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Syntheses and Polymerization of Bio-based Diketopiperazine Monomers and their Self-assembly

Abstract

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Part 1: Research Content

Background: The development of bio-based polymers is essential for establishing a sustainable green society. Conventional bio-based aliphatic polymers such as polyesters and polycarbonates have unsatisfactory thermal and mechanical properties, although several attempts have been made to improve these properties. One of the most effective strategies in this regard is to incorporate an aromatic component into the polymer backbone.

Polyimides (PIs), a class of super-high-performance plastics, are widely used in electronic devices and in aerospace applications due to their outstanding mechanical durability as well as high thermal and chemical stabilities, which enable them to tolerate harsh environments. PIs were initially synthesized from petrochemical-based monomers, but there have been a few recent attempts to synthesize them from bio-based monomers. In particular, attempts have been made to prepare partial or completely bio-based PIs using a bio-based aromatic diamine, 4,4'-diaminotruxillic acid (4ATA), and various dianhydrides. With regard to molecular design, we found that the alicyclic structure sandwiched between two aromatic rings imparted rigidity to produce thermally resistant polyimides with a T_{d10} value of 425 ^{o}C, while the glass transition temperature, T_g, was found to be 350 ^{o}C, while retaining important functions, such as optical transparency, in the case of 4ATA [1].

In order to synthesize a structure in which heterocyclic compounds are sandwiched by two aromatic rings, we carried out the dimerization of 4-aminophenylalanine (4-APhe) and obtained a 2,5-diketopiperazine (2,5-DKP) derivative. The core structure of several drugs contains central 2,5-DKP ring, but 2,5-DKP has not been extensively used as a building block to synthesize functional polymeric materials. In the present study, we have designed a monomer containing a centrosymmetric amide functionality in the 2,5-DKP ring, apart from two aromatic rings that can induce self-assembly of the corresponding polymer chains through hydrogen bonding and π-π interactions. Particle formation can be expected as a result of the chain self-assembly, rendering these polyimides suitable for applications such as fillers, heat resistant super-hydrophobic coatings, and ultralow-dielectric-constant films.

Aim: In this study, we are focusing on 4APhe, a bio-based aromatic amino acid derived from glucose fermentation, as a starting material to generate a novel bio-derived monomer for the syntheses of high performance polymers such as polyimides (PIs) and polyureas (PUs). To wider the application potentials and increase the values of the polymers, incorporating self-assembly property into such bio-based high performance polymers was our target.

By cyclic dipeptide formation of 4APhe, the novel bio-based monomer, 3,6-di(4-aminophenylmethyl)-2,5-diketopiperazine (DKP-4APhe) were synthesized where the 2,5-DKP ring can induce self-assembly due to its centrosymmetric cyclic amide groups. The polymerization of two high performance polymers, PIs and PUs, from the obtained bio-based DKP monomers with commercialized counterparts is demonstrated. The diversity of DKP derivatives was also extended by controlling their stereochemistry at α-carbon. The influence of stereochemistry of DKP based diamine monomers on the developed polymers' properties and their self-organization were also worth to explore.

Experimental: The synthesis of the bio-based aromatic diamine, DKP-4APhe, was carried out from 4APhe through a simple coupling of stepwise protection and deprotection. The monomers with different stereochemistry at two α-carbon (LL and DL type) from the dimerization were generated (Figure 1). The characterizations of these novel monomers were thoroughly analyzed by ^{1}H-NMR, FTIR and ESI-MS.

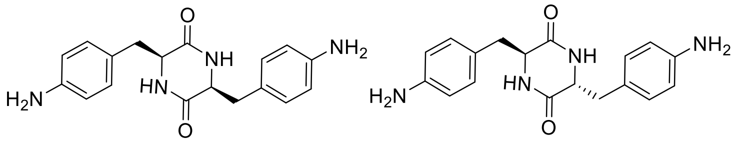
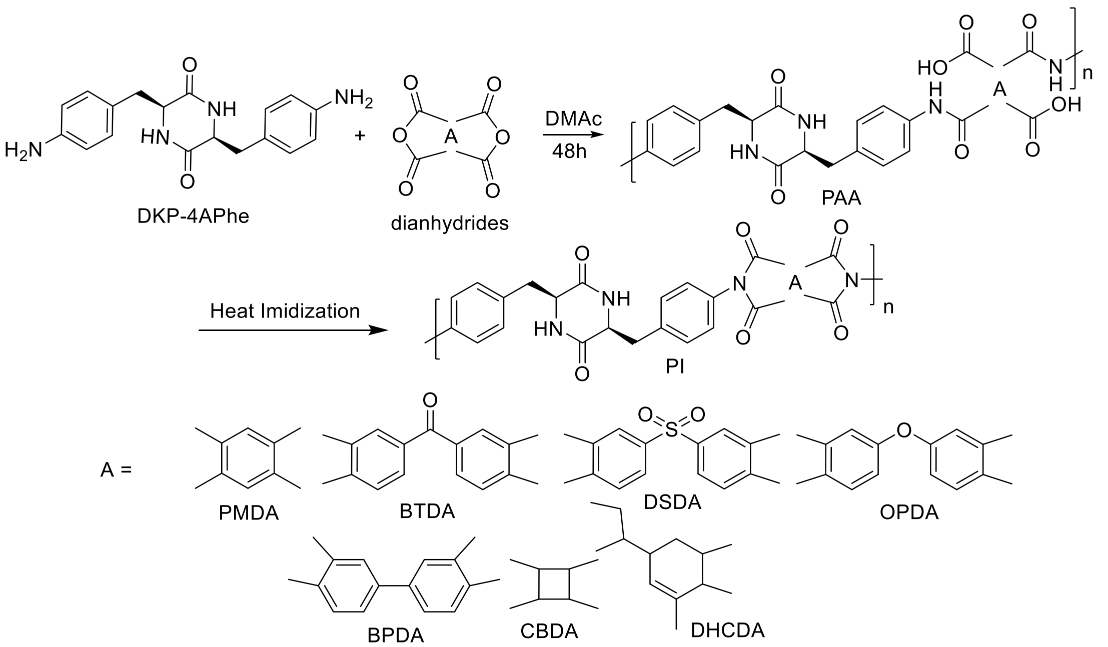


Figure 1 Chemical structure of bio-based aromatic diketopiperazine diamines derived from cyclodipeptide formation of 4-aminophenylalanine (4APhe) (DKP-4APhe) with LL (compound 1) and DL (compound 2) sterochemistry.

The corresponding PIs and PUs having 2,5-DKP heterocyclic structure in the backbone are prepared by polycondensation with commercially available aromatic dianhydrides (scheme 1) and diisocyanates, respectively. The present study investigated the particle formation ability of the PIs and PUs and attempts to control their morphology starting from a spherical form into various non-spherical shapes through a simple solvent displacement method. To characterize our self-assembled polymers, SEM was used to observe each morphologies, and FTIR exploited to explain how the polymer self-assemble into each form in term of hydrogen bonding.

Scheme 1. Syntheses of bio-based aromatic poly(amic acid)s and polyimides from DKP-4APhe.



Part 2: Research Purpose

Results and Discussion:

High performance DKP-based biopolyimides with morphology control feature were here established. From the dimerization of biomass 4-amino-L-phenylalanine (4APhe), a newly-designed bio-based aromatic diamines having diketopiperazine (DKP) as a central core (DKP-4APhe) was generated. The polymerization of DKP-4APhe with various dianhydrides could introduce high rigidity from alicyclic building blocks to the polymer structures and help generate high thermal resistant polyimide (PIs).

Among all the polyimide molecules in the present study, the PI from PMDA showed the highest T_{d10} of 432 °C. In addition, its T_g value could not be estimated, presumably because it is higher than the temperature at which the PI decomposes. The charge transfer characteristic to polyimides and hydrogen bonding between the imide group and DKP ring or between DKP moieties could be a reason for high thermal stability. However, due to flat structure of LL-DKP units, polyimides with low molecular weight was obtained as a result of highly dense packing of polymer chains.

By changing the conformation isomer of DKP-based polyimides to DL type, polyimide with greatly increased molecular weights could be generated. The prepared DL-polyimide film exhibited lower yellow index and higher transparency compared to the commercial PI, Kapton®. The DL-polyimide film derived from BTDA also showed ductile property with 10.5% elongation.

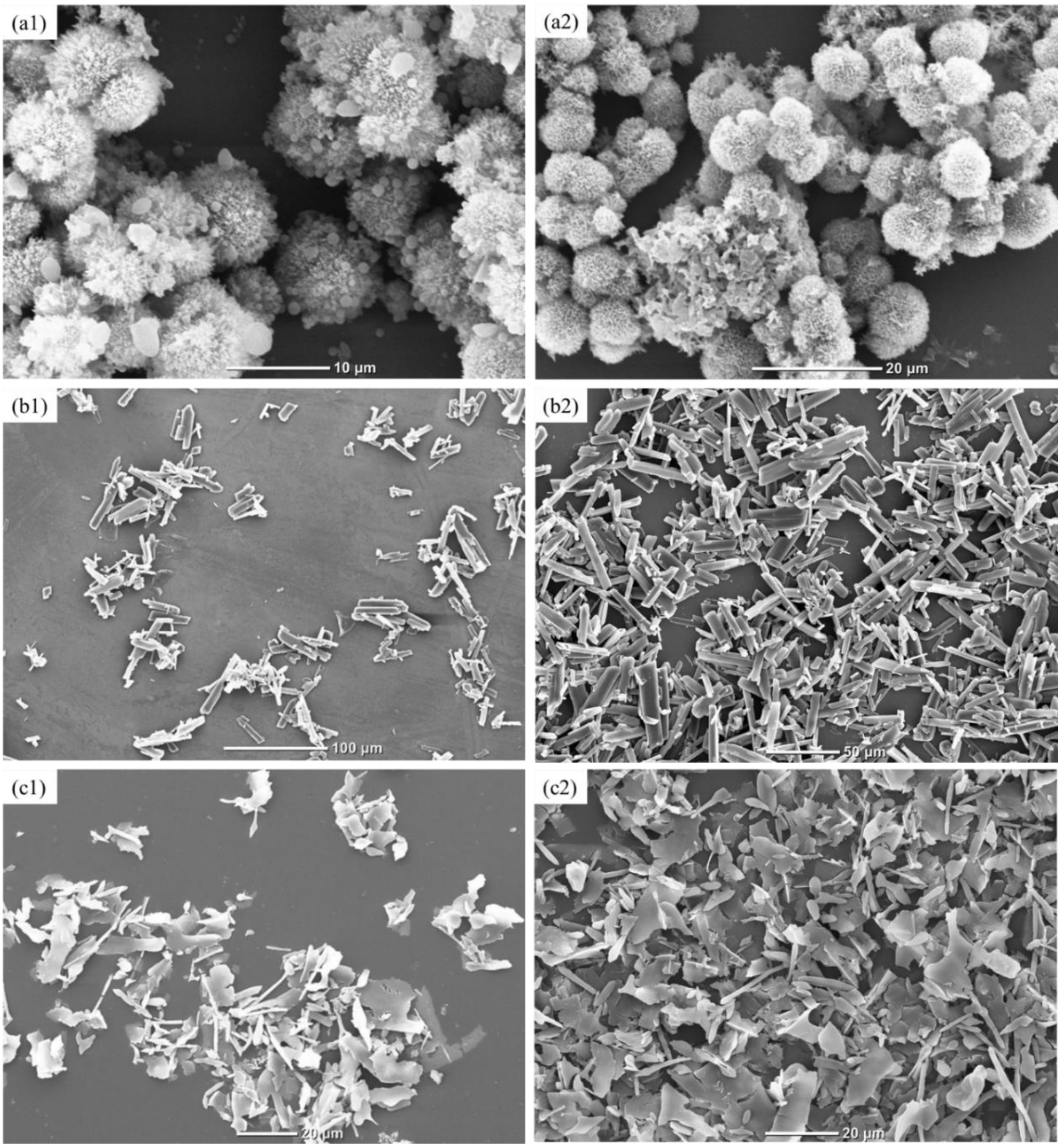


Figure 2. SEM images of PAA-BTDA obtained by redispersion of PAA spheres into (a1) 20% acetone/water, (b1) 40% methanol/water and (c1) cyclohexane, following sonication and conversion to PI by two-step imidization given (a2), (b2) and (c2), respectively.

Due to superior hydrogen bonding ability of DKP and the embedded aromatic in the polymer chains, the self-assembly property could be bestowed on the developed PAAs and PIs. Here, the poly(amic acid) (PAA) precursors formed nanospheres upon reprecipitation over dimethylacetamide (DMAc) into water. The nanospheres were then added to solvents with different polarities and sonicated to induce deformation of the spherical forms into spiky balls, flakes, or rods. The PAA particle morphologies were retained in the PIs after the two-step imidization. Finally, the PI particles with self-assembling DKP moieties were formed, and their morphologies were fine-tuned using different mixed solvents (Figure 2). FTIR analyses indicated that hydrogen bonding was enhanced in the rod-like particles, presumably due to the self-assembly of the DKP moiety.

Conclusion: We synthesized the aromatic diamine, 3,6-di(4-aminophenylmethyl)-2,5-diketopiperazine (DKP-4APhe), by dimerization of a functionalized α-amino acid, 4APhe, where the 2,5-DKP ring can induce self-assembly due to multiple sites for hydrogen bonding formation. DKP-4APhe was polymerized with various dianhydrides to obtain bio-based PAAs, which were converted into PIs with high thermal resistance. The developed bio-based PIs showed high thermal stability with highest T_{d10} of 432 ^{o}C and no glass transition below the thermal decomposition temperatures. Using the simple solvent displacement method from DMAc into water, PAA and PI spheres having smooth surfaces were formed. The PAA spheres underwent morphological changes into spiky ball-, rod-, or flake-like particles upon varying the solvent polarity. The morphology observed at the PAA stage was retained in the PI particles, even after the two-step imidization. To summarize, bio-based PI particles with high thermal resistance were prepared, which can be potentially used as fillers for reinforcing aromatic polymer matrixes. Indeed, non-spherical particle morphologies may enhance filler-matrix interactions.

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Keywords: Diketopiperazine, Self-assembly, Bio-based polymers, Polyimides, Amino acids

Part 3: Research Accomplishment

Publication: T. Hirayama, A. Kumar, K.Takada, T. Kaneko, Morphology-controlled Self-assembly and Synthesis of Biopolyimide Particles from 4-Amino-L-phenylalanine, ACS Omega, **2019** (accecpted).

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