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Sustainability in Polymer Sciences

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Sustainable development involves an increasing number of considerations, including ecological improvement, resource utilization, and energy circulation, due to continuous economic growth and social progress. Now, the great demand for energy and materials is exhausting previously accessible fossil resources. What's worse, using energy and materials from these sources brings air pollution and complicated waste issues, as traditional materials accumulate and do not necessarily biodegrade. Since no resource can be the perfect substitute for fossil resources for the time being, it is still a serious challenge to harmonize the promotion of society and economy with nature. We need to focus on the diversity of materials and energy sources, the protection and remediation of ecology and environment, and the various positive elements of health and life.

In terms of resource origins, substituting massive renewable biomass in nature for fossil resources is considered as a promising strategy. The natural polymers derived from biomass resources are expected to be an important basis for future materials. They can avoid environmental accumulation and pollution given their known degradability and are thereby considered to be environmentally friendly. Another approach is to convert biomass into "micromolecules" to be used as chemical agents and energy fuels. These micromolecules can polymerize into synthetic polymers with inherent biodegradability. Through processing and structural designs, the natural and synthetic polymers obtain various functions, promoting their applications in separation, electromagnetism, and biomedicine. For example, bio-based polymers can be endowed with good filterability, shielding, and electrostatic adsorption properties by electrospinning, which is suitable for medical protective equipment, such as masks, protective clothing.

Especially, the application of the functional bio-based polymers in medicines has greatly promoted the improvement of life and health level. Most bio-based polymers, like natural polysaccharides, show good biocompatibility and low toxicity, having great potential for tissue engineering, drug delivery, and medical devices. For instance, the chemical/physical interaction between the active groups of polysaccharides and drugs makes them ideal drug carriers. Besides, due to the degradability and suitable mechanical strength of bio-based polymers, they can be used as structural supports for tissue-compatible functional materials, replacing traditional low-biocompatible metals. Meanwhile, the decrease in strength and stiffness during the degradation process can gradually transfer the load to the repaired bone, making it suitable for medical devices, like bone nails.

Notably, the utilization of biomass resources depends on their origins. They come from wood, straw, bamboo, etc., containing a large number of natural polymers. Recently, wastes from biomass materials mixed with grease/latex and planting waste have also been utilized to develop complete bio-based degradable materials. The strategy for using these natural polymers is mainly divided into direct utilization and biorefinery. The polymers directly used covers natural polysaccharides (cellulose, chitin, chitosan and starch), lignin, animal/plant-derived proteins, and grease. They can be isolated from biomass resources for diverse applications. By contrast, the micromolecules and energy fuels mentioned previously are obtained through biorefinery.

When we further convert bio-based products into materials, we still need to focus on the components and structures of the materials. Increasing attention is paid to multi-component synergistic strategies, rather than modifying the physicochemical properties of a single component. Interestingly, using biomass wastes sometimes can not only improve the strength and ductility of materials, but also greatly reduce their cost. The aggregation state of the bio-based materials is important, especially for the crystalline structure in nanoscale. Nanocrystals of biomass materials can be used as a reinforcing phase. The assembly of those biomass nanocrystals is also useful, as they can create structural colors and further induce photobleaching-free photoluminescence, benefiting to the development of advanced optical materials.

Besides the natural texture, biomass materials are widely used as templates in structural materials, such as biochar and biomimetic materials. Various biochar materials can be obtained, and their applications depend on the structures and composition of the biomass origins. For example, hierarchically porous tubular carbon can be obtained from natural wood by selectively removing lignin and undergoing two consecutive thermal treatment steps. Such a porous material has high surface area, high adsorption capacity, and large electrochemical capacitance, exerting great application potential in adsorption, energy storage/conversion, and catalysis. By contrast, the biochar from bamboo has been used as catalyst to upgrade bio-oil and obtain high-quality syngas, due to high pore texture, high content of minerals, oxygen-containing and acid functional group on surface. The biomimetic materials are inspired by the natural texture structure of the organization in plants and animals. The design and construction of biomimetic materials also learn from nature in the aspects of molecule and aggregation state. For example, chitosan can be used as a matrix, followed by mineralization, silk fibroin infiltration, and hot-pressing, to build a synthetic nacre with good ultimate strength and fracture toughness.

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All the above utilization of biomass resources can reduce the carbon tax. Their degradability reduces white pollution, energy consumption and air pollution from incineration treatment. For instance, synthetic polymers from biomass resources, such as polylactic acid and polyglycolic acid, can be converted into carbon dioxide and water by hydrolysis and enzymatic hydrolysis.

The bio-based materials can also be used directly in environmental treatment. For example, heavy metal ions can be absorbed by starch and chitin. When the porous structure of biomass resource origin is introduced too, the absorption performance can be further improved significantly. Bio-based polymers are also applied for soil protection, sand fixation, and fertilizer releasing.

Apart from environment friendliness, sustainable development based on biomass resources also focuses on energy fields. As mentioned before, we can produce fuels by refining natural polymers. Meanwhile, we can obtain fuel gas and alcohols via fermenting biomass resources. Recently, using bio-based polymers in energy devices has attracted increasing attention. Biochar has been used as supercapacitors, battery electrodes, and anode materials of carbon fuel cells. Sodium lignosulfonate, a lignin derivative, has also been used as binder of carbon anodes in sodium-ion batteries for its high capacity retention and stability.

Porous dielectric polymers based on biomass resources show advances in energy collections and biocompatibility. They can be used as self-powered sensors to monitor human sports. Meanwhile, the lightweight feature of those polymeric sensors makes them portable. Considering their high biocompatibility, they can be used to prepare embedded devices.

Thus, we can find that the utilization of biomass resources benefits sustainable development throughout their whole life cycle, including raw material production, material processing and manufacturing, application and services, waste disposal, and recycling and reuse. All these achievements are closely related to the development of polymer science. The green refining and polymerization processes have been carried out to develop non-toxic catalyst system and pollution-free solvent systems. The progress in polymer science also improves the process and manufacture of polymer materials in energy saving and environmental protection. For example, with green solvent systems, such as spinning water system and ionic liquid system for low-temperature dissolving cellulose, the environmental pollution during the manufacturing and refining process of wood can be significantly reduced. In the last decade, new manufacturing methods, like bionic technology and additive manufacturing, have been proposed and rapidly developed. They can make full use of materials and convert raw materials into lightweight and high-performance materials.

On the other hand, the technologies of directly recycling bio-based and even fossil-based materials and biological/chemical recycling treatments have been developed. Among them, chemical recycling has become the most commonly used approach that can realize the circular use of energy sources. Now, we can degrade the recovered polymers into monomers, and convert them into high-quality fuels and chemical raw materials through cracking.

In summary, the above research of polymer science focus on ecological environment, human health, energy, resource utilization, etc. Those researches not only realize the utilization of diverse, sustainable and multi-functional resources, but also effectively increase the bio-based content of polymer-based materials to promote “carbon neutrality” and sustainable development. Great promotion has been made in diversified utilization of resource sources, resource conservation, ecological environmental protection, energy source diversity, energy-saving approaches, human health, and the full-cycle green recycling of polymers. More efforts should be paid to promote the coordinated engineering progress in the fields of human, society and nature.

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