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Introduction

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1.1 Introduction

The discovery and development of synthetic polymeric materials in the twentieth century is undisputedly recognized as one of the most significant inventions humans have made to improve the quality of life. Durability, light weight, processability, and diverse physiochemical properties are just a few merits why polymeric materials are widely used for the manufacture of simple water bottles to setting up modern space stations. Outstanding processability features along with adequate physical properties have resulted in polymeric materials displacing many other materials, such as wood, metal, and glass to a considerable extent. Packaging, construction, transportation, aerospace, biomedical, energy, and military are few examples of industrial sectors, where polymeric materials prevail. Global production of plastic has risen from 204 million tons in 2002 to about 299 million tons in 2013 [1]. Manufacture of non-natural polymers is largely associated with the utilization of essentially non-renewable fossil feedstocks, either natural gas or petroleum. Approximately, 5–8% of the global oil production is used for plastic production [2]. Accompanying environmental problems include, but are not limited to, generation of solid waste that accumulates in landfills and oceans, production pollution and related environmental problems [3]. A major underlying issue in the use of plastics is the enormous carbon footprint associated with their production as portrayed by burning 1 kg of plastics to generate about 3–6 kg of CO_2 (including production and incineration) [2]. In addition, their impervious nature to enzymatic breakdown and “linear” consumption as opposed to natural counterparts results in relentless generation of solid waste from most commercial polymers. Although polymers can be recycled to produce new materials or incinerated to recover its heating source value, such an endeavor is neither clearly understood by the majority of consumers nor technological advances are available in most parts of the world. Depleting oil reserves as well as these detrimental environmental impacts observed in the twentyfirst century have driven government, academia, private sectors, and non-profit organizations to explore sustainable polymers from renewable biomass as a long-term alternative. In addition, the consumers’ preference as well as the governmental landscape has shaped in favor of sustainable products for a greener

Sustainable Polymers from Biomass, First Edition. Edited by Chuanbing Tang and Chang Y Ryu.

environment. Significant advancements have been made to discover sustainable polymers that are cost-effective to manufacture, as well as compete or out-perform traditional materials in mechanical aspects as well as from environmental standpoints [4]. The valuable contributions to the field by several recent books [5, 6] and reviews [7–11] broadly discuss about sustainable polymeric materials. Our objective is to provide a perspective of the efforts to convert small molecular biomass into sustainable polymers in different continents. This introductory chapter overviews sustainable polymers in general and briefly summarizes the content of each chapter afterward.

1.2 Sustainable Polymers

Given the influence of polymers as an indispensable resource for the modern society, it should be taken as a firm concern for sustainable development. There are many statements to define the term of sustainability. For example, "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs" is the working definition provided by the report *Our Common Future*, published in 1987 by the World Commission on Environment and Development [12]. In most cases, the terms renewable polymers and sustainable polymers are used with overlapping meanings and without any distinction. Contrary to common belief, it should be noted that not all renewable polymers are sustainable. Typically, renewable polymers are made from renewable chemical feedstocks. However, to be sustainable, those renewable polymers should be more environmentally friendly to produce and use. Sustainable polymers should demand less non-renewable chemicals or energy for their synthesis and processing, make less pollution emissions, and be amenable to be decomposed and even composted after reaching their service lifetime (Figure 1.1).

The past two decades have overseen a great level of scientific advancements that have paved paths toward the primary stages of an era of sustainability, carbon neutrality, and independence from petroleum sources for making polymeric materials. Rapid expansion of this field can be visualized by the exponential

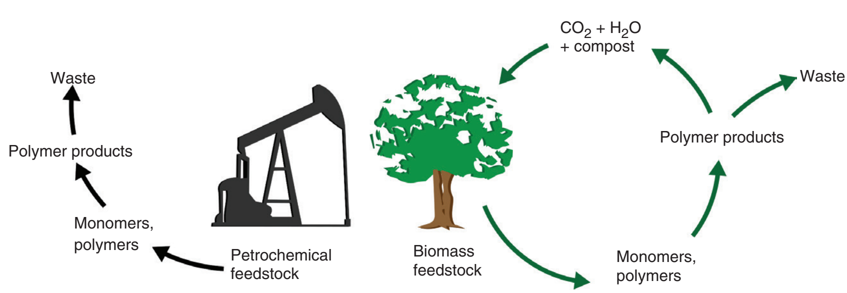

Figure 1.1 A comparison between traditional petrochemical-based polymers and sustainable polymers.

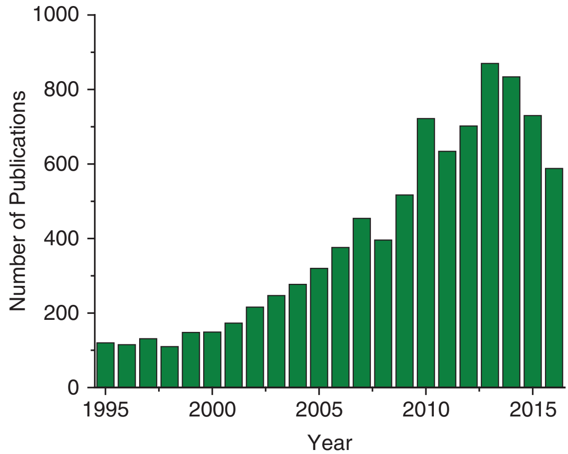

Figure 1.2 Scientific publications with the keyword "sustainable polymers" published from 1995 to 2016. (SciFinder.)

increase in the number of scientific reports published on sustainable polymers in recent years (Figure 1.2), appearance of dedicated scientific journals such as *ACS Sustainable Chemistry and Engineering* and the steady increase of the market share of renewable bio-based material products, for example, NatureWorks Ingeo™, DuPont™ Sorona®. Although the worldwide production capacity of bio-based polymers is only 5.7 million tons (2% of total polymer capability) in 2014, it is expected to triple to nearly 17 million tons by 2020. The compound annual growth rate (CAGR) for the production capacity of bio-based polymers is impressive at about 20%, whereas the CAGR for the petroleum-based polymers is at 3–4% [13].

The principal aspects of the concept of sustainable materials are to utilize renewable biomass resources for raw materials as opposed to petrochemical sources and to ideally incorporate degradability to the novel materials such that sustainable polymers inherit a cyclic life cycle considering the time factor.

As illustrated in Figure 1.3, the plastic industry has a considerable influence on global carbon cycle. "Fossil-sourced" carbon dioxide release is so overwhelming that natural photosynthesis or other natural sinks cannot effectively moderate for the equilibration of the global ecosystem. However, a material feedstock transition from fossil-based chemicals to the renewable biomass-derived compounds for the production of sustainable polymer materials would diminish their contribution to the greenhouse effects because of their low carbon or carbon neutral characteristics. As against the geographically uneven distributions of world-wide fossil oil resources, natural biomass is widely available in many geographic areas for the development of local or regional supply of chemical and material feedstock resources without significant technological intervention. In addition, the market price fluctuations would be much favorable compared to those from crude oil resources and can provide a steady and stable supply over a long period of time.

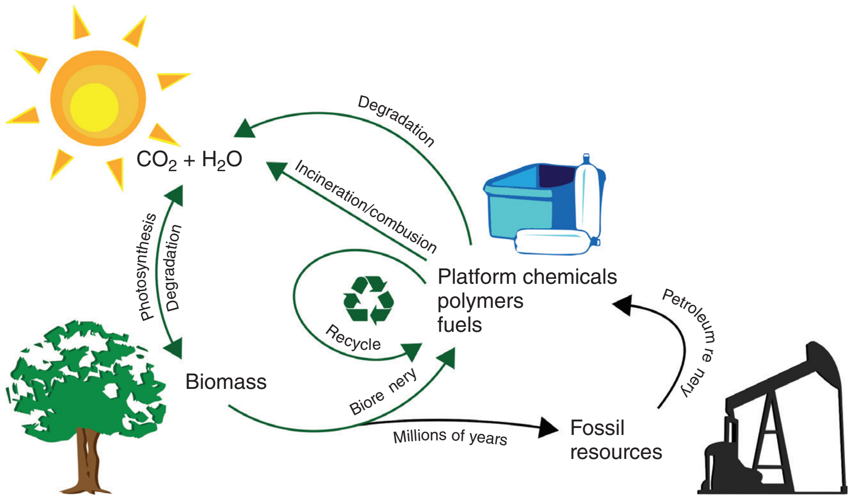

Figure 1.3 A schematic diagram to illustrate the concepts of sustainable polymers from biomass.

1.3 Biomass Resources for Sustainable Polymers

Global primary production of the biosphere exceeds 100 billion metric tons of carbon per year, which include contributions from both terrestrial and marine communities [14]. It is obvious that this primary production either mostly ends up in food chains or decays and sediments. Useful raw materials for making sustainable polymers are hidden in the biomass. Unfortunately, the utilization of biomass for sustainable polymer production is lagging behind largely due to the price and property competitiveness of fossil oil counterparts, as well as their well-established routine processing technologies for polymer industry. In addition, as the human population grows rapidly, the demand for biomass usage for food and energy purposes has perceived an escalating interest. Nevertheless, a modern "gold rush" is witnessed in recent years to unlock the true potential of biomass chemicals. Generation of sustainable polymers from agricultural feedstocks such as sugar cane, soybean, corn, potatoes, and other plants has limitations due to competing food necessities. Therefore, there are significant efforts that focus on developing nonfood renewable biomass including waste resources, such as lignocellulosic resources, paper mill waste, agricultural waste, and food waste.

1.3.1 Natural Biopolymers

Naturally occurring biopolymers such as rubber, cotton, and starch were used extensively for a long time before the invention of synthetic polymers less than a century ago. In recent years, the reviving efforts of biopolymer research in materials science have been very active. In particular, there is enormous growth in the research on biopolymers such as cellulose, chitosan, and lignin (Figure 1.4) to discover novel hybrid materials with improved properties as well as for commercialization.