Concluding Remarks

As seen above in the 12 chapters, fundamental and important aspects of *Enzymatic Polymerization towards Green Polymer Chemistry* are presented. In particular, enzymatic syntheses of polysaccharides, polyesters, polypeptides, poly(aromatic)s, and vinyl polymers, as well as enzymatic polymer modifications, are comprehensively covered in an up-to-date manner.

Enzymatic polymerizations involve several important characteristics; they are related to, e.g., catalyst enzymes, catalytic efficiency, new catalysis, reaction conditions, high reaction selectivities, starting materials, and product polymers. (1) Catalyst enzymes are natural renewable products and environmentally benign without showing toxicity. Immobilized enzymes can be recovered and repeatedly used. (2) Enzymatic reactions normally show high catalytic efficiency (high turnover number). (3) New enzymatic catalysis enabled for the first time to synthesize natural polysaccharides with complicated structure such as cellulose, chitin, hyaluronic acid, and chondroitin, which were not possible to prepare via conventional methods. (4) Enzymatic polymerizations proceed under mild reaction conditions, which allow to use not only an organic solvent but also a green solvent, like water, supercritical carbon dioxide, and an ionic liquid. Enzymatic catalysis induced a "dehydration polymerization in water" to produce polyesters, which is a new finding in organic chemistry. (5) The reactions exhibit characteristics of enzymatic catalysis and high reaction selectivities such as chemo-, regio-, stereo-, enantio-, and chiroselectivities, producing minimal by-products. It is normally very hard to control these selectivities with conventional chemical catalysts. (6) Enzymatic polymerizations allow to employ many renewable bio-based materials (biomass) as starting substrates in place of fossil-based raw materials. (7) Product polymers from these substrates are nontoxic and biodegradable in many cases, which are benign to nature.

Green polymer chemistry is brought about by the above mentioned characteristics of enzymatic polymerizations. The reactions produced actually a variety of value-added functional polymers via green processes. These polymers are expected

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as practically employed for daily necessaries, biomaterials, drug delivery systems, pharmaceuticals, and other application areas. As typical examples, phosphorylase-catalyzed synthesized amylose is currently used mainly for chiral-separation column carrier, which is prepared and sold by Glico Nutrition Co. and PS·Biotec Inc. (see Chap. 3). Another event happened for the enzymatic polymerization; Kaneka Co. built a pilot-scale plant in 2011 for production of polyhydroxyalkanoates (PHAs), polyesters that can be used as bio-based and biodegradable plastics (see Chap. 7). Enzymatic polymer modifications are widely conducted in industry area, like processes of "biobleaching" and degumming, and many such examples for various polymers are mentioned in Chap. 12.

The importance of green polymer chemistry is stressed here again. Due to the earth warming climate partly because of the increased carbon dioxide emission, we suffer big disasters more often recently than before. The other environmental crisis recently pointed out is that large and small plastic trashes or particles (micro-plastics ≤ 5 mm size) are found in many areas on the earth, in particular, not only in the sea but also on the seashore. This situation gives big damages to the ocean ecology, bringing about losing many lives due to their harmful actions, which eventually affect the human beings. Micro-plastics and other plastic trashes are from the traditional polymers like polyethylene, poly(ethylene terephthalate), nylon, etc. which are mainly originated from disposable plastic goods such as shopping bags, straws, dishes, cups, bottles, and others including the thrown-away. It is said that these plastics reach to around 8 million tons/year in the world and 85% of ocean pollutants are due to them. To prevent these problems because of such environmental pollutions, EU countries, some states in the USA, and some other countries have decided not to use and/or not to produce the disposable plastic goods, e.g., typically disposable straw. This issue was also seriously discussed at the G7 Summits, Quebec, Canada, in June 2018; it becomes recently one of the most important trends worldwide to reduce plastic wastes.

In addition, it is to be noted that public great attention on the 17 Sustainable Development Goals (SDGs) of the 2030 Agenda for Sustainable Development, which was adopted by United Nations in September 2015, has recently grown. SDGs have 17 goals, and green polymer chemistry provides a good example for achieving SDGs.

Now, enzymatic polymerization shall enable to mitigate or even exclude such a serious problem by pursuing green polymer chemistry as observed above. The polymerization produces biodegradable and nontoxic plastics, e.g., some polyesters, from renewable starting materials, and bio-based materials, not from the diminishing fossil resources. These polymers prepared in such processes can be employed in place of the traditional polymers, yet not becoming an origin of pollutants. This direction utilizing the enzymatic polymerization for producing environmentally benign plastics in a green process is a definitely right way to contribute for maintaining the sustainable society for the future.

We believe this book will serve the readers for gaining helpful information, good ideas, and right direction to their further/future activities. We also hope that the

readers will utilize these information not only for maintaining the sustainable society but also for realization of the better society in the future.

Finally, we express our deep thanks to all the chapter authors, who willingly accepted our invitation to write the chapter manuscript. Further, we are much thankful to Springer Co. and the staffs, who kindly invited us to edit this book *Enzymatic Polymerization towards Green Polymer Chemistry* for the Springer book series *Green Chemistry and Sustainable Technology*. It is very fortunate for us to do this, because the edition is just timely.

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