Polymer Chemistry

ROYAL SOCIETY OF CHEMISTRY

EDITORIAL

View Article Online
View Journal | View Issue

Check for updates

Cite this: *Polym. Chem.*, 2022, **13**, 2400

DOI: 10.1039/d2py90051c

rsc.li/polymers

Introduction to molecularly defined polymers: synthesis and function

Jeremiah A. Johnson, [a] Filip E. Du Prez [b] and Elizabeth Elacqua *[c]

Published on 13 4 2022. Downloaded on 2025/10/18 20:16:40.

Scientists have long been inspired to synthesize macromolecules with the precision and structural complexity of nature. Whereas nature integrates covalent and non-covalent interactions, programs handedness, and controls atomic connectivity with high fidelity, realizing fully synthetic systems that rival these structures remains a daunting challenge. On the other hand, new strategies that synthesize polymers with nature-inspired *molecularly-defined* structures promise to achieve the next generation of functional materials with properties that could not be achieved with non-discrete polymeric structures. Polymer chemists are looking worldwide for synthetic strategies that feature an ability to achieve: (i) precise atom connectivity (*e.g.*, primary sequence control and/or definition), and/or (ii) precise secondary or tertiary structures (*e.g.*, helices) and (iii) three-dimensional functional group presentation (*i.e.*, stereochemistry, or more commonly "tacticity" in polymer science). In this context, this themed collection, with 2 mini-reviews and 22 research papers, presents a collection of original contributions covering the latest developments in the synthesis and application of oligomers and polymers with controlled, defined, and/or precise molecular scale structures. As guest editors for this editorial, we selected a number of manuscripts to exemplify and highlight a couple of goals and strategies in this important research topic.

A prominent goal in this field, manifested in several contributions to this themed collection, remains the identification of design principles that would allow synthetic macromolecules to rival the structure and function of natural systems (*e.g.*, DNA and proteins). Common synthetic approaches center on folding single chains of macromolecules into controllable and/or predictable shapes to mimic the secondary structure elements of proteins, and ultimately to derive complex three-dimensional architectures. For example, Weck and coworkers (DOI: **10.1039/d1py00373a**) have harnessed the ability of nickel-mediated isocyanate polymerization to afford helical polymers, featuring both achiral pyridine and chiral menthol-based side chains. The resultant poly(isocyanate) copolymers fold into static helices, wherein the dispersed pendant pyridine moieties achieve the formation of supramolecular helical brush copolymers through assembly with poly(styrene) that has been end-functionalized with a SCS-Pd^{II}-pincer unit (*i.e.*, a carbon–sulfur–carbon based ligand coordinating Pd(II)).

Although much work has been accomplished using non-amide-based polymers and discovering methods to engender helices, sheets, and coils using controlled polymerization techniques, such as ROMP, ATRP, and anionic polymerization, methods to control the assembly of single-chains allow for further studies of how size and shape impact folding into discrete structures. In this context, Surin, Steinkoenig, Du Prez and coworkers (DOI: **10.1039/d1py00229e**) have synthesized a series of *N*,*S*-picolyl-functionalized oligo(amidoester)s using solid-phase synthesis. Their approach allowed for discrete distances to be defined between both ligands that, upon nickel-mediated folding, afforded single-chain oligomer nanoparticles wherein controlled loop sizes could be obtained, as confirmed using DOSY measurements. When moving from metals to hydrogen bonding units, Liu, Palmans and coworkers (DOI: **10.1039/d0py01157f**) have focused on the synthesis of sequence-defined structures, which have been equipped with two benzene-1,3,5-tricarboxamide (BTA) motifs at defined positions. After the synthetic effort, they have shown that the series of octamers with supramolecular motifs formed secondary structures arising from hydrogen-bond formation in bulk, as well as in dilute solutions. Finally, Zuckermann and coworkers (DOI: **10.1039/d1py00426c**) have utilized the shape complementarity of sequence-defined peptoids (*i.e.*, peptidomimetics consisting of *N*-alkylated glycine oligomers) to achieve a selective assembly between the chains, which resulted in different molecular shapes, ranging from trapezoids up to zig-zag structures.

[a]*Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA, USA*
[b]*Polymer Chemistry Research Group, Centre of Macromolecular Chemistry (CMaC), Department of Organic and Macromolecular Chemistry, Faculty of Sciences, Ghent University, Krijgslaan 281 S4-bis, Ghent B-9000, Belgium*
[c]*Department of Chemistry, The Pennsylvania State University, University Park, PA 16802, USA. E-mail: eze31@psu.edu*

This journal is © The Royal Society of Chemistry 2022

Published on 13 4 2022. Downloaded on 2025/10/18 20:16:40.

They have suggested that this protocol could become a way to construct hierarchically-ordered peptoid materials that approach the complexity found in biomacromolecular nanostructures.

Several new strategies to attain sequence-defined macromolecules have allowed for precision backbones to be obtained. Kamigaito and coworkers (DOI: 10.1039/d0py01564d) have achieved precision vinyl copolymers, following an iterative atom transfer radical addition (ATRA) and acyclic diene metathesis (ADMET) strategy. Key to this approach was developing a precise telechelic vinyl macromonomer that, upon ADMET, propagated the desired sequence. The resultant polymers comprised perfect and periodic styrene–acrylate–styrene–ethylene–methylene sequences with solely C–C bonds within the backbone. Junkers and coworkers (DOI: 10.1039/d1py00735a) have exploited reversible addition fragmentation chain transfer (RAFT) polymerizations, in combination with flow procedures, to polymerize a consistent acrylamide monomer library that mimics essential amino acids. In their systematic study, five monomers have been selected as model monomers, each representing one of the five major groups of amino acids. Other efforts to obtain sequence definition exploit differences in monomer reactivity. In an example featuring supramolecular preorganization, Elacqua and coworkers (DOI: 10.1039/d1py01378d) have investigated reactive aryl/perfluoroaryl (Ar/ArF) stacked monomeric units for pressure-induced polymerizations. Their strategy utilized a co-crystalline monomer, benzaldehyde : pentafluorophenol. The monomer's solid-state organization featured strict alternation of the Ar and ArF units, such that, upon application of pressure (up to 21 GPa), polymerization occurred to afford functionalized alternating copolymer nanothreads.

New methods and strategies for the synthesis of precise macromolecules have driven investigations to investigate how molecular features can be leveraged to enable novel functions. One area where precise macromolecules may play critical roles in the future is in biological applications, wherein interactions between biopolymers and synthetic polymers can be optimized at the molecular level. In this regard, Hartmann and coworkers (DOI: 10.1039/d1py00422k) have described the solid-phase synthesis of a new family of "amphiphilic precision glycomacromolecules" (APGs), which feature easily tunable carbohydrate-presenting hydrophilic head groups and fatty-acid tails. The authors prepared 8 APGs with varied carbohydrate identity, charge, compositions of hydrophilic and hydrophobic domains, and linkers capable of subsequent polymerization. Solution self-assembly studies revealed subtle dependencies on the critical micelle concentrations and self-assembled morphologies that could be traced back to molecular features of the APGs. Finally, the authors showed that these APGs could be used to inhibit the binding of green fluorescent protein (GFP)-expressing *E. coli* to mannan-coated surfaces, suggesting that precise macromolecules could play a role as next-generation antibiotic materials.

Macromolecular precision is also expected to play key roles in optimizing future devices based on semiconducting organic polymers. In this vein, Nelson and coworkers (DOI: 10.1039/d0py01292k) have explored the synthesis of a new family of alternating "donor–acceptor" copolymers, featuring the highly electron deficient benzo[1,2-*b*:4,5-*b*0] dithiophene-11,55-tetraoxide (BDTT). Indeed, while organic semiconducting materials have witnessed expansive growth in the past few decades, there remain few examples of n-type semiconducting organic polymers due to challenges in the chemical manipulation of electron deficient aromatic monomers. Nelson and coworkers have developed a regioselective double iodination reaction to enable the synthesis of a novel iodinated BDTT monomer, allowing the incorporation of BDTT into copolymers. Stille cross-coupling polymerization of this monomer with electron rich aromatic bis-stannanes yielded novel alternating copolymers with tunable HOMO and LUMO levels based on the comonomers used. Fluorescence quenching studies revealed the electron accepting nature of the BDTT-based copolymers, demonstrating how precise alternating copolymer design can be used to provide new candidates for n-type organic semiconductors.

Finally, the roles of macromolecular precision in dictating the properties of bulk materials must be further understood to address material manufacturing challenges. With an eye toward future polysilanes as precursors to ceramic materials, Klausen and coworkers (DOI: 10.1039/d1py00383f) have developed a new family of polycyclosilanes with fascinating backbone structures comprising 6-membered cyclosilanes linked together in either 1,4 or 1,3 relationships. By tuning the polymerization catalyst used, these authors synthesized both linear and cyclic 1,3-substituted polycyclosilanes, and probed the impact of atomic connectivity and macromolecular topology on the thermal properties of these materials. Interestingly, only the cyclic topology gave rise to a distinguishable glass transition temperature, whereas both constitutional isomers of the linear polycyclosilanes showed no thermal transitions. Moreover, the cyclic polycyclosilane displayed a much lower percentage of thermal degradation to produce volatile products between 200–400 °C (as measured by TGA). This difference was attributed to the cleavage of Si–Si bonds in the polymer backbones: cleavage of the cyclic polycyclosilane generates a linear polymer that must cleave again to form volatile products. Altogether, these results may guide the design of novel silicon-based polymers with optimal processing windows for ceramic precursors.