements were performed using synchrotron light source. The samples were prepared by placing the as-synthesized and thermally annealed BCOs between Kapton tape along with a stainless washer as a spacer. The bulk samples were annealed at 80, 130, 160 and 210 °C for 6 hours under vacuum conditions.

In the *Chapter 2*, the author confirmed the formation of lamellae (LAM) structures in BCOs consisting of glucose and farnesol (Far) (Glc₁-hex-Far, $f_{\text{sugar}} = 0.29$) under various thermal annealing conditions. In this study, to increase the proportion of the hydrophilic segment, the author designed a series of BCOs (Glc_{*n*}-hex-Far; *n* = 3, 5, and 7) combining farnesol with maltotriose, maltopentaose, and maltoheptaose with f_{sugar} of 0.51, 0.62, and 0.69, respectively. First, according to the WAXS profiles of Glc_{*n*}-hex-Far under different annealing conditions, only a broad halo peak was observed in the *q* range of 7.5–18 nm^{−1}, corresponding to 3.5–8.4 Å, which falls within a range where crystalline structures can appear. However, the broad nature of the peak suggests a more disordered or short-range ordered structure rather than a well-defined crystalline phase. This confirmed that these BCOs are amorphous without crystallization (**Figure S4.18**). In the SAXS profile of the as-synthesized Glc₃-hex-Far sample, only a broad peak was observed at $q = 1.27 \text{ nm}^{-1}$ (**Figure 4.1(a)**). However, due to the lack of higher order scattering peaks, microphase-separated morphology could not be identified. In contrast, in the SAXS profile of the Glc₃-hex-Far sample annealed at 80 °C, two peaks are observed at $q = 1.18$ and 2.15 nm^{-1} , corresponding to the reflection planes (211) and (400) of the GYR structure with $q/q^* = \sqrt{6}$ and $\sqrt{16}$, respectively. The lattice constant of the GYR structure ($a_{\text{GYR}} = 12.4 \text{ nm}$) was calculated using $a_{\text{GYR}} = 2\pi(h^2 + k^2 + l^2)^{1/2}/q_{hkl}$ (**Figure 4.1(d)**).

Additionally, the peaks at $q = 1.28, 1.46, \text{ and } 2.54 \text{ nm}^{-1}$, corresponding to $q/q^* = \sqrt[3]{6}, \sqrt[3]{8}$, and $\sqrt[3]{24}$, respectively, were observed in the SAXS profile of Glc₃-hex-Far annealed at 130 °C, which were assigned to the (211), (220), and (332) reflection planes of GYR structure ($a_{\text{GYR}} = 11.9 \text{ nm}$), respectively. In the *Chapter 2*, the author confirmed the formation of a LAM structure in Glc₁-hex-Far with f_{sugar} of 0.29. Therefore, the increased curvature by the increased f_{sugar} is responsible for the formation of GYR structure predominantly composed of the hydrophilic sugar segment. The SAXS profiles of the Glc₃-hex-Far annealed above 160 °C (160 °C-annealed and 210 °C-annealed) showed no peak, suggesting that order-disorder transition occurred between 130 and 160 °C.

Next, SAXS measurements were also conducted for Glc₅-hex-Far with f_{sugar} of 0.62. As a result, scattering peaks corresponding to the (10), (11), and (21) planes associated with the HEX structure were observed in the as-synthesized and 80 °C annealed samples (**Figures 4.1(b) and (c)**). In the SAXS profile of the 130 °C-annealed sample, a peak corresponding to the (20) plane rather than the (21) plane of the HEX structure was observed. The cylinder-to-cylinder distance (d_{c-c}) of the as-synthesized, 80 and 130 °C-annealed samples, calculated from the primary peak using $d_{c-c} = 4\pi/\sqrt{3}q_{(10)}$, was determined to be 6.4, 6.5 and 6.5 nm, respectively. The formation of the HEX structure of Glc₅-hex-Far could be attributed to its higher f_{sugar} compared to the GYR-forming Glc₃-hex-Far. The increased proportion of the hydrophilic sugar segment within the unit volume leads to the formation of the HEX structure, which qualitatively follows the trend of conventional BCP phase behavior.

Among the sugar-farnesol combinations, Glc₇-hex-Far has the highest f_{sugar} of 0.69, which exhibited the scattering peaks corresponding to the HEX structure ($d_{c-c} = 7.5 \text{ nm}$) at $q = 0.84, 1.45, \text{ and } 2.22 \text{ nm}^{-1}$ only in the SAXS profile of the as-synthesized sample (**Figure 4.1(c)**). From 80 °C-annealed sample, only a broad peak was observed at around

Sugar-Rich Microphase-Separated Structures by Sugar–Terpenoid Block Co-oligomers

$q = 0.91 \text{ nm}^{-1}$, indicating periodic structure with approximately $d = 7.8 \text{ nm}$. However, the type of morphology could not be identified due to the lack of higher order scattering peak. Furthermore, thermal annealing at temperatures above $130 \text{ }^{\circ}\text{C}$ resulted in transition into disordered phase, as evidenced by the absence of scattering peak.

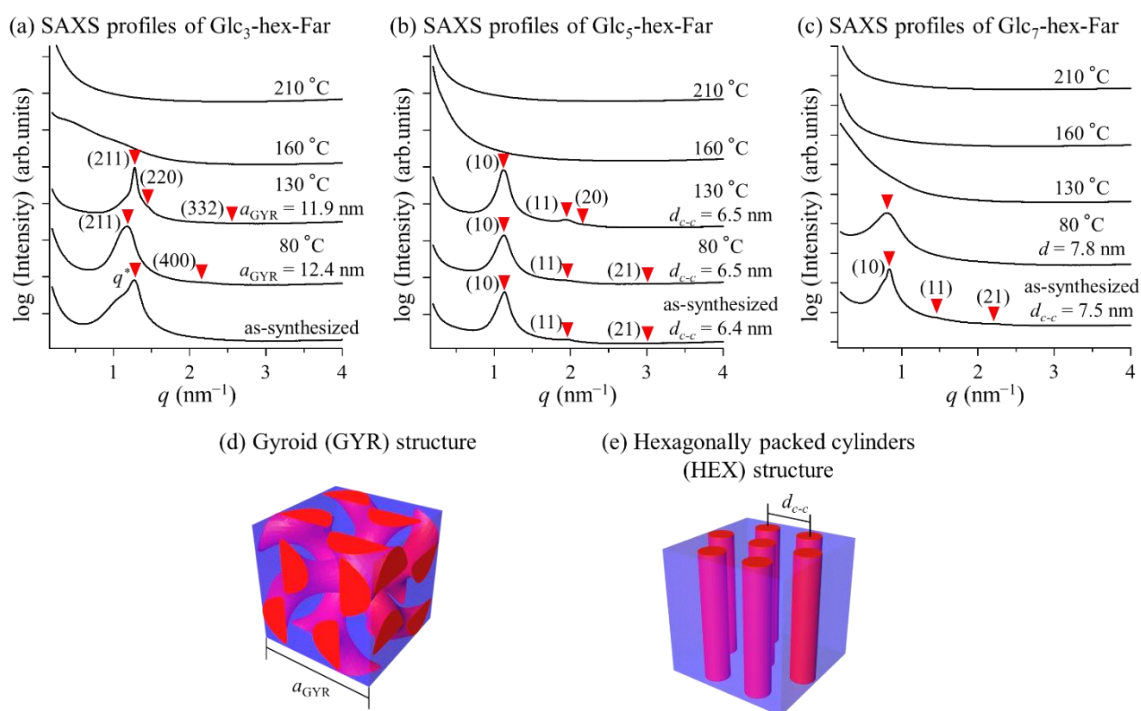


Figure 4.1. SAXS profiles of the as-synthesized and thermally annealed (a) Glc₃-hex-Far, (b) Glc₅-hex-Far, and (c) Glc₇-hex-Far. The schematic illustrations of the (d) gyroid and (e) hexagonally packed cylinder structures.

The GYR and HEX morphologies were identified in sugar-farnesol BCOs with f_{sugar} ranging from 0.51 to 0.69. With promising results, by using the same type of hydrophilic sugar chains and combining them with hydrophobic chains of varying lengths, such as phytol (Phy) and DL- α -tocopherol (DLToc), the author systematically investigated the microphase separation behavior of sugar-based BCOs across a wide range of f_{sugar} .

Similar to the sugar-farnesol BCO system, the BCOs composed of Phy and DLToc

showed no evidence of crystallization from the WAXS analysis (**Figures S4.19** and **S4.20**). For Glc₃-hex-Phy ($f_{\text{sugar}} = 0.46$) and Glc₃-hex-DLToc ($f_{\text{sugar}} = 0.42$), scattering peaks corresponding to LAM structure with the d around 6.0 nm were observed (**Figure 4.2**). The formation of the LAM structure at sugar volume fractions below 0.5 is attributed to the significant asymmetry in the chemical conformations of the sugar and terpenoid chains. On the other hand, Glc₅-hex-Phy ($f_{\text{sugar}} = 0.57$) and Glc₇-hex-Phy ($f_{\text{sugar}} = 0.63$), predominantly exhibited peaks corresponding to the HEX structure in their SAXS profiles (**Figure 4.3**). The HEX structure is considered sugar-rich based on the volume fraction of the sugar. In the SAXS profiles of Glc₅-hex-DLToc ($f_{\text{sugar}} = 0.53$), scattering peaks derived from the HEX structure were observed even at high temperatures (**Figure 4.4(a)**). Furthermore, upon 210 °C annealed Glc₅-hex-DLToc, the d_{c-c} of the HEX structure changed drastically from 7.0 to 7.9 nm. This could be due to caramelization of the sugar chain at high temperatures, rather than self-assembly of the molecular induced by thermal annealing. In-situ SAXS experiments also showed that the HEX structure was maintained up to 200 °C (**Figure 4.4(b)**). However, beyond 200 °C, the primary and secondary peak position changed dramatically. DSC and TGA analyses highlighted chemical reactions occurring near 210 °C, with DSC detecting both endothermic and exothermic events while TGA identified weight loss behavior (**Figures S4.16(h)** and **S4.17(h)**).

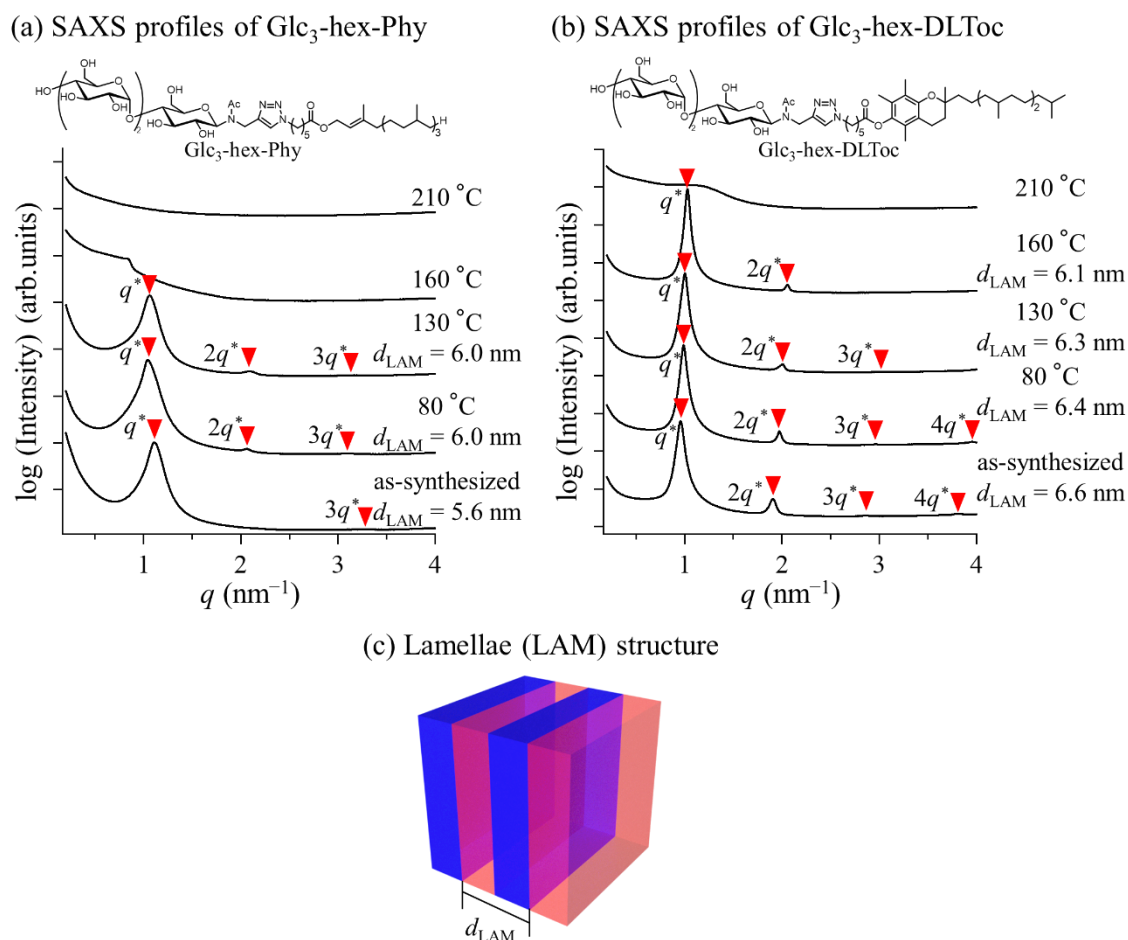


Figure 4.2. SAXS profiles of the as-synthesized and thermally annealed (a) Glc₃-hex-Phy, (b) Glc₅-hex-DLToc. (c) The schematic illustration of the LAM structure.

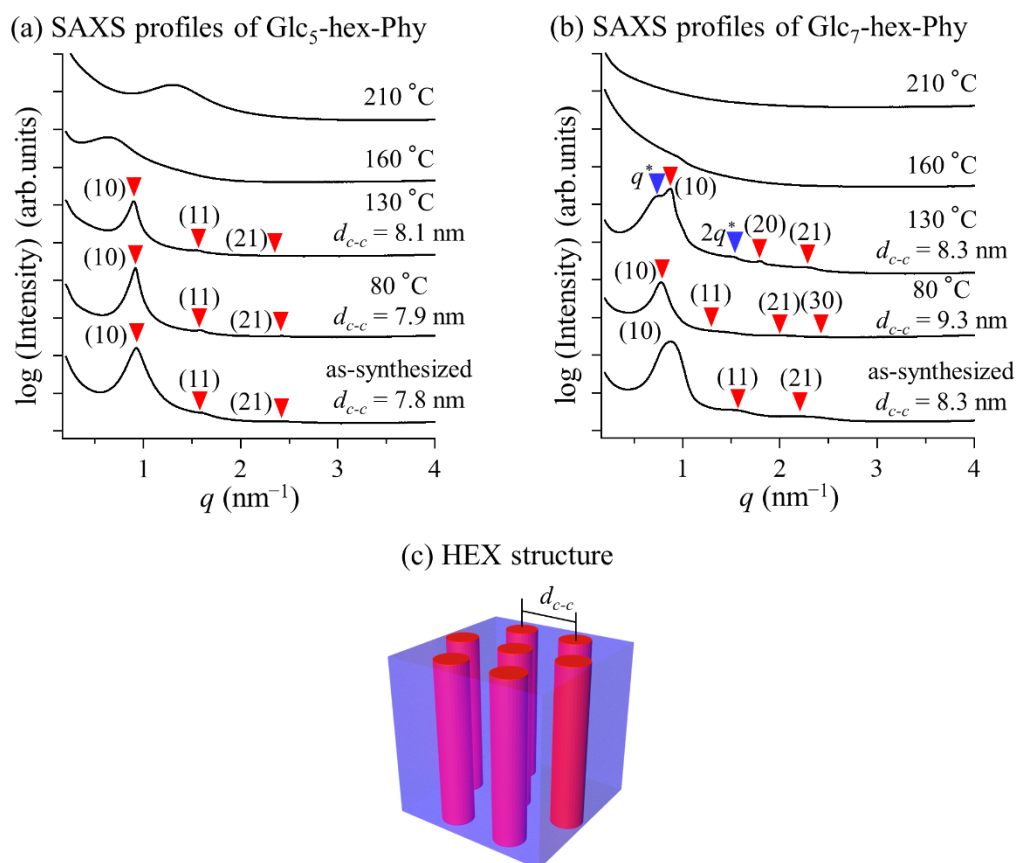


Figure 4.3. SAXS profiles of the as-synthesized and thermally annealed (a) Glc₅-hex-Phy and (b) Glc₇-hex-Phy. (c) The schematic illustration of the HEX structure.

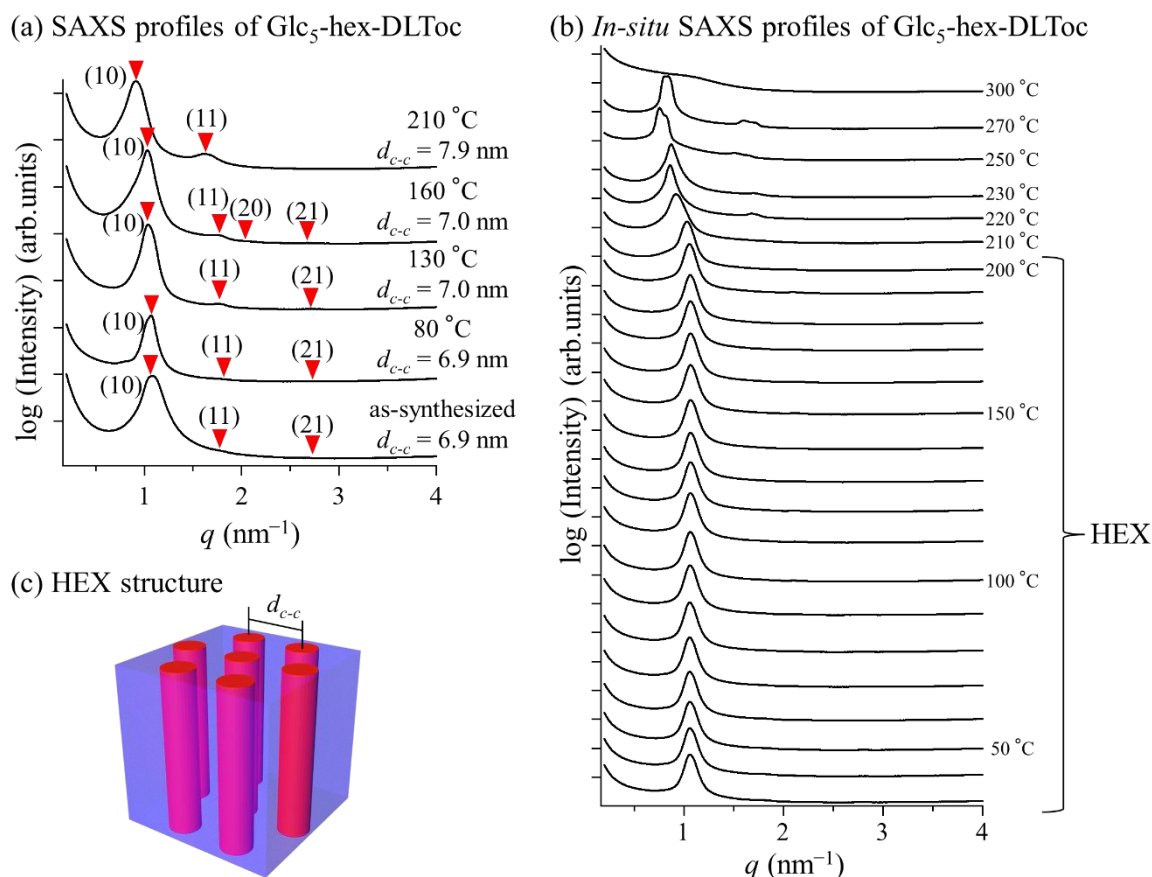


Figure 4.4. (a) SAXS profiles of the as-synthesized and thermally annealed Glc₅-hex-DLToc (b) *In-situ* SAXS profiles of the Glc₅-hex-DLToc. (c) The schematic illustration of the HEX structure.

In the SAXS profiles of Glc₇-hex-DLToc samples ($f_{\text{sugar}} = 0.60$), the peaks derived from various structures were observed (**Figure 4.5(a)**). For the as-synthesized sample, the peaks at $q = 0.60$ and 1.18 nm^{-1} , corresponding to the (100) and (200) planes of the LAM structure, were detected (**Figure 4.5(b)**). In addition, the peaks at $q = 0.85$, 0.96 , and 1.59 nm^{-1} , attributed to the (101), (003), and (201) planes of the HPL_{ABC} structure, also were observed. The d of the LAM structure was determined to be 10.4 nm , while the lattice parameters of the HPL_{ABC} structure were calculated to be $a_{\text{HPL}} = 1/(3(1/d_{101}^2 - 1/c_{\text{HPL}}^2)/4)^{1/2} = 9.2 \text{ nm}$ and $c_{\text{HPL}} = 3(d_{003}) = 19.7 \text{ nm}$, where a_{HPL} and $c_{\text{HPL}}/3$ correspond to the perforation distance and the lamellar stacking periodicity, respectively. Assuming the f_{sugar} of 0.60 for Glc₇-hex-DLToc, the HPL_{ABC} structure consists of perforated layers

composed of hydrophobic DLToc, with the matrix formed by hydrophilic sugar chain. Previous studies revealed that in the bulk state, Glc₁-hex-DLToc ($f_{\text{sugar}} = 0.21$) formed the highly ordered HPL_{ABC} structure with the tocopherol as the matrix. The ability of Glc₇-hex-DLToc to form the HPL_{ABC} structure with reversed major and minor components offers enhanced versatility for the nanotemplate application of microphase-separated structures. As the annealing temperature increased to 80 and 130 °C, the intensity of primary peak derived from LAM structure weakened noticeably, while the secondary peak disappeared (**Figure 4.5(a)**). Under annealing conditions at 160 °C, the structure predominantly transitioned to HEX phase with $d_{c-c} = 7.7$ nm (**Figure 4.5(c)**). Further annealing at 210 °C led phase transitions related most likely due to caramelization, similar to those observed in Glc₅-hex-DLToc.

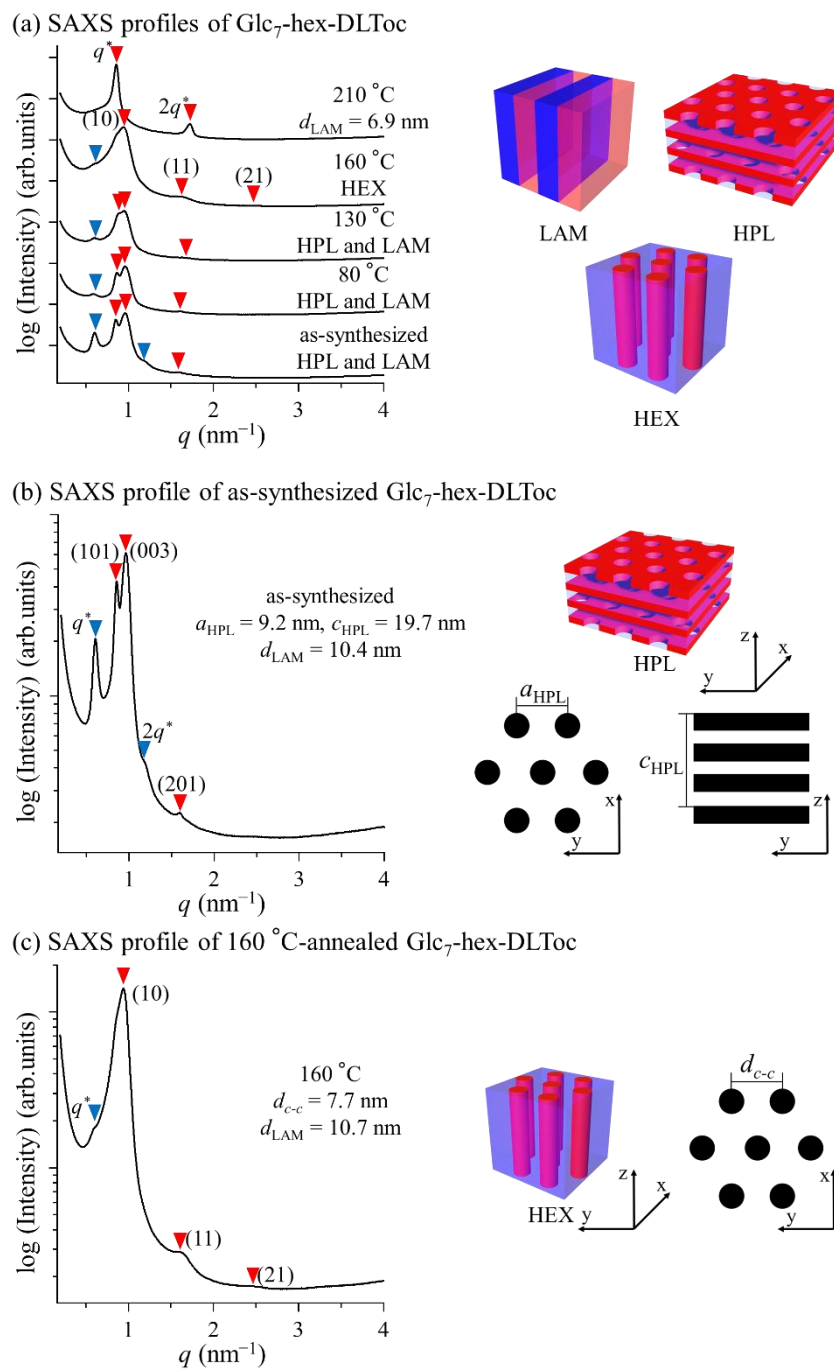


Figure 4.5. SAXS profiles of the as-synthesized and thermally annealed (a) Glc₇-hex-DLToc and expanded SAXS profile of (b) as-synthesized and (c) 160 °C-annealed sample .

4.3.3 Microphase-Separated Structure in The Thin Film State

Next, the author investigated the microphase-separated structures of the BCOs in the thin film state by grazing incidence small-angle X-ray scattering (GISAXS). The BCO thin films were prepared by depositing 75 μL of 1 wt% BCO solution in HFIP onto a native silicon substrate, followed by spin coating at 3000 rpm for 60 seconds. The BCO thin film samples were annealed at 130 $^{\circ}\text{C}$ for 6 hours under vacuum conditions.

The GISAXS measurements allowed detailed morphological analysis of the sugar-rich structures in the thin film state. The two-dimensional (2D) scattering patterns of the Glc₃-hex-Far, Glc₅-hex-Far, and Glc₇-hex-Phy thin films exhibited HEX morphology oriented parallel to the Si substrate (**Figures 4.6(a), (c), (e), and (g)**). In particular, 2D scattering images of samples annealed at 130 $^{\circ}\text{C}$, the peaks corresponding to (020) and (110) planes of the HEX structure were clearly observed. For the detailed structural analysis, one-dimensional (1D) in-plane scattering profiles were extracted from the 2D scattering images of Glc₃-hex-Far, Glc₅-hex-Far, and Glc₇-hex-Phy thin films at $\alpha_f = 0.93^{\circ}$, 0.97° and 0.96° , respectively (**Figures 4.6(b), (d), and (f)**). The d_{c-c} of each sample was calculated to be 5.4, 7.1, and 8.2 nm using the Bragg's equation ($d = \lambda / (2 \sin(2\theta_f/2))$).

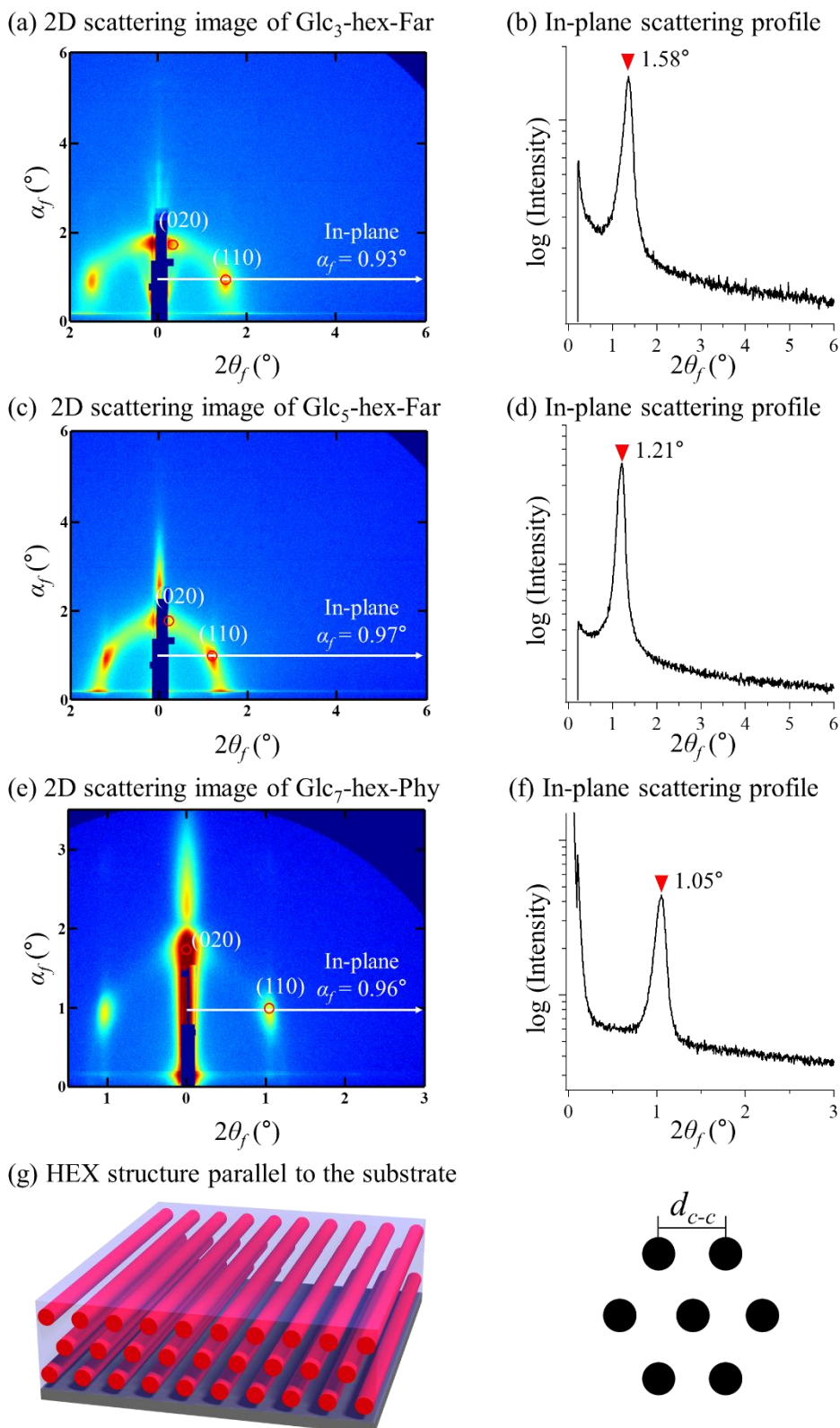


Figure 4.6. Representative GISAXS 2D scattering image of the thin film (a) Glc₃-hex-Far, (c) Glc₅-hex-Far, and (e) Glc₇-hex-Phy after thermal annealing at 130 °C for 6 hours. (b), (d), and (f) are 1D in-plane scattering profiles along the equatorial line peak derived from including (110) lattice plane as derived from (a), (c), and (e), respectively. (g) Schematic illustrations depicting the HEX structure oriented parallel to the Si substrate.

In the Glc₅-hex-DLToc thin film under the same 130 °C annealing conditions, primary and secondary scattering peaks were observed on the Yoneda line, indicating the presence of perpendicular structure to the Si substrate (**Figures 4.7(a) and (e)**). For the detailed structural analysis, 1D in-plane scattering profile was extracted from the 2D scattering image on the Yoneda line at $\alpha_f = 0.13^\circ$ (**Figure 4.7(b)**). The 1D in-plane scattering profile showed two scattering peaks at $2\theta_f = 1.14$ and 1.97° , corresponding to the (10) and (11) plane of the perpendicular HEX structure ($d_{c-c} = 8.7$ nm) to the Si substrate.

The HEX structure oriented perpendicularly to the substrate is expected to have potential applications in nanostructured templating technologies. Therefore, solvent vapor annealing was utilized to achieve sharper phase separation boundaries and more ordered structures.^{52,53} The solvent vapor annealing exposes BCP to solvent vapor, selectively swelling parts or the entirety of the material to induce nanostructure formation. Borsali et al. demonstrated this technique using maltoheptaose-polystyrene BCPs with THF-water mixtures at varying ratios, effectively controlling cylinder alignment and orientation.⁵⁴ For Glc₅-hex-DLToc, where the sugar volume fraction is 0.53, THF/H₂O = 1/4 (v/v) solvent mixture, exhibiting high solubility for both blocks was utilized to facilitate structure formation. The solvent vapor annealing was performed by placing the thin film samples and the mixed solvent in a sealed oven at 30 °C under ambient pressure for 6 hours.

As a result of solvent vapor annealing, new scattering spots were observed at the 2D scattering image (**Figure 4.7(c)**). In 1D in-plane scattering profile extracted from 2D scattering image at $\alpha_f = 0.13^\circ$, scattering peaks with stronger intensities were identified on the Yoneda line at $2\theta_f = 1.09, 1.91, 2.91^\circ$, which corresponds to the (10), (11), and (21) planes of the perpendicular HEX structure ($d_{c-c} = 9.1$ nm) to the Si substrate (**Figure**

4.7(d)). Furthermore, scattering spots correspond to (020), (110), and (130) planes of the parallel HEX structure to the Si substrate were observed (**Figure 4.7(c)**). Therefore, investigating different ratios of the solvent mixture could potentially enable the formation of cylinder structures with alternative orientations.

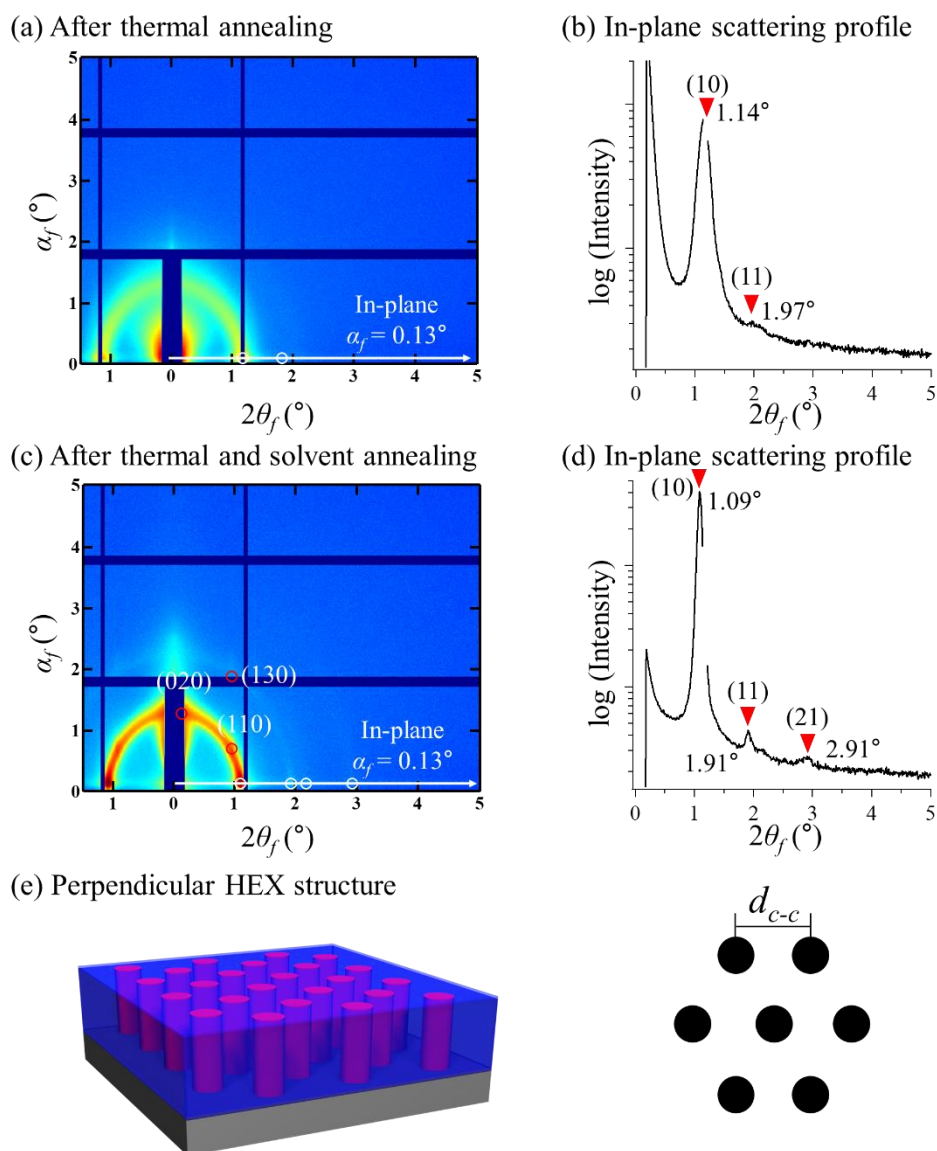


Figure 4.7. Representative GISAXS 2D scattering image of the thermally annealed at 130 °C for 6 hours thin film (a) Glc₅-hex-DLToc and (c) mixture solvent annealed after thermal annealing Glc₅-hex-DLToc. The 1D in-plane scattering profiles (b) and (d) along the equatorial line on the Yoneda line from (a) and (c), respectively. (e) Schematic illustrations showing the vertical HEX structure on the Si substrate.

In the 2D scattering image of the Glc7-hex-DLToc thin film annealed at 130 °C, scattering spots originating from the perpendicular structure were observed on the Yoneda line (**Figure 4.8(a)**). The 1D in-plane scattering profile extracted at $\alpha_f = 0.28^\circ$ exhibited scattering peaks at $2\theta_f = 1.14$ and 2.18° , which were converted to $q = 1.67$ and 3.19° , respectively (**Figure 4.8(b)**). The ratio $q/q^* = 1$, and 2 indicates that the peaks originated from the LAM structure ($d_{\text{LAM}} = 7.5$ nm) oriented perpendicular to the Si substrate (**Figure 4.8(c)**). To achieve highly ordered structure, solvent annealing was conducted using the same method as described previously. Interestingly, not only the peaks corresponding to the LAM structure aligned perpendicular to the Si substrate, additional scattering spots corresponding to the HPL_{ABC} structure were also observed (**Figure 4.8(d)**). In the 1D in-plane profile extracted at $\alpha_f = 0.14^\circ$ from the 2D scattering image, peaks originating from the perpendicular LAM structure were observed at $2\theta_f = 1.12^\circ$ and 2.25° . Additionally, a peak at $2\theta_f = 0.88^\circ$ was attributed to the distance between perforations ($a_{\text{HPL}} = 11.2$ nm) (**Figure 4.8(e)**). Furthermore, the out-of-plane scattering profile extracted at $2\theta_f = 0.21^\circ$ showed two scattering peaks at $\alpha_f = 1.25^\circ$ and 2.52° , corresponding to the (003) and (006) diffractions of the lamellar stacking of HPL_{ABC} parallel to the Si substrate, indicating a domain spacing of 20.6 nm (**Figure 4.8(f)** and (g)).

***Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers***

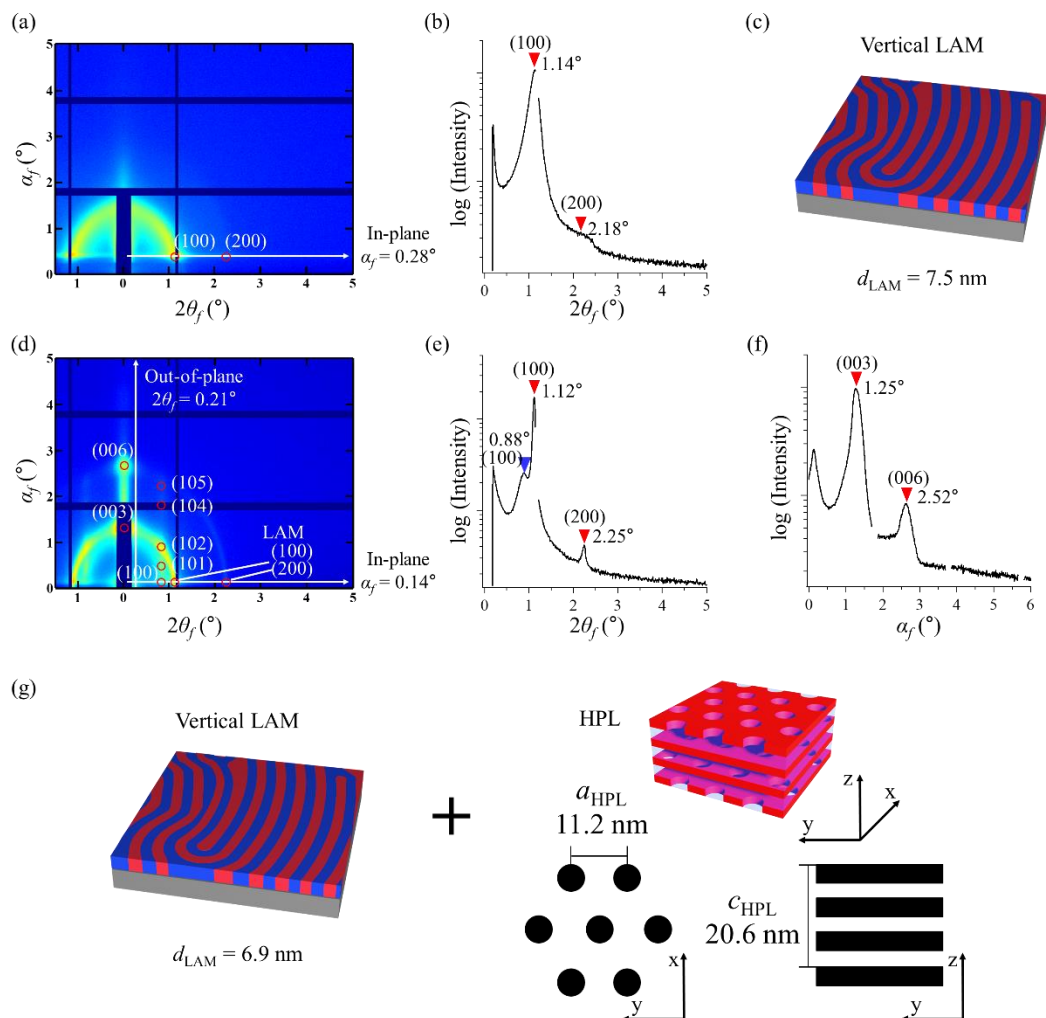


Figure 4.8. Representative GISAXS 2D scattering image of the thermally annealed at 130 °C for 6 hours thin film (a) Glc7-hex-DLToc and (d) mixture solvent annealed after thermal annealing Glc7-hex-DLToc. The 1D in-plane scattering profiles (b) and (e) along the equatorial line on the Yoneda line from (a) and (d), respectively. (f) The 1D out-of-plane scattering profile along the meridian line including peaks derived from (003) and (006) lattice plane. Schematic illustrations showing the (c) vertical LAM and (g) HPL structure with vertical LAM structure on the Si substrate.

GISAXS measurements of thin-film samples of the sugar-rich BCOs demonstrated the formation of HEX and LAM structures, either parallel or perpendicular to the Si substrate. Furthermore, solvent annealing with good solvents for both blocks enhanced the formation of HPL_{ABC} structures and alignment of the nanostructure. The potential to obtain various structures in the thin film state indicates that these BCOs could be a promising material for applications, such as lithographic masks and nanotemplate as lithographic masks and nanotemplates for the synthesis of porous materials.

4.3.4 Self-Assembly Behavior of Sugar–Terpenoid BCO System

4.3.4.1 Flory-Huggins Interaction Parameter of The Sugar–Terpenoid BCO System

Herein, the author considered Flory-Huggins interaction parameter (χ) between sugar and terpenoids to summarize into a phase diagram for the sugar–terpenoid system. The Flory-Huggins interaction parameter χ is a parameter introduced when expressing the mixing Gibbs free energy of the polymers using lattice model in the following equation:^{55–}

57

$$\Delta G^M = \Delta H^M - T\Delta S^M = RTV_M[(f_A/N_A)\ln f_A + (f_B/N_B)\ln f_B + \chi_{A,B}f_Af_B] \quad (1)$$

where R is the gas constant, T is the temperature, V_M is the volume of one lattice unit, f_i is the volume fraction, and N_i is the degree of polymerization of material i . Specifically, the parameter χ included in the enthalpy term capturing this non-ideal behavior between the materials. The parameter χ for conventional BCP can be estimated using parameters such as degree of polymerization, Kuhn length, and R_g through methods such as domain-spacing by atomic force microscopy,²⁵ order-disorder transition temperature by SAXS measurement,^{58,59} and small-angle neutron scattering.⁶⁰ However, the very small molecular weight of BCO prevents the estimation of the parameter χ using these mentioned methods. On the other hand, Hildebrand expressed the enthalpy term using the solubility parameter (δ) of the materials.⁶¹ Consequently, the parameter χ can be expressed by the following equation:

$$H^M = V_M(\delta_A - \delta_B)^2 f_A f_B \quad (2)$$

$$\chi_{A,B} = V_M(\delta_A - \delta_B)^2 / RT \quad (3)$$

The solubility parameter of a polymer segment (δ_i) can be expressed in terms of its cohesive energy density, which represents the energy required to completely separate the

segment into its constituent molecules, and its molar volume. Mathematically, it is given by:

$$\delta_i = (\Delta E_i^{\text{Coh}}/V_i)^{1/2} \quad (4)$$

Here, ΔE_i^{Coh} is the cohesive energy of the polymer segment, and V_i is the volume. This parameter plays a key role in understanding polymer compatibility and miscibility in systems. To indirectly estimate E^{Coh} and V for small molecular weight BCOs, the author adopted Fedors' group-contribution method⁶², which evaluates the contributions of various functional groups.

Farnesol, as indicated by its chemical structure, contains four methyl ($-\text{CH}_3$) groups, five methylene ($-\text{CH}_2-$) groups, three methenyl ($-\text{CH}=\text{}$) groups, three vinyl ($>\text{C}=\text{}$) groups, and one hydroxyl ($-\text{OH}$) group (**Figure 4.9**). Here, for the BCO, the $-\text{OH}$ group is present as ester ($-\text{CO}_2-$) group after condensation reaction, so it was replaced with its E^{Coh} and V for the calculations. The E^{Coh} and V of farnesol in the BCO calculated by group-contribution method were $87,400 \text{ J mol}^{-1}$ and $256.5 \text{ cm}^3 \text{ mol}^{-1}$, respectively. The volume calculated using the group-contribution method shows a similar value to the volume derived from the actual molecular weight of farnesol ($222.37 \text{ g mol}^{-1}$) and its density (0.886 g cm^{-3}), calculated as $251 \text{ cm}^3 \text{ mol}^{-1}$. Finally, the solubility parameter of farnesol in the BCO was calculated to be $18.46 (\text{J cm}^{-3})^{1/2}$ by equation (4). Following the same concept, the calculations for the cohesive energy, molar volume, and solubility parameter of terpenoids and sugar chains were summarized in **Table 4.2**. The calculated solubility parameters of hydrophobic terpenoid segments (farnesol: 18.46, phytol: 17.68, tocopherol: 19.02, and solanesol: 18.01) and hydrophilic sugar segments (Glc₁: 45.33, Glc₂: 44.55, Glc₃: 44.26, Glc₄: 44.11, Glc₅: 44.01, Glc₆: 43.95 and Glc₇: 43.90) were used to estimate the χ value by Equation (3) (**Figures S4.21 and S4.22**). For V_M and T were applied commonly used value of $100 \text{ cm}^3 \text{ mol}^{-1}$ and the temperature adopted for 30°C ,

***Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers***

respectively (**Table 4.3**). Due to the significant differences in solubility parameters between sugar and terpenoid chains, the calculated χ value ranged from 24.57 to 30.34 at 30 °C. Based on these high χ values, it is suggested that by selecting monodispersed and discrete sugar and terpenoid chains with poor compatibility, ultrafine and diverse microphase-separated structures could be achieved.

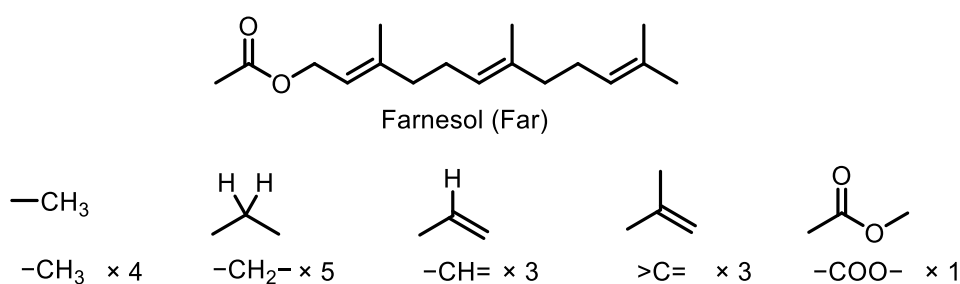


Figure 4.9. Functional groups of farnesol in the BCO.

Table 4.2. Calculation of the cohesive energy, molar volume, and solubility parameter of sugar and terpenoid chains by group-contribution method

Chain	Total E^{Coh} (J mol ⁻¹) ^a	Total M.V. (cm ³ mol ⁻¹) ^a	Solubility parameter δ ((J cm ⁻³) ^{1/2}) ^b
Farnesol	87,400	256.5	18.46
Phytol	95,210	337.3	17.68
Tocopherol	158,100	437.1	19.02
Solanesol	226,660	698.7	18.01
Glc ₁	145,690	70.9	45.33
Glc ₂	261,580	131.8	44.55
Glc ₃	377,470	192.7	44.26
Glc ₄	493,360	253.6	44.11
Glc ₅	609,250	314.5	44.01
Glc ₆	725,140	375.4	43.95
Glc ₇	841,030	436.3	43.90

^aCohesive energy and molar volume of each terpenoids according to Fedors' group-contribution method, referring to each group in **Table S4.1**.⁶²

Table 4.3. Calculation of χ values for sugar–terpenoid BCOs at 30 °C

	Farnesol	Phytol	Tocopherol	Solanesol
Glc ₁	28.65	30.33	27.47	29.61
Glc ₂	-	-	-	27.94
Glc ₃	26.41	28.03	25.28	27.33
Glc ₄	-	-	-	27.02
Glc ₅	25.91	27.51	24.79	26.82
Glc ₆	-	-	-	26.69
Glc ₇	25.69	27.29	24.57	26.60

4.3.4.2 Understanding Microphase-Separation via Phase Diagram of Sugar–Terpenoid BCO

Through the studies in *Chapters 2–4*, the author has identified various morphologies with terpenoid-rich and sugar-rich composition across a wide range of sugar volume fractions, specifically between 0.16 and 0.69. To achieve a comprehensive understanding of the overall microphase-separation behavior of the obtained BCOs, various conceptual phase diagrams were constructed. First, SAXS measurements were utilized to determine the representative morphologies of each BCO in the bulk state (d values were calculated from the first SAXS peak for LAM, HEX and GYR structures, and from a_{HPL} for HPL structure). These were plotted against the sugar volume fractions and the fully extended lengths of BCOs obtained from simulations (**Figure S4.23**). The results revealed that shorter sugar chains combined with the same terpenoid, or shorter terpenoids combined with the same sugar chain, tend to form smaller microphase-separated structures proportional to their molecular length (**Figure 4.10**). In addition, the microphase-separated behaviors of all sugar–terpenoid BCOs, analyzed through SAXS measurements, were plotted as a function of sugar volume versus annealing temperature (**Figure 4.11**). The phase diagram revealed that as the sugar segment's volume fraction increased, the morphology transitioned sequentially in the order of terpenoid rich-HEX, -HPL, -GYR, LAM, sugar rich-GYR, -HPL and -HEX. The phase diagram of the BCO system displays a distinct leftward skew, centered around sugar volume fraction of 0.36. This notable skewness is attributed to the conformational asymmetry between the sugar and terpenoid combinations, which can be likened to rod-like and coil-like structures, resulting in marked differences in their self-assembly behavior. It is expected that this phase diagram will be valuable for predicting the phase separation behavior of various sugar-containing BCOs materials.

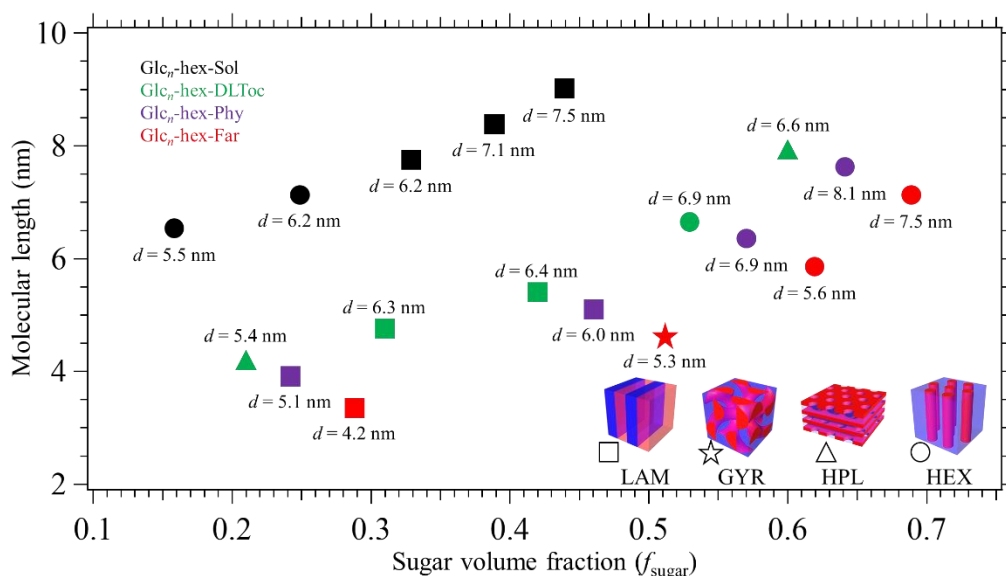


Figure 4.10. Phase diagram of sugar-terpenoid $\text{Glc}_n\text{-hex-Sol}$ ($n = 1$; 180 °C annealed, $n = 2$; 130 °C annealed, $n = 2-5$; 100 °C annealed; black), $\text{Glc}_n\text{-hex-DLToc}$ ($n = 1, 2, 3, 5$, and 7; 80 °C annealed; green), $\text{Glc}_n\text{-hex-Phy}$ ($n = 1, 3, 5$, and 7; 80 °C annealed; purple), and $\text{Glc}_n\text{-hex-Far}$ ($n = 1, 3, 5$, and 7; 80 °C annealed; red) BCO system based on plotted of microphase-separated morphologies as a function of sugar volume fraction and the molecular length of BCOs.

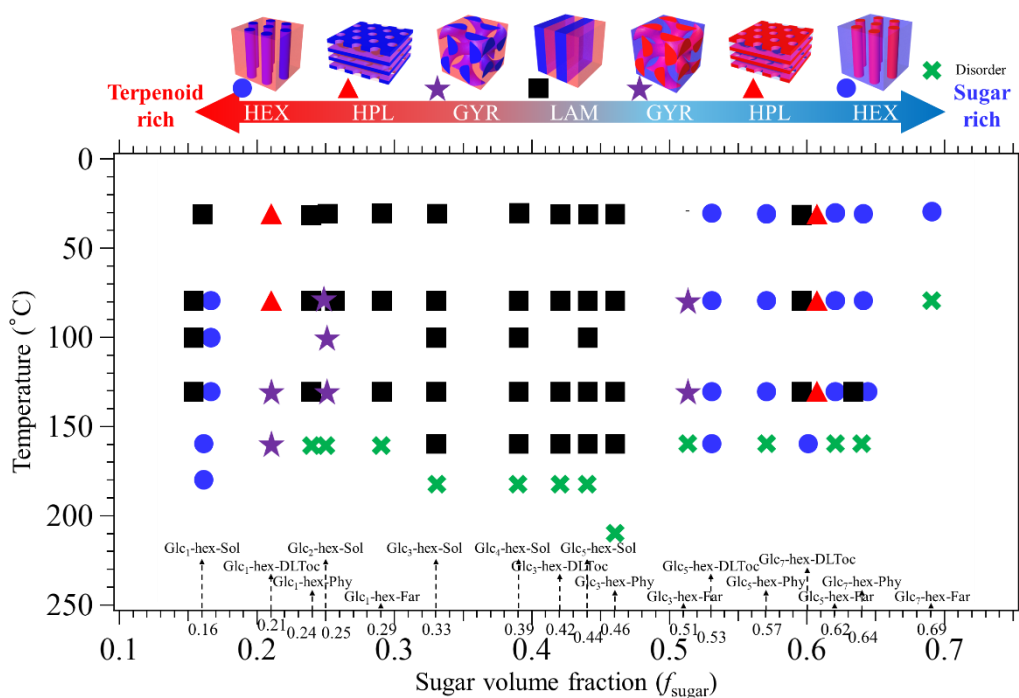


Figure 4.11. Phase diagram of sugar-terpenoid BCO system based on plotted of microphase-separation morphologies as a function of sugar volume fraction and annealing temperature.

4.4 Conclusion

In this study, the author systematically investigated the microphase-separation behavior of sugar-rich block co-oligomers (BCOs) composed of relatively long maltooligosaccharides and hydrophobic terpenoid segments with sugar volume fraction of 0.41 to 0.69. Sugar-rich BCOs have primarily been reported to exhibit lamellar (LAM) and hexagonally packed cylinders (HEX) nanostructures. However, in this BCO system, we utilized small-angle X-ray scattering (SAXS) analysis in the bulk state to elucidate the sugar-rich microphase-separated morphologies, revealing significant diversity, including LAM, gyroid (GYR), HEX, and hexagonally perforated lamellae (HPL). Grazing incidence small-angle X-ray scattering (GISAXS) analysis of the thin films revealed that the microphase-separated morphologies in the sugar-rich BCO system, including LAM, HEX, and HPL structures were consistent with those observed in the bulk state. Moreover, the GISAXS results demonstrated that the orientation and alignment of these nanostructures could be controlled through solvent annealing, highlighting the potential for tailoring morphologies in thin film applications. The Flory-Huggins interaction parameter (χ), calculated from solubility parameters using the Fedors' group-contribution method, indicated significant incompatibility between sugar and terpenoid segments, with χ values ranging from 24.57 to 30.34. In addition, the phase diagram provided key insights into the phase behavior and structural transitions in the sugar–terpenoid BCO system, establishing a predictive framework for designing desired morphologies through compositional and processing control. Overall, this study not only strengthens the foundations related to the microphase separation behavior of BCOs but also offers valuable insights into design and processing strategies that can lead to diverse nanofabrication applications.

4.5 References

- 1 Stoykovich, M. P.; Nealey, P. F. Block Copolymers and Conventional Lithography. *Mater. Today* **2006**, 9, 20–29.
- 2 De La Olvera Cruz, M. Theory of Microphase Separation in Block Copolymer Solutions. *J. Chem. Phys.* **1989**, 90, 1995–2002.
- 3 Bates, F. S.; Fredrickson, G. H. Block Copolymers-Designer Soft Materials. *Phys. Today* **1999**, 52, 32–38.
- 4 Bates, F. S.; Bair, H. E.; Hartney, M. A. Block Copolymers near the Microphase Separation Transition. 1. Preparation and Physical Characterization of a Model System. *Macromolecules* **1984**, 17, 1987–1993.
- 5 Matsen, M. W.; Bates, F. S. Unifying Weak- and Strong-Segregation Block Copolymer Theories. *Macromolecules*, **1996** 29, 1091–1098.
- 6 Urade, V. N.; Wei, T.-C.; Tate, M. P.; Kowalski, J. D.; Hillhouse, H. W. Nanofabrication of Double-Gyroid Thin Films. *Chem. Mater.* **2007**, 19, 768–777.
- 7 A. M. Urbas, M. Maldovan, P. DeRege and E. L. Thomas, Bicontinuous Cubic Block Copolymer Photonic Crystals. *Adv. Mater.* **2002**, 14, 1850–1853.
- 8 Peng, S.; Zhang, R.; Chen, V. H.; Khabiboulline, E. T.; Braun, P.; Atwater, H. A. Three-Dimensional Single Gyroid Photonic Crystals with a Mid-Infrared Bandgap. *ACS Photonics* **2016**, 3, 1131–1137.
- 9 Fruchart, M.; Jeon, S. Y.; Hur, K.; Cheianov, V.; Wiesner, U.; Vitelli, V. Soft Self-Assembly of Weyl Materials for Light and Sound. *Proc. Natl. Acad. Sci. U. S. A.* **2018**, 115, E3655–E3664.

- 10 Li, X.; Wang, C.; Zhou, J.; Yang, Z.; Zhang, Y.; Deng, H. Ultra-Fast Block Copolymers for Sub-5 nm Lithographic Patterning. *J. Photopolym. Sci. Technol.* **2018**, *31*, 483–486.
- 11 Ji, S.; Wan, L.; Liu, C. C.; Nealey, P. F. Directed Self-Assembly of Block Copolymers on Chemical Patterns: A Platform for Nanofabrication. *Prog. Polym. Sci.* **2016**, *54–55*, 76–127.
- 12 Shao, Y.; Hou, B.; Li, W.; Yan, X.; Wang, X.; Xu, Y.; Dong, Q.; Li, W.; He, J.; Bin Zhang, W. Three-Component Bolaform Giant Surfactants Forming Lamellar Nanopatterns with Sub-5 nm Feature Sizes. *Macromolecules* **2023**, *56*, 1562–1571.
- 13 Hou, B.; Zhang, W.-B.; Shao, Y. Unconventional 2D Periodic Nanopatterns Based on Block Molecules. *Chinese J. Polym. Sci.* **2023**, *41*, 1508–1524.
- 14 Oh, J.; Suh, H. S.; Ko, Y.; Nah, Y.; Lee, J. C.; Yeom, B.; Char, K.; Ross, C. A.; Son, J. G. Universal Perpendicular Orientation of Block Copolymer Microdomains Using a Filtered Plasma. *Nat. Commun.* **2019**, *10*, 2912.
- 15 Phillip, W. A.; O'Neill, B.; Rodwogin, M.; Hillmyer, M. A.; Cussler, E. L. Self-Assembled Block Copolymer Thin Films as Water Filtration Membranes. *ACS Appl. Mater. Interfaces* **2010**, *2*, 847–853.
- 16 Li, L.; Schulte, L.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S. Gyroid Nanoporous Membranes with Tunable Permeability. *ACS Nano* **2011**, *5*, 7754–7766.
- 17 Li, L.; Szweczykowski, P.; Clausen, L. D.; Hansen, K. M.; Jonsson, G. E.; Ndoni, S. Ultrafiltration by Gyroid Nanoporous Polymer Membranes. *J. Memb. Sci.* **2011**, *384*, 126–135.

- 18 Crossland, E. J. W.; Kamperman, M.; Nedelcu, M.; Ducati, C.; Wiesner, U.; Smilgies, D.-M.; Toombes, G. E. S.; Hillmyer, M. A.; Ludwigs, S.; Steiner, U.; Snaith, H. J. A. Bicontinuous Double Gyroid Hybrid Solar Cell. *Nano Lett.* **2008**, 9, 2807–2812.
- 19 Zalusky, A. S.; Olayo-Valles, R.; Taylor, C. J.; Hillmyer, M. A. Mesoporous Polystyrene Monoliths. *J. Am. Chem. Soc.* **2001**, 123, 1519–1520.
- 20 Wang, X.-B.; Lo, T.-Y.; Hsueh, H.-Y.; Ho, R.-M. Double and Single Network Phases in Polystyrene-block-poly(L-lactide) Diblock Copolymers. *Macromolecules* **2013**, 46, 2997–3004.
- 21 Barriga, H. M. G.; Holme, M. N.; Stevens, M. M. Cubosomes: The Next Generation of Smart Lipid Nanoparticles? *Angew. Chemie. Int. Ed.* **2019**, 58, 2958–2978.
- 22 Park, W. I.; Kim, Y.; Jeong, J. W.; Kim, K.; Yoo, J. K.; Hur, Y. H.; Kim, J. M.; Thomas, E. L.; Alexander-Katz, A.; Jung, Y. S. Host-Guest Self-Assembly in Block Copolymer Blends. *Sci. Rep.* **2013**, 3, 3190.
- 23 Lee, J.; Moon, J.; Kim, J.; Malgras, V.; Heo, Y.; Kim, H.; Lee, S.; Liu, H. K.; Dou, S. X.; Yamauchi, Y.; Park, M.; Kim, J. H. Everlasting Living and Breathing Gyroid 3D. *ACS Nano* **2019**, 13, 9607–9619.
- 24 Sinturel, C.; Bates, F. S.; Hillmyer, M. A. High χ -Low N Block Polymers: How Far Can We Go? *ACS Macro Lett.* **2015**, 4, 1044–1050.
- 25 Cushen, J. D.; Bates, C. M.; Rausch, E. L.; Dean, L. M.; Zhou, S. X.; Willson, C. G.; Ellison, C. J. Thin Film Self-Assembly of Poly(trimethylsilylstyrene-*b*-*d*,*l*-lactide) with Sub-10 nm Domains. *Macromolecules* **2012**, 45, 8722–8728.

***Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers***

- 26 Jung, Y. S.; Chang, J. B.; Verploegen, E.; Berggren, K. K.; Ross, C. A. A Path to Ultranarrow Patterns Using Self-Assembled Lithography. *Nano Lett.* **2010**, *10*, 1000–1005.
- 27 Kennemur, J. G.; Yao, L.; Bates, F. S.; Hillmyer, M. A. Sub-5 nm Domains in Ordered Poly(cyclohexylethylene)-block-poly(methyl methacrylate) Block Polymers for Lithography. *Macromolecules* **2014**, *47*, 1411–1418.
- 28 Cushen, J. D.; Otsuka, I.; Bates, C. M.; Halila, S.; Fort, S.; Rochas, C.; Easley, J. A.; Rausch, E. L.; Thio, A.; Borsali, R.; Willson, C. G.; Ellison, C. J. Oligosaccharide/Silicon-Containing Block Copolymers with 5 nm Features for Lithographic Applications. *ACS Nano* **2012**, *6*, 3424–3433.
- 29 Aissou, K.; Otsuka, I.; Rochas, C.; Fort, S.; Halila, S.; Borsali, R. Nano-Organization of Amylose-*b*-Polystyrene Block Copolymer Films Doped with Bipyridine. *Langmuir* **2011**, *27*, 4098–4103.
- 30 Otsuka, I.; Isono, T.; Rochas, C.; Halila, S.; Fort, S.; Satoh, T.; Kakuchi, T.; Borsali, R. 10 nm Scale Cylinder–Cubic Phase Transition Induced by Caramelization in Sugar-Based Block Copolymers. *ACS Macro Lett.* **2012**, *1*, 1379–1382.
- 31 Isono, T.; Komaki, R.; Lee, C.; Kawakami, N.; Ree, B. J.; Watanabe, K.; Yoshida, K.; Mamiya, H.; Yamamoto, T.; Borsali, R.; Tajima, K.; Satoh, T. Rapid Access to Discrete and Monodisperse Block Co-oligomers from Sugar and Terpenoid toward Ultrasmall Periodic Nanostructures. *Commun. Chem.* **2020**, *3*, 135.
- 32 Lee, C.; Ree, B. J.; Chen, K.; Komaki, R.; Katsuhara, S.; Yamamoto, T.; Borsali, R.; Tajima, K.; Chen, H. L.; Satoh, T.; Isono, T. Ultrasmall 3D Network Morphologies from Biobased Sugar–Terpenoid Hybrid Block Co-oligomers in The Bulk and The Thin Film States. *Giant* **2024**, *17*, 100211.

- 33 Chen, K.; Lee, C.; Chen, C. Y.; Satoh, T.; Isono, T.; Chen, H. L. Phase Behavior of Sugar-based Block Co-oligomer Modulated by Molecular Chirality. *Giant* **2024**, *19*, 100308.
- 34 Nowak, S. R.; Lachmayr, K. K.; Yager, K. G.; Sita, L. R. Stable Thermotropic 3D and 2D Double Gyroid Nanostructures with Sub-2-nm Feature Size from Scalable Sugar–Polyolefin Conjugates. *Angew. Chemie. Int. Ed.* **2021**, *60*, 8710–8716.
- 35 Nishimura, T.; Katsuhara, S.; Lee, C.; Ree, B. J.; Borsali, R.; Yamamoto, T.; Tajima, K.; Satoh, T.; Isono, T. Fabrication of Ultrafine, Highly Ordered Nanostructures Using Carbohydrate-Inorganic Hybrid Block Copolymers. *Nanomaterials* **2022**, *12*, 1–14.
- 36 Isono, T.; Ree, B. J.; Tajima, K.; Borsali, R.; Satoh, T. Highly Ordered Cylinder Morphologies with 10 nm Scale Periodicity in Biomass-Based Block Copolymers. *Macromolecules* **2018**, *51*, 428–437.
- 37 Tomasik, P. Chemical Modifications of Polysaccharides. *Chem. Funct. Prop. Food Saccharides* **2003**, *2013*, 123–130.
- 38 Witte, M. D.; Minnaard, A. J. Site-Selective Modification of (Oligo)Saccharides. *ACS Catal.* **2022**, *12*, 12195–12205.
- 39 Kazemi Shariat Panahi, H.; Dehhaghi, M.; Amiri, H.; Guillemin, G. J.; Gupta, V. K.; Rajaei, A.; Yang, Y.; Peng, W.; Pan, J.; Aghbashlo, M.; Tabatabaei, M. Current and Emerging Applications of Saccharide-Modified Chitosan: a Critical Review. *Biotechnol. Adv.* **2023**, *66*, 108172.

- 40 Marradi, M.; Chiodo, F.; García, I.; Penadés, S. Glyconanoparticles as Multifunctional and Multimodal Carbohydrate Systems. *Chem. Soc. Rev.* **2013**, *42*, 4728–4745.
- 41 Slaney, A. M.; Wright, V. A.; Meloncelli, P. J.; Harris, K. D.; West, L. J.; Lowary, T. L.; Buriak, J. M. Biocompatible Carbohydrate-Functionalized Stainless Steel Surfaces: A New Method For Passivating Biomedical Implants. *ACS Appl. Mater. Interfaces* **2011**, *3*, 1601–1612.
- 42 Nandanan, E.; Jana, N. R.; Ying, J. Y. Functionalization of Gold Nanospheres and Nanorods by Chitosan Oligosaccharide Derivatives. *Adv. Mater.* **2008**, *20*, 2068–2073.
- 43 Guo, L.; Yan, D. D.; Yang, D.; Li, Y.; Wang, X.; Zalewski, O.; Yan, B.; Lu, W. Combinatorial Photothermal and Immuno Cancer Therapy Using Chitosan-Coated Hollow Copper Sulfide Nanoparticles. *ACS Nano* **2014**, *8*, 5670–5681.
- 44 Reichardt, N. C.; Martín-Lomas, M.; Penadés, S. Glyconanotechnology. *Chem. Soc. Rev.* **2013**, *42*, 4358–4376.
- 45 Zhang, Y.; Chan, J. W.; Moretti, A.; Uhrich, K. E. Designing Polymers with Sugar-based Advantages for Bioactive Delivery Applications. *J. Control. Release* **2015**, *219*, 355–368.
- 46 Davis, M. E.; Brewster, M. E. Cyclodextrin-based Pharmaceuticals: Past, Present and Future. *Nat. Rev. Drug Discov.* **2004**, *3*, 1023–1035.
- 47 Chawla, K.; Yu, T.; Liao, S. W.; Guan, Z. Biodegradable and Biocompatible Synthetic Saccharide–Peptide Hydrogels for Three-Dimensional Stem Cell Culture. *Biomacromolecules* **2011**, *12*, 560–567.

- 48 Moros, M.; Hernáez, B.; Garet, E.; Dias, J. T.; Sáez, B.; Grazú, V.; González-Fernández, Á.; Alonso, C.; Fuente, J. M. de la. Monosaccharides versus PEG-Functionalized NPs: Influence in the Cellular Uptake *ACS Nano* **2012**, 6, 1565–1577.
- 49 Manickam Achari, V.; Nguan, H. S.; Heidelberg, T.; Bryce, R. A.; Hashim, R. Molecular Dynamics Study of Anhydrous Lamellar Structures of Synthetic Glycolipids: Effects of Chain Branching and Disaccharide Headgroup. *J. Phys. Chem. B* **2012**, 116, 11626–11634.
- 50 Hashim, R.; Zahid, N. I.; Velayutham, T. S.; Aripin, N. F. K.; Ogawa, S.; Sugimura, A. Dry Thermotropic Glycolipid Self-Assembly: A Review. *J. Oleo Sci.* **2018**, 67, 651–668.
- 51 Cushen, J. D.; Shanmuganathan, K.; Janes, D. W.; Willson, C. G.; Ellison, C. J. Synthesis of Amphiphilic Naturally-Derived Oligosaccharide-block-Wax Oligomers and Their Self-Assembly. *ACS Macro Lett.* **2014**, 3, 839–844.
- 52 Fukunaga, K.; Elbs, H.; Magerle, R.; Krausch, G. Large-Scale Alignment of ABC Block Copolymer Microdomains via Solvent Vapor Treatment. *Macromolecules* **2000**, 33, 947–953.
- 53 Sinturel, C.; Vayer, M.; Morris, M.; Hillmyer, M. A. Solvent Vapor Annealing of Block Polymer Thin Films. *Macromolecules* **2013**, 46, 5399–5415.
- 54 Otsuka, I.; Tallegas, S.; Sakai, Y.; Rochas, C.; Halila, S.; Fort, S.; Bsiesy, A.; Baron, T.; Borsali, R. Control of 10 nm Scale Cylinder Orientation in Self-Organized Sugar-based Block Copolymer Thin Films. *Nanoscale* **2013**, 5, 2637–2641.

***Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers***

- 55 Flory, P. J.; Orwoll, R. A.; Vrij, A. Statistical Thermodynamics of Chain Molecule Liquids. II. Liquid Mixtures of Normal Paraffin Hydrocarbons. *J. Am. Chem. Soc.* **1964**, *86*, 3515–3520.
- 56 Flory, P. J. Statistical Thermodynamics of Liquid Mixtures. *J. Am. Chem. Soc.* **1965**, *87*, 1833–1838.
- 57 Flory, P. J.; Eichinger, B. E.; Orwoll, R. A. Thermodynamics of Mixing Polymethylene and Polyisobutylene. *Macromolecules* **1968**, *1*, 287–288.
- 58 Zalusky, A. S.; Olayo-Valles, R.; Wolf, J. H.; Hillmyer, M. A. Ordered Nanoporous Polymers from Polystyrene–Polylactide Block Copolymers. *J. Am. Chem. Soc.* **2002**, *124*, 12761–12773.
- 59 Andersen, T. H.; Tougaard, S.; Larsen, N. B.; Almdal, K.; Johannsen, I. Surface Morphology of PS–PDMS Diblock Copolymer Films. *J. Electron Spectros. Relat. Phenomena* **2001**, *121*, 93–110.
- 60 Russell, T. P.; Hjelm, R. P. J.; Seeger, P. A. Temperature Dependence of the Interaction Parameter of Polystyrene and Poly(methyl methacrylate). *Macromolecules* **1990**, *23*, 890–893.
- 61 Hildebrand, J.; Scott, R. *The Solubility of Nonelectrolytes*. Reinhold Publishing Corporation, 1950.
- 62 Fedors, R. A Method for Estimating Both the Solubility Parameters and Molar Volumes of Liquids. *Polym. Eng. Sci.* **1974**, *14*, 147–154.

4.6 Supporting Information

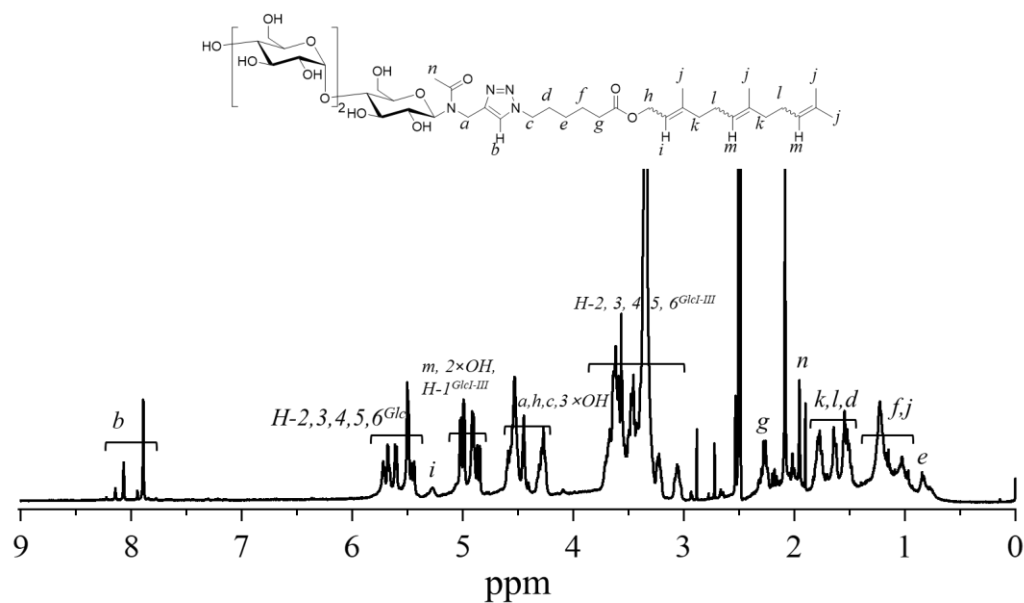
Synthesis of Glc_n-hex-Far ($n = 3, 5, 7$)

Figure S4.1. ^1H NMR spectrum of Glc₃-hex-Far (DMSO- d_6 , 400 MHz).

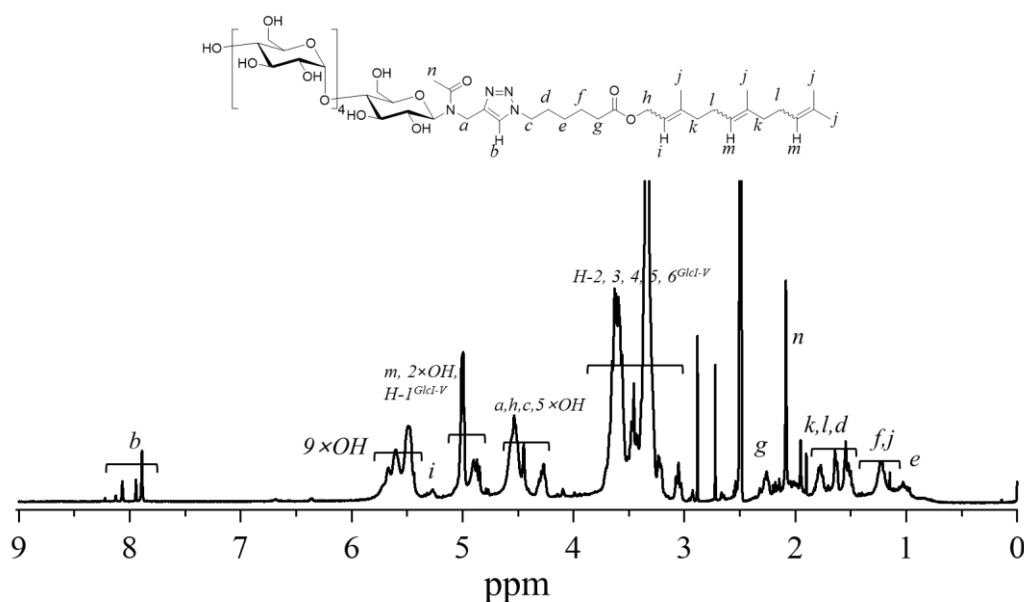


Figure S4.2. ^1H NMR spectrum of Glc₅-hex-Far (DMSO- d_6 , 400 MHz).

**Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers**

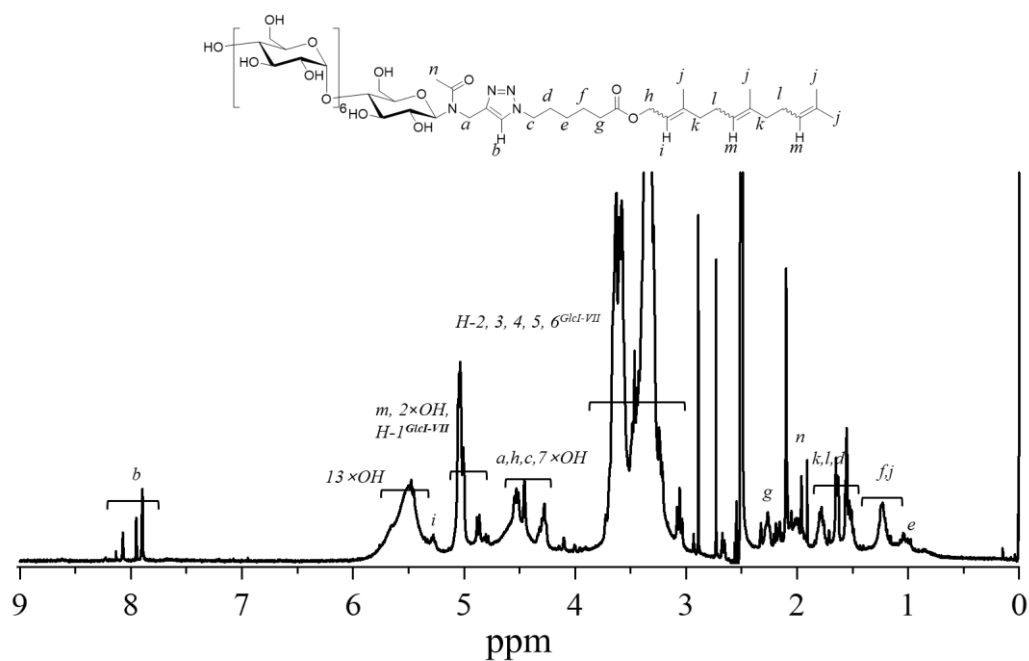


Figure S4.3. ^1H NMR spectrum of Glc₇-hex-Far (DMSO- d_6 , 400 MHz).

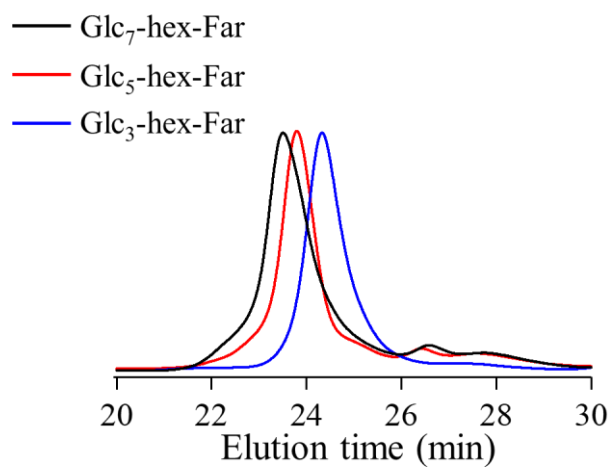


Figure S4.4. SEC traces of Glc₃-hex-Far (blue), Glc₅-hex-Far (red), and Glc₇-hex-Far (black) (eluent, DMF containing 0.01 mol L⁻¹ LiCl; flow rate, 0.6 mL min⁻¹).

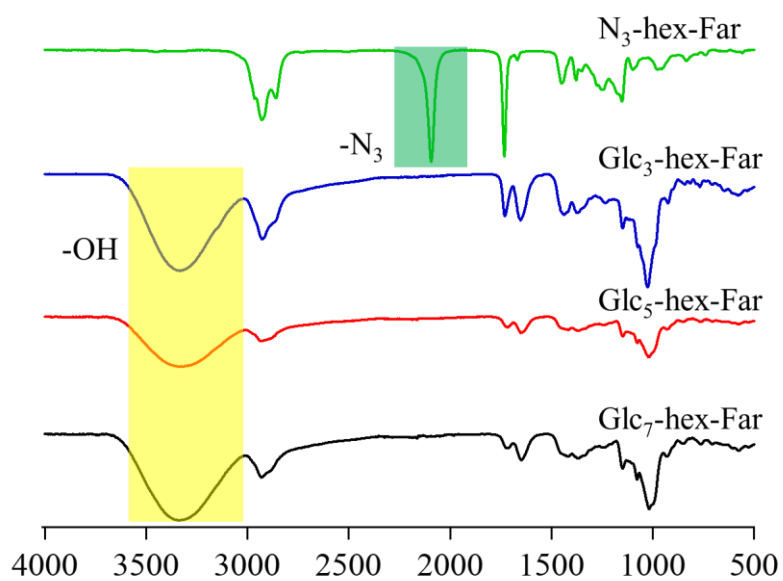


Figure S4.5. (a) FT-IR spectra of N₃-hex-Far (green), Glc₃-hex-Far (blue), Glc₅-hex-Far (red), and Glc₇-hex-Far (black).

Synthesis of Glc_n-hex-Phy (*n* = 3, 5, 7)

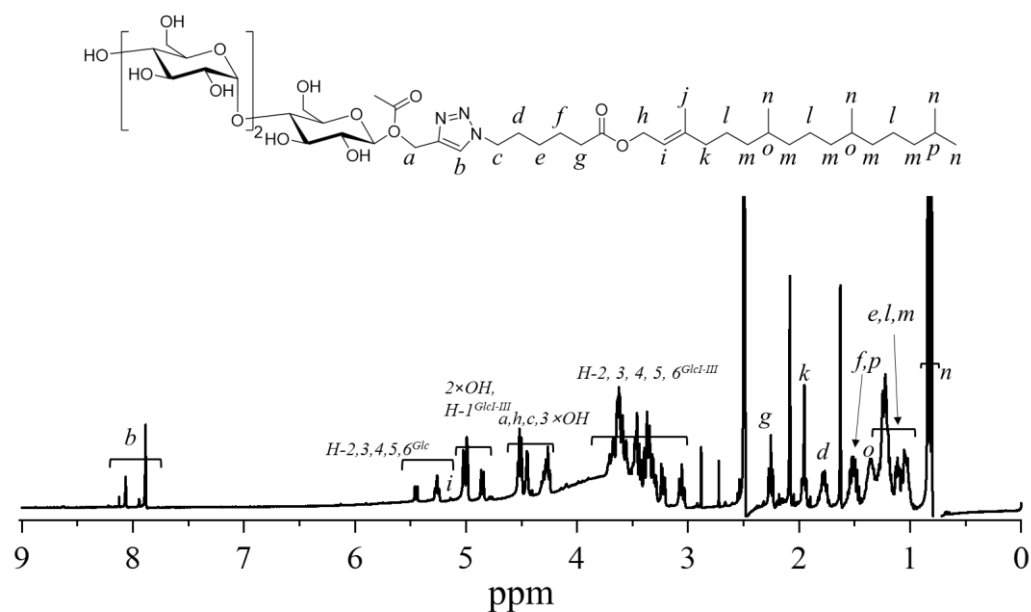


Figure S4.6. ¹H NMR spectrum of Glc₃-hex-Phy (DMSO-*d*₆, 400 MHz).

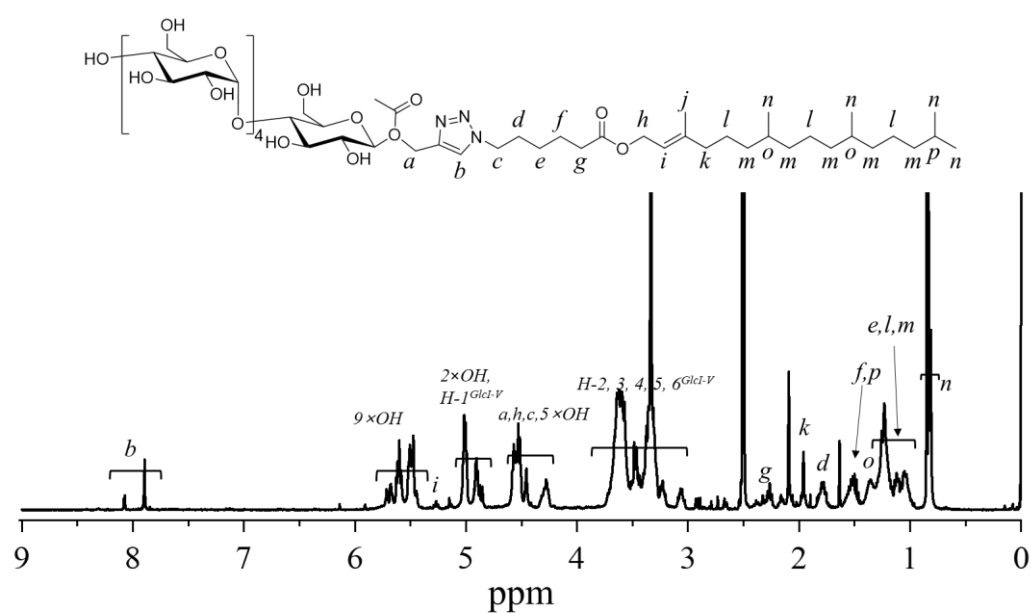


Figure S4.7. ¹H NMR spectrum of Glc₅-hex-Phy (DMSO-*d*₆, 400 MHz).

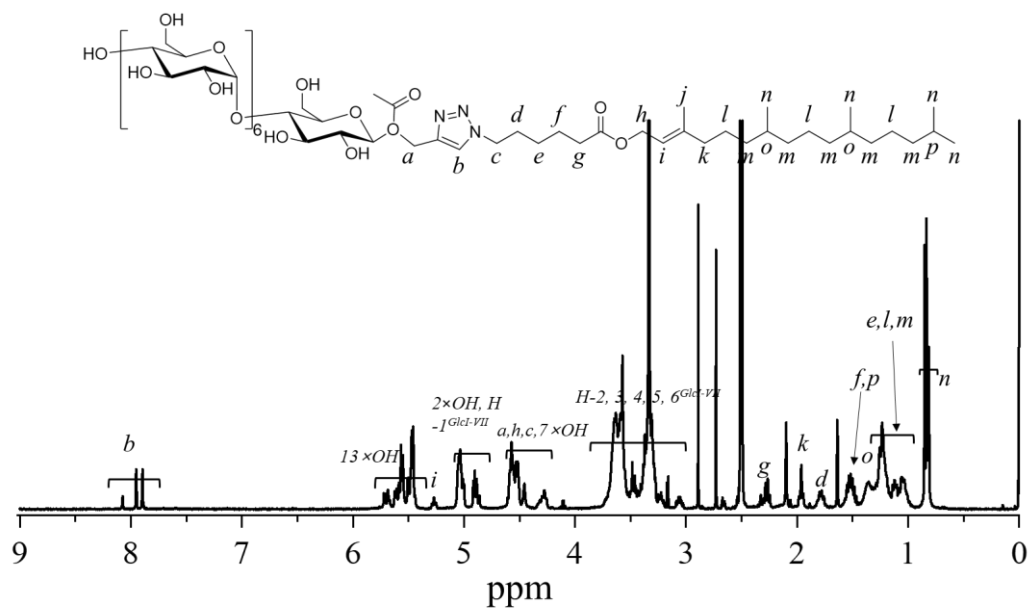


Figure S4.8. ^1H NMR spectrum of Glc₇-hex-Phy (DMSO- d_6 , 400 MHz).

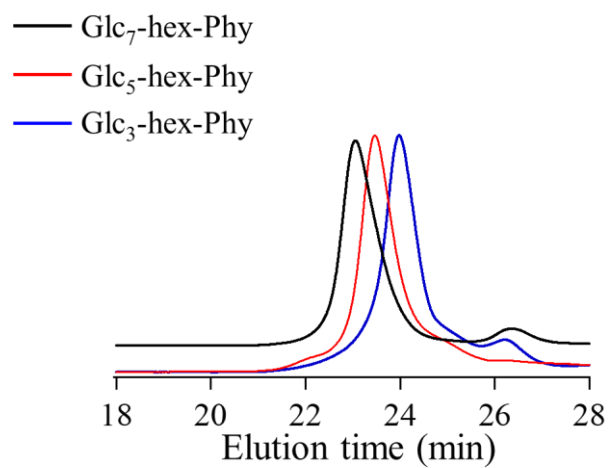


Figure S4.9. SEC traces of Glc₃-hex-Phy (blue), Glc₅-hex-Phy (red), and Glc₇-hex-Phy (black) (eluent, DMF containing 0.01 mol L^{-1} LiCl; flow rate, 0.6 mL min^{-1}).

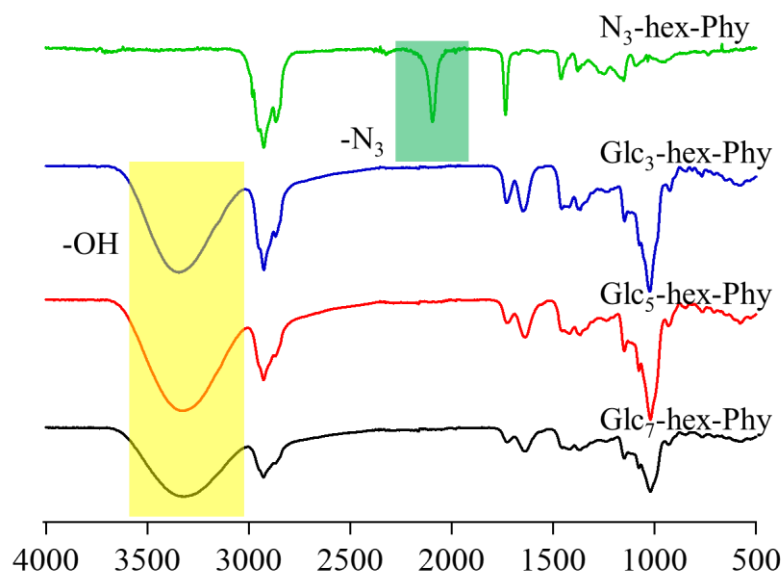


Figure S4.10. (a) FT-IR spectra of N₃-hex-Phy (green), Glc₃-hex-Phy (blue), Glc₅-hex-Phy (red), and Glc₇-hex-Phy (black).

Synthesis of $\text{Glc}_n\text{-hex-DLToc}$ ($n = 3, 5, 7$)

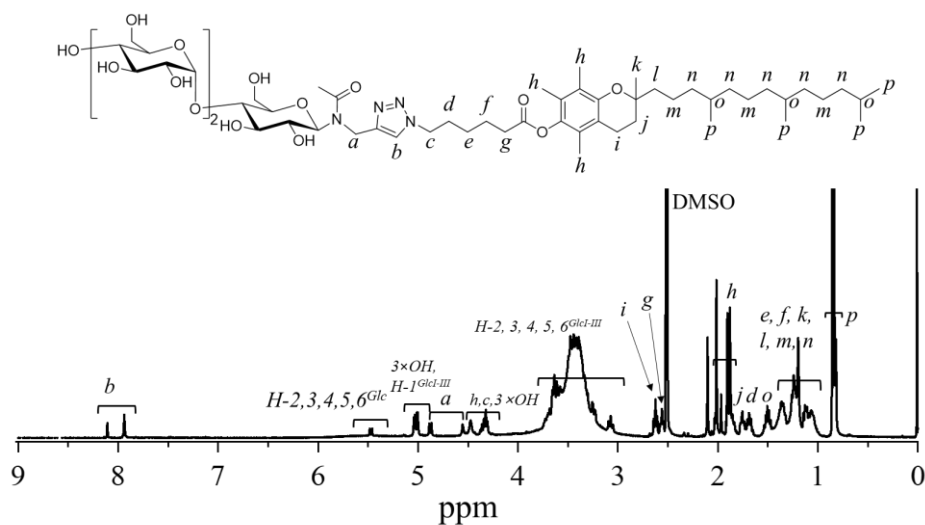


Figure S4.11. ^1H NMR spectrum of $\text{Glc}_3\text{-hex-DLToc}$ ($\text{DMSO-}d_6$, 400 MHz).

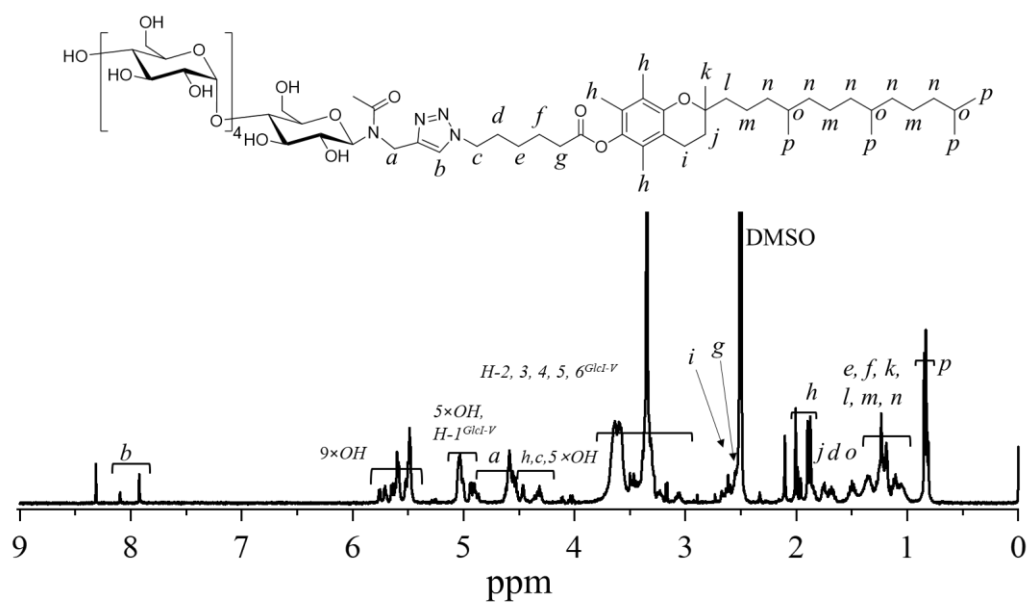


Figure S4.12. ^1H NMR spectrum of $\text{Glc}_5\text{-hex-DLToc}$ ($\text{DMSO-}d_6$, 400 MHz).

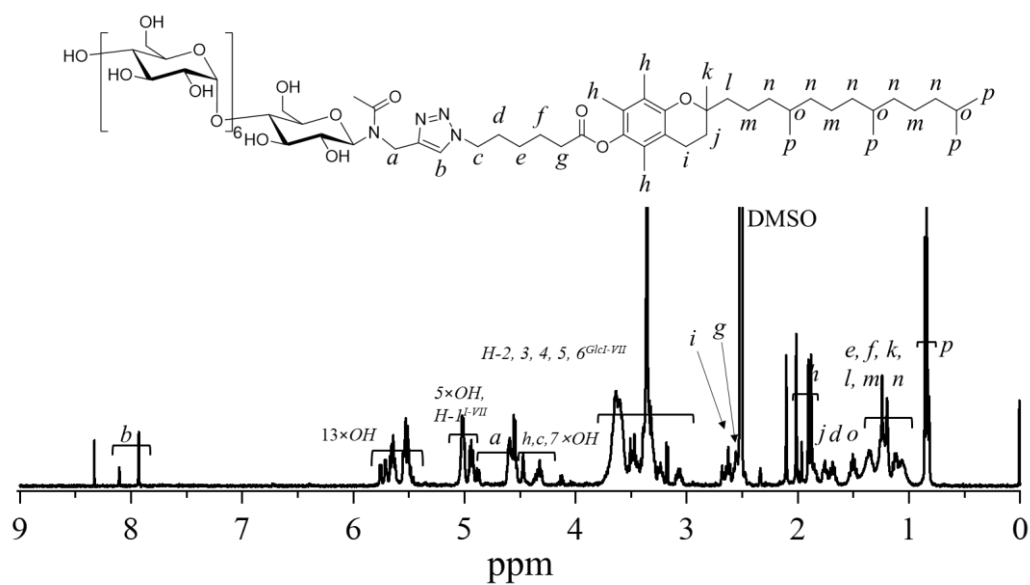


Figure S4.13. ^1H NMR spectrum of Glc₇-hex-DLToc (DMSO- d_6 , 400 MHz).

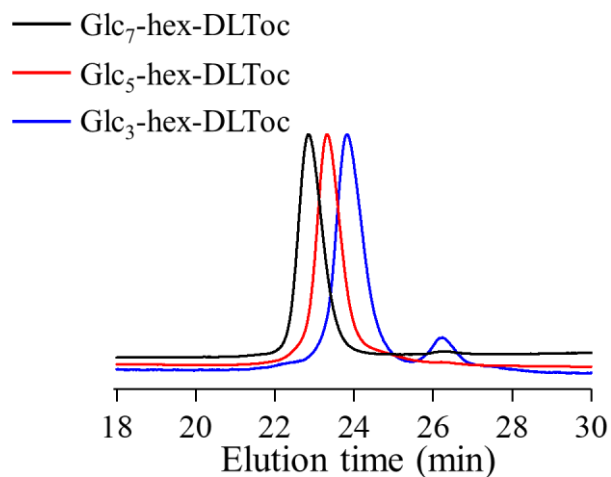


Figure S4.14. SEC traces of Glc₃-hex-DLToc (blue), Glc₅-hex-DLToc (red), and Glc₇-hex-DLToc (black) (eluent, DMF containing 0.01 mol L⁻¹ LiCl; flow rate, 0.6 mL min⁻¹).

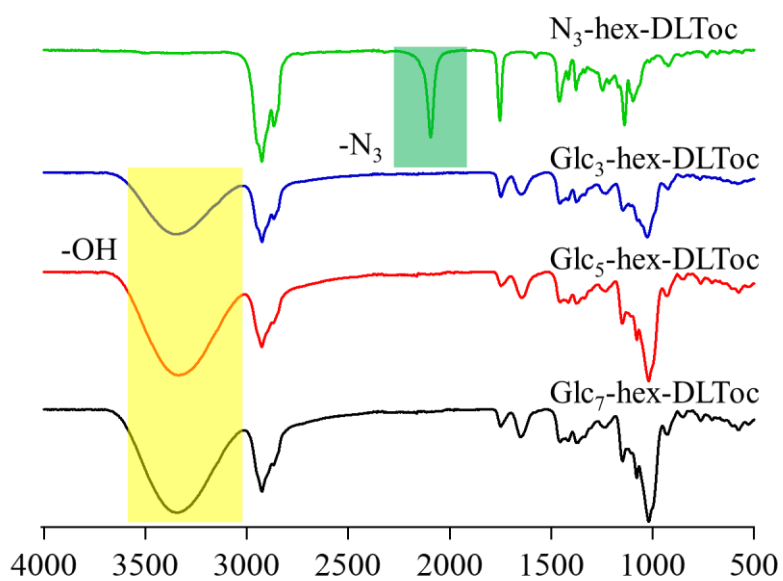


Figure S4.15. (a) FT-IR spectra of N₃-hex-DLToc (green), Glc₃-hex-DLToc (blue), Glc₅-hex-DLToc (red), and Glc₇-hex-DLToc (black).

DSC measurement of BCOs

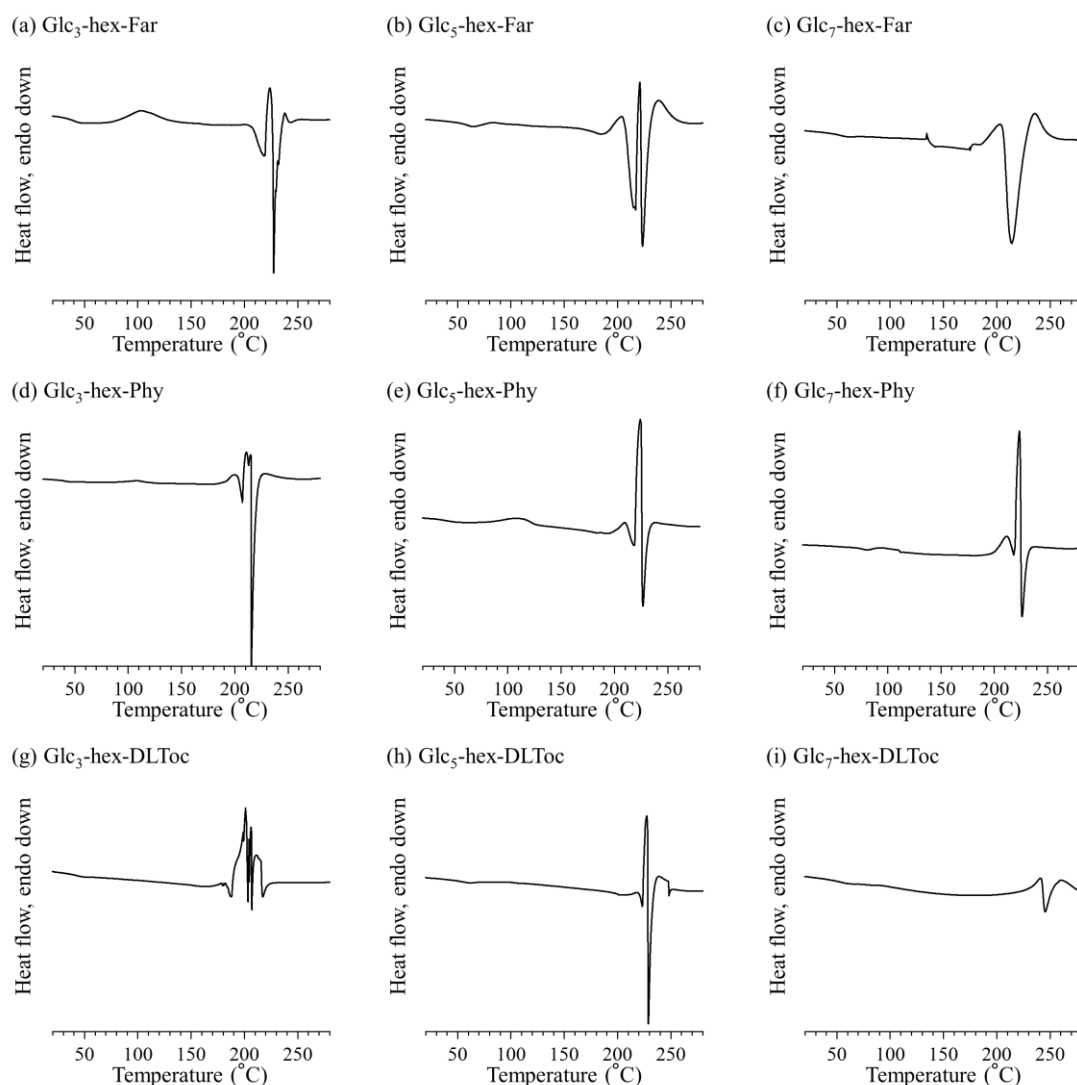


Figure S4.16. DSC traces of (a) Glc₃-hex-Far, (b) Glc₅-hex-Far, (c) Glc₇-hex-Far, (d) Glc₃-hex-Phy, (e) Glc₅-hex-Phy, (f) Glc₇-hex-Phy, (g) Glc₃-hex-DLToc, (h) Glc₅-hex-DLToc, and (i) Glc₇-hex-DLToc, during the second heating run (heating and cooling rate, 10 °C min⁻¹).

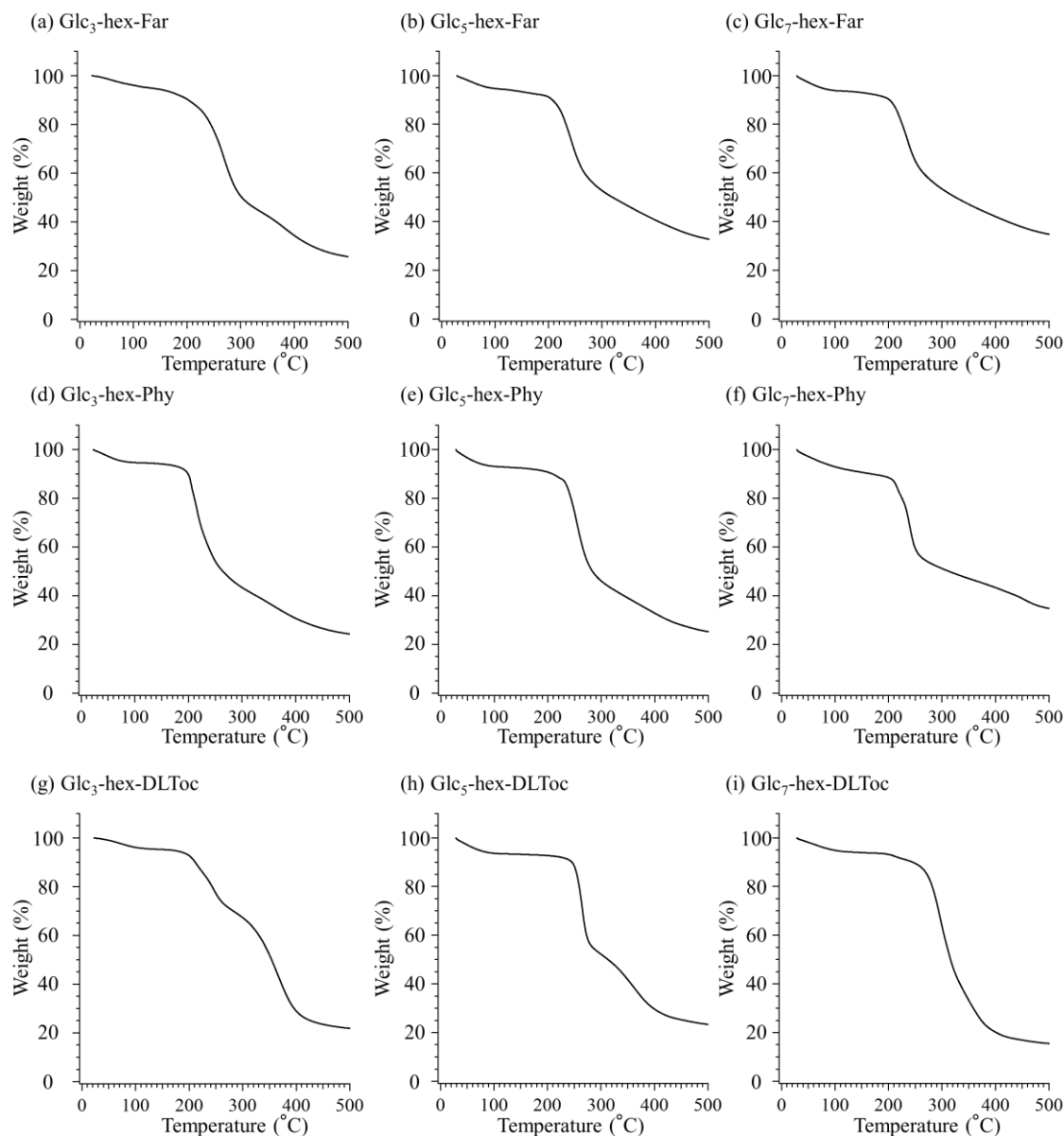
TGA measurement of BCOs

Figure S4.17. TGA traces of (a) Glc₃-hex-Far, (b) Glc₅-hex-Far, (c) Glc₇-hex-Far, (d) Glc₃-hex-Phy, (e) Glc₅-hex-Phy, (f) Glc₇-hex-Phy, (g) Glc₃-hex-DLToc, (h) Glc₅-hex-DLToc, and (i) Glc₇-hex-DLToc with a heating rate of 10 °C min⁻¹ from 30 °C to 500 °C.

WAXS measurement of BCOs

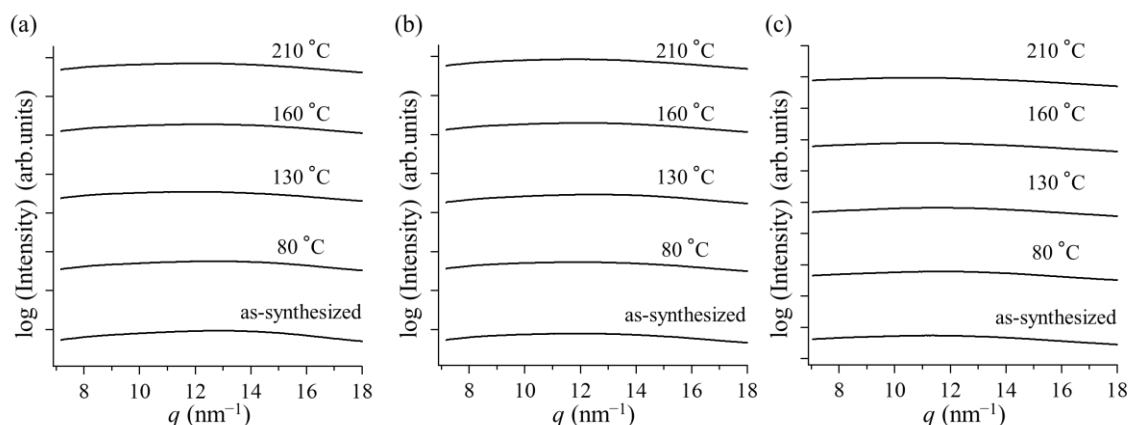


Figure S4.18. WAXS profiles of BCOs the as-synthesized and thermally annealed (a) Glc₃-hex-Far, (B) Glc₅-hex-Far, and (C) Glc₇-hex-Far.

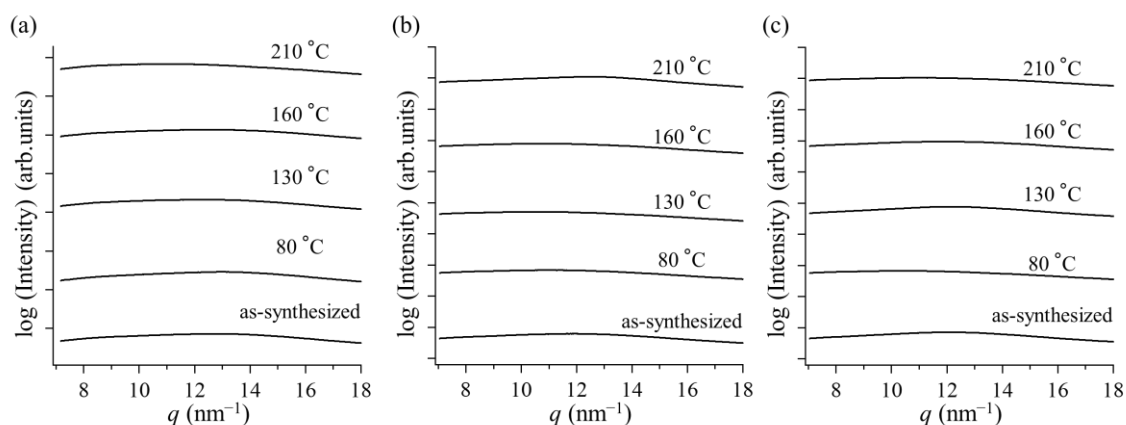


Figure S4.19. WAXS profiles of BCOs the as-synthesized and thermally annealed (a) Glc₃-hex-Phy, (B) Glc₅-hex-Phy, and (C) Glc₇-hex-Phy.

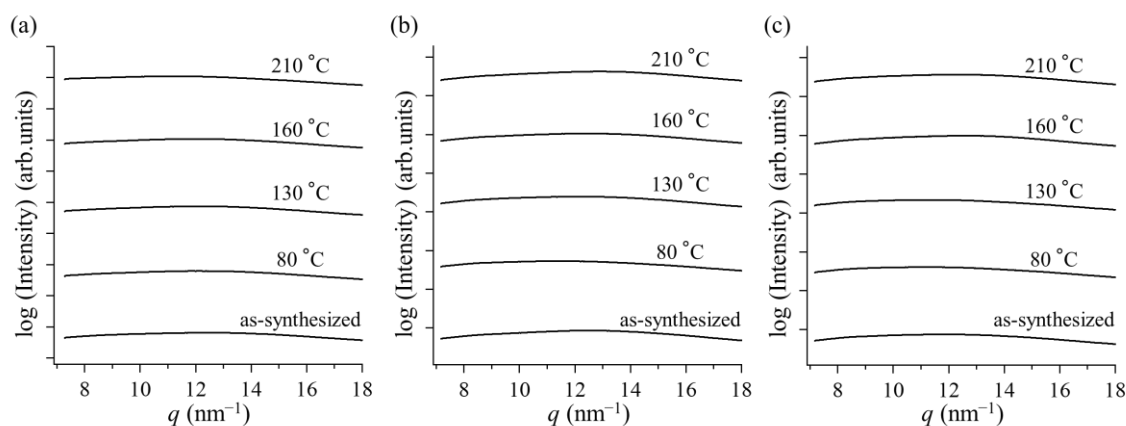
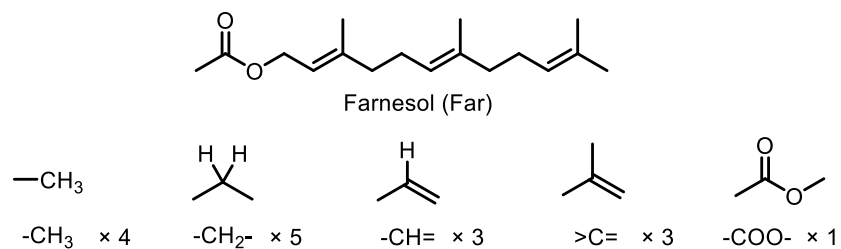


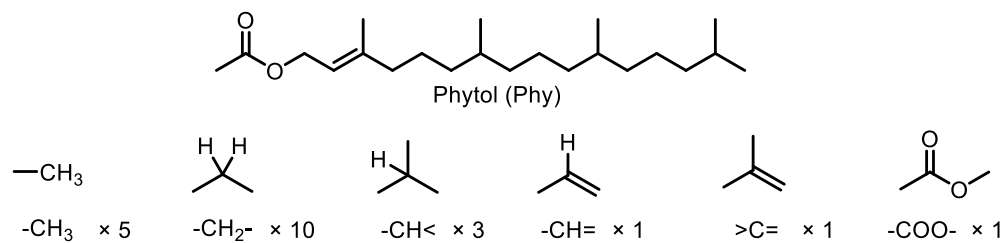
Figure S4.20. WAXS profiles of BCOs the as-synthesized and thermally annealed (a) Glc₃-hex-DLToc, (B) Glc₅-hex-DLToc, and (C) Glc₇-hex-DLToc.

Functional group of terpenoid and sugar chains for group-contribution method

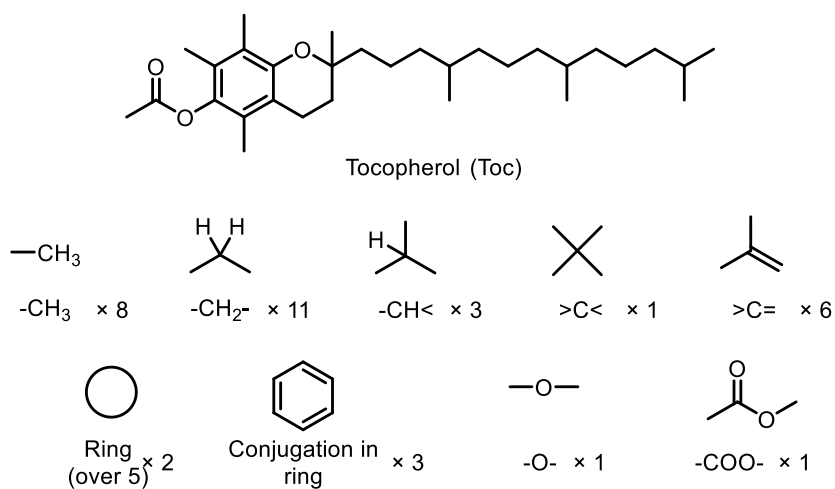
(a)



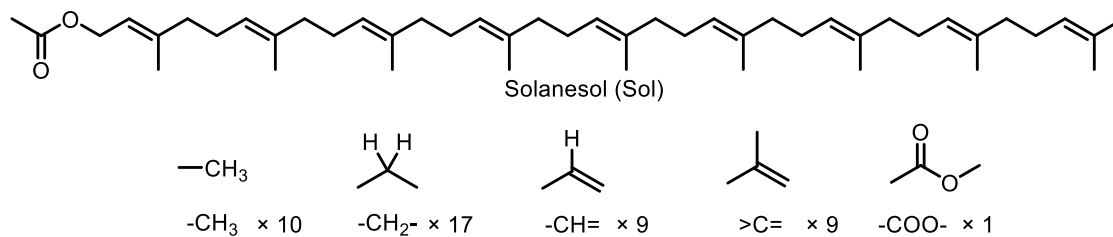
(b)



(c)



(d)

**Figure S4.21.** Atom groups of (a) farnesol, (b) phytol, (c) tocopherol, and (d) solanesol.

***Sugar-Rich Microphase-Separated Structures by
Sugar–Terpenoid Block Co-oligomers***

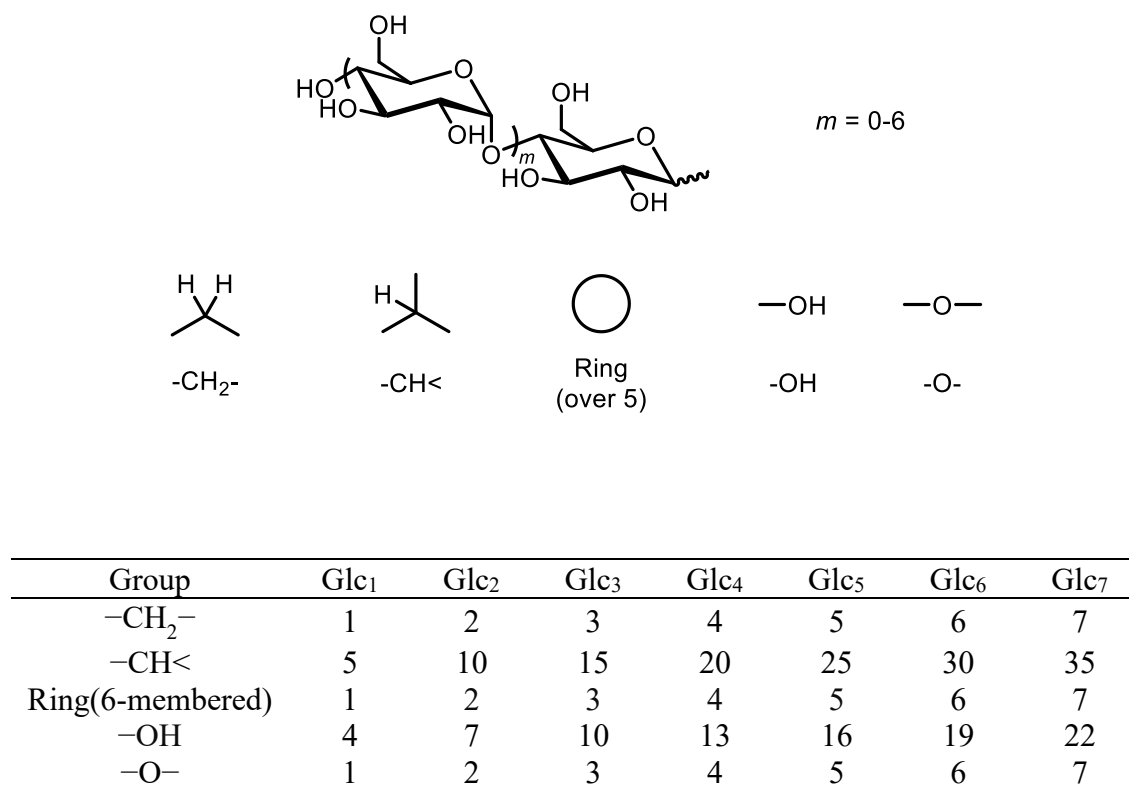
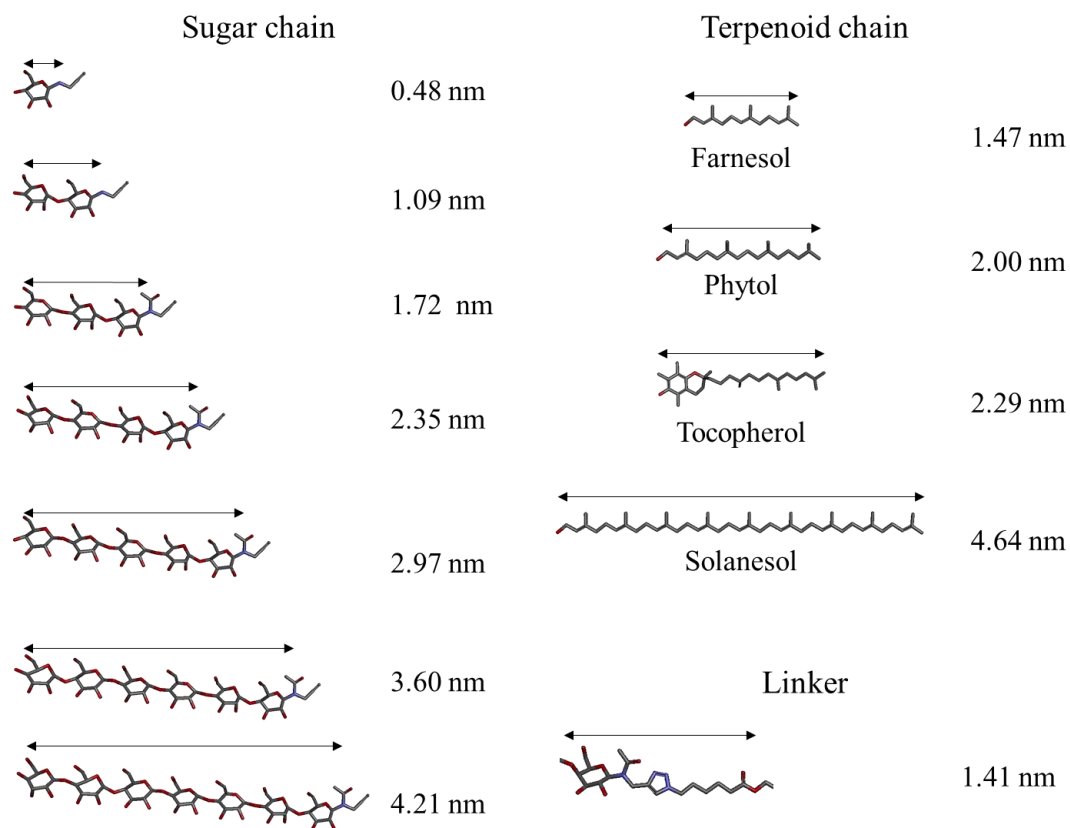


Figure S4.22. Functional groups of sugar chain.

Table S4.1. The cohesive energy and molar volume of each group

Group ^a	Cohesive Energy (E^{Coh}) (J/mol) ^a	Molar Volume (M.V.) (cm ³ /mol) ^a
-CH ₃	4,710	33.5
-CH ₂ -	4,940	16.1
-CH<	3,430	-1.0
-CH=	4,310	13.5
>C<	1,470	-19.2
>C=	4,310	-5.5
-CO ₂ -	18,000	18
Ring(6-membered)	1,050	16
Conjugated double bond	1,670	-2.2
-O-	3350	3.8
-CO ₂ -	18,000	18
-OH	29,800	10

^aCohesive energy and molar volume according to Fedors' group-contribution method.⁶²

Chain lengths by simulation**Figure S4.23.** Estimation of molecular length of sugar chain, terpenoid chain and linker.

Chapter 5

Conclusions

In this dissertation, the author proposed a novel approach to address the challenges associated with the design and application of BCPs by focusing on high χ -low N sugar-terpenoid BCOs. These monodisperse BCOs were successfully synthesized via click reaction, integrating well-defined hydrophilic oligosaccharides and hydrophobic terpenoid building blocks. This innovative strategy aims to develop materials that exhibit sub-10 nm nanoscale morphologies, which not only expand the understanding of microphase-separated structures in both bulk and thin film states but also hold significant promise for various applications in nanotechnology. The research achievements and critical findings presented in each chapter of this dissertation are summarized as follows:"

Chapter 2. Synthesis of Monodisperse High χ -Low N Block Co-oligomers for Ultrasmall Microphase-Separated Structures

The author explored the design, synthesis, and self-assembly behaviors of monodisperse BCOs composed of hydrophilic oligosaccharides (glucose, maltose, maltotriose, maltoheptaose, maltopentaose, maltohexaose, and maltoheptaose) and hydrophobic terpenoids (farnesol, DL- α -tocopherol, and solanesol). A straightforward click reaction was employed to synthesize these novel BCOs, enabling tailored segment compositions and degrees of polymerization. The author detailed how these BCOs self-assemble into well-ordered microphase-separated morphologies, specifically lamellar (LAM), double gyroid (GYR), and hexagonally packed cylinders (HEX), with domain spacings ranging from 4 to 8 nm, as determined by small angle X-ray scattering (SAXS) measurements. The influence of sugar volume fraction on morphology and domain spacing was carefully examined, highlighting the versatility and tunability of these BCO systems. The significance of these findings was underscored by the potential applications of these BCOs in advanced nanolithography and nanoporous materials. The author

suggested that these innovative materials can expand the scope and versatility of microphase-separated structures.

Chapter 3. Three-Dimensional Network Microphase-Separation Morphologies with Sugar–Terpenoid Block Co-oligomers

The author focused on the development of ultrafine three-dimensional (3D) network morphologies, including GYR and *ABC*-stacked hexagonally perforated lamellae (HPL_{ABC}), achieved by the sugar–terpenoid BCOs. These BCOs employed glucose as the hydrophilic segment and various lengths of terpenoids, such as farnesol, phytol, and tocopherol, as the hydrophobic segments. Through the SAXS measurements, the author demonstrated that tocopherol played a crucial role in facilitating the formation of complex 3D network structures, while the other terpenoids predominantly lead to LAM phases because of their short length. The differences in morphology were attributed to the distinct molecular shapes and volume fractions of the sugar blocks. Notably, the HPL_{ABC} and GYR morphologies were maintained in the thin film states, as revealed by grazing incidence small-angle X-ray scattering (GISAXS) analysis, exhibiting remarkable stability even after high-temperature annealing. The author investigated the influence of stereochemistry in tocopherol's hydrocarbon chain on microphase separation and highlighted ongoing research into the effects of chirality. Furthermore, the use of a rigid benzoate linker as a BCO junction point revealed enhance chirality effects, contributing to the formation of distinct morphologies. These insights deepened the understanding of molecular design principles for precise BCOs, paving the way for constructing intricate nanostructural templates with ultrasmall domain spacings.

Chapter 4. Sugar-Rich Microphase-Separated Structures by Sugar–Terpenoid Block Co-oligomers

The author systematically investigated the microphase separation behavior of sugar-rich BCOs composed of maltooligosaccharides and hydrophobic terpenoids, with sugar volume fractions ranging from 0.41 to 0.69. Utilizing SAXS and GISAXS measurements, the author identified a diverse array of sugar-rich LAM, GYR, HEX, HPL_{ABC} structures in both bulk and thin film states. In addition, the results highlighted the significant impact of solvent annealing on the alignment and orientation of microphase-separated structures in the thin film state, demonstrating the potential to tailor morphologies for specific applications. Furthermore, the calculated Flory-Huggins interaction parameter (χ) revealed significant incompatibility between the sugar and terpenoid segments. The phase diagrams were critical as they provided insights into phase-separated behavior, offering a framework for understanding and predicting the microphase-separated morphology in the sugar–terpenoid BCO system. The findings from this chapter not only enhance the understanding of BCO microphase-separated behavior but also offer valuable strategies for designing tailored morphologies for nanofabrication applications. The integration of various parameters and their effects on the microphase-separated behavior contributed to the development innovative materials capable of meeting advanced technological needs.

In conclusion, the author successfully developed the high χ -low N sugar-terpenoid BCOs with discrete and monodisperse features to achieve well-defined single nanoscale microphase-separated structures. This research not only addressed the challenges associated with the design and application of BCP but also provided a valuable framework for understanding the microphase separation behavior of BCOs in the bulk and the thin film states. The insights gained from this study are expected to serve as useful guidelines for next-generation technological applications in areas such as nanolithography and nanofabrication.