Sustainable Polymers: From Recycling of Non-Biodegradable to Renewable Resources Composites and Foams

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Abstract *Sustainable polymers and composites provide possibility to be environmental impact free materials for the future applications. These materials could be used as recycling post-consumer plastic products, biodegradable polymers made from renewable resources, and reducing the materials used by making either foamed parts or stronger polymer composites. Using natural cellulose fibers as fillers for biodegradable polymers would also result in fully biodegradable green composites and help to reduce the matrix polymer material used. It is hoped that these approaches will help to accelerate and facilitate recycling and the reduction of polymers, as well as promote an increased adoption of polymers and composites from renewable resources. More details on the aforementioned topics have been presented in this paper.*

Keywords:

Sustianable polymers, recycling, biodegradable plastics, renewable resources, composites and foams

1. Introduction

Since 1976, plastics have become the most widely used material in the world [1]. Today, approximately 100 million tons of plastics and polymeric materials are produced worldwide every year. Plastics are used in the appliance, automotive, construction, electronics, packaging, and transportation industries, as well as in a wide array of consumer products. Human society has gone through periods called the Stone, Bronze, Copper, Iron, and Steel Ages based on the material that was utilized the most during that time. At present, the total volume of plastics produced worldwide has surpassed that of steel, copper, and aluminum combined by volume and continues to increase. Without a doubt, we have entered the Age of Plastics [2]. Among all polymers produced, five major synthetic polymers account for over 90% of the plastics produced worldwide—polyethylene (PE), poly(ethylene terephthalate) (PET), polypropylene (PP), polystyrene (PS), and polyvinyl chloride (PVC)—all of which are produced from “non-renewable” resources such as petroleum (crude oil), natural gas, and coal [2].

The words “polymers” and “plastics” are interchangeably used in this paper. A more precise definition of “plastics” is polymeric compounds mixed with some kind of additives for cost reduction, ease of processing, and enhanced performance. Polymers are rarely used alone and most, if not all, of the end products that reach consumers are plastics.

These plastics are very durable, thus leading to the increasingly worrisome issue of disposing of these plastic products after consumers have used them. For example, when we eat a sandwich which is wrapped in plastic, where does the plastic wrap go after we finish the sandwich? It goes into landfills, of course, leaving many people to wonder if we have gone too far in our use of plastics and the non-biodegradable waste they produce.

2. Recycling

One solution to decrease plastic waste is to recycle it. Similar to organic materials, plastics degrade depending upon the passage of time and exposure to thermal and mechanical heat generated during and after processing [3]. Recycled plastics must retain the charac-teristics of their virgin material [4]. To compensate for possible deterioration in properties through recycling, additives can be incorporated to improve the recycled material’s properties [4]. Moreover, plastic waste should be recovered as a single-material. Different polymers are usually mutually incompatible; that is, different macro¬molecules repel each other and phase separation occurs. The mechanical properties of incompatible polymers are usually inferior. The surface structure following phase separation is also poor. If the second phase of the polymer is uniformly dispersed in the first phase, its particles can be bound to the first by adding compatibilizers in order to improve its properties [4]. Also, reprocessing of mixed plastics with different melting points causes degradation, leading, in turn, to deterioration in physical properties.

For example, PET and PVC cannot be melt-processed together because PVC burns at PET's melt temperature (270°C). If the same mixture is processed at 170°C, which is suitable for PVC, the PET would remain solid, thus preventing the desired mixing [5]. Items such as PET soft drink bottles or natural HDPE milk bottles are abundant in the United States, where curbside collection and drop-off centers are common, thus providing ideal feedstock. In addition, recycled materials can also be blended with enough virgin resin so as to attain the required end properties or as an inner layer in co-extrusion or co-injection molding processes [4],[6].

The degradation of condensation thermoplastics, via hydrolysis, alcoholysis, thermal cleavage, and other mechanisms, is known to be severe. Those mechanisms decrease the range of acceptable applicationsdue to the loss of molecular weight in the recycled materials. One practical and cost-competitive approach uses a chain extender (CE) while reclaiming the recycled materials to increase the molecular weight. Chain extension technology uses nonlinear chain extension. That is, epoxy-functional styrene–acrylic-based, or styrene-free–acrylic-based reactive polymers are used to extend the initial polymer with long chain branched structures. Fig. 1 shows schematically the multi-functional chain extension concept [7].

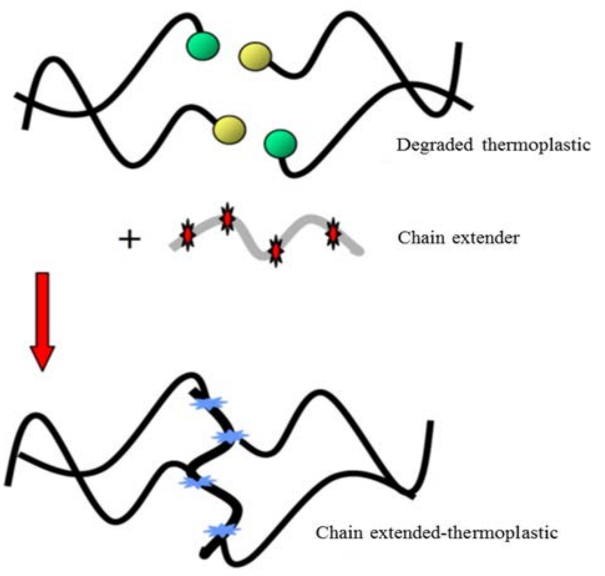

Fig. 1 Schematic representation and the principle of chain extension [7]

The recycling of plastics, although extremely useful in terms of cost and raw plastic reduction, sometimes offers a perfect excuse to overlook the inevitable negative result of synthetic polymer production [7]. Recent advances in genetic engineering, natural fiber development, and composite sciences offer innovative opportunities to improve materials from renewable resources, which can be biodegradable and recyclable, to finally obtain sustainable sources [8].

3. Renewable Resources

Another solution to plastic waste is tomake plastics degrade at an accelerated pace after they have been discardedor toproduce plastics from renewable resources. Biodegradable plastics, designed to decompose through the action of living microorganisms, are an alternative to conventional plastics when recovery or recycling are impractical [9]. Biodegradable polymers can be further broken down into two main groups: renewable and non-renewable polymers. Essentially, renewable biodegradable polymers utilize a renewable resource (e.g., a plant by-product) in the development of the polymer, rather than a non-renewable (e.g. petroleum-based) resource. A renewable material can be reproduced again and again. For example, when we use plantation wood to produce paper we can plant more trees to replace it. Obviously, long-term research and development (R&D) focuses on renewable and biodegradable polymers, but initial R&D work on petroleum-based biodegradable polymers has shed insight on many of the initial bio¬degradable products. The use of biodegradable plastics from renewable sources is not only a promising solution to the growing environmental issues by conserving limited non-renewable resources (petroleum) and reducing CO_2 emissions, but is also an excellent opportunity for agricultural industries around the world to produce raw materials and feedstock for this thriving industry [10]. It could be argued that the current use of polymer materials is unsustainable. Therefore, it is necessary to seek a sustainable approach to the manufacturing and use of these materials. At present, their cost prevents the wide use of biodegradable plastics [5]. However, the spiraling costs of petroleum-based polymers and the scaled-up pro¬duction of polymers from renewable resources will make the latter more competitive in the foreseeable future. Fig. 2 illustrates the classification of biodegradable polymers.

4. Composites and Foams

Our aim for the future must be to design products that can minimize the use of materials and energy in the manufacturing and usage stages and minimize waste and emission to the environment. The goal of this study is to minimize the materials used through micro-cellular foams and enhancement of material properties such as increasing

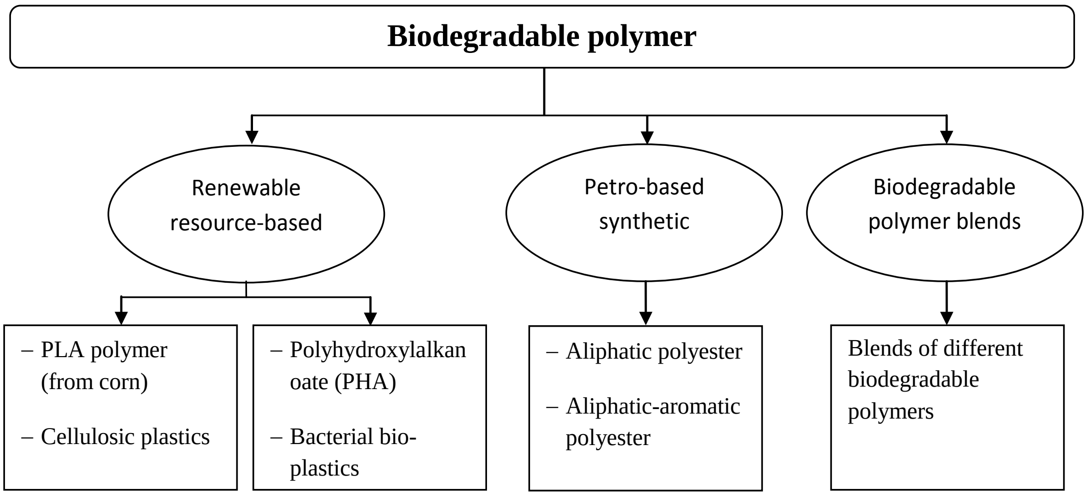

Fig. 2 Classification of biodegradable polymers [8]

the degree of polymer crystallinity and introducing reinforcing fillers in polymer composites.

Microcellular foam is a polymeric foam with bubble sizes of 100 microns or less and cell densities higher than 1 × 10^6 cell/mm^3. Microcellular foams are also sought for weight reduction in very thin films and sheets and for improved impact strength without significant mechanical property changes [11]-[14]. Three basic steps of producing microcellular foams are mixing/saturation, cell nucleation, and cell growth (Fig. 3) [15]. Microcellular foams have been widely used in various applications such as cushioning, insulation, packaging, and absorb¬ency. Foams with interconnected pore structures have recently been studied for their appli¬cations in tissue engineering as scaffolds for cell attachment and growth [15].

A composite material is a material system composed of two or more physically distinct phases. Composites can be designed that are very strong and stiff, yet very light in weight, giving them greater strength-to-weight and stiffness-to-weight ratios [17]. Weight reduction is a key consideration in many industries; notably, the aerospace and automotive industries. A lighter vehicle could mean better fuel efficiency [18].

Natural fibers can also be used as reinforcing fillers for composites as harvested. A large range of natural fibers have been successfully used in composites in recent years, including jute, hemp, kenaf, ramie, sisal, flax, and sugar cane bagasse fibers. They have low densities and high strengths and stiffnesses relative to their densities. Furthermore, theyare low cost, biodegradable, and nonabrasive, unlike other reinforcing fibers [19]. However, a disadvantage of natural fibers is that they are incompatible with typically hydrophobic polymers due to their hydrophilicnature, thus making it challenging to use them as reinforcements in polymers. In addition, insufficient wetting of natural fibers by the polymer matrix has been shown to lower the tensile strength and stiffness of a composite, as a poor interface cannot effectively transfer the stress from the polymer matrix to the fibers. Moisture absorption is another problem of natural fibers, as the moisture presence causes voids, thus reducing the strength of the composite. The moisture content will vary depending on the relative humidity or wetting of the composite. Moisture also interferes with the melt compounding and processing of the composites since processing temperatures on the order of 180 to 200°C are necessary. When the moisture is removed from the natural fibers, they become brittle, thereby losing their effectiveness as reinforcements [20].

The production of nanoscale fibers and their application in composite materials have gained increased attention due to their high strength and stiffness, combined with being low weight, biodegradable, and renewable[21]. It is necessary to breakthe cell plant materials into nanoscale fibers in order to achieve the reinforcing effects of the plant material. Table 1 shows that as the size of the filler component becomes smaller, the tensile strength and modulus become greater. The modulus of elasticity of a perfect crystal of native cellulose was measured by different authors and is estimated to be between 130 and 250 GPa. The tensile strength of the crystal structure was assessed to be approximately 0.8 to 10 GPa [22]. However, the separation of plant fibers into smaller elementary constituents has typically been a challenging process to perfect, requiring high amounts of energy [22], [23].

Since many polymers are composites of amorphous and crystalline phases, the amount of each phase will determine its final properties. Other details such as the nature of the crystal structure and the size and number of spherulites also play a role. Orientation of crystalline polymers can increase the degree of crystallinity in a polymer and improve its thermal stability as well as its mechanical properties [24]. Increasing the degree of crystallinity improves certain mechanical properties as well as the chemical resistance of the material.

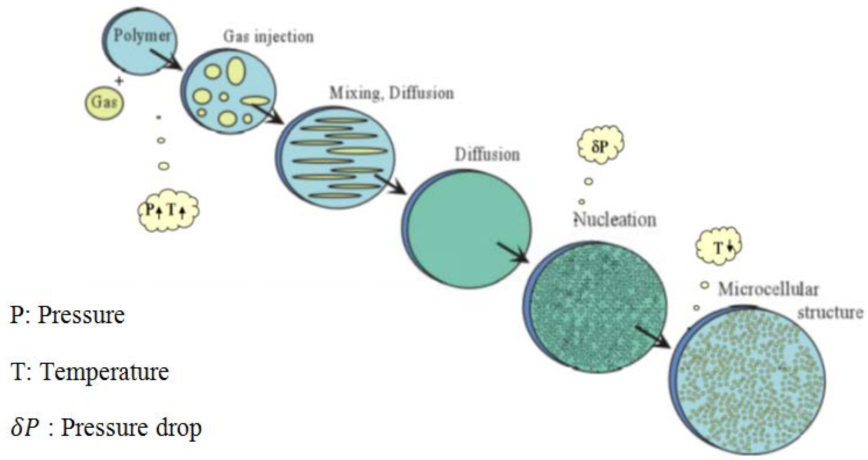

Fig. 3 Schematic of the microcellular foaming process [16]

Disintegration Process	Component	Modulus of Elasticity	Tensile Strength
Pulping	Wood	10 GPa	100 MPa
Mechanical/chemical dissolving	Fiber	40 GPa	400 MPa
Mechanical/chemical dissolving	Fiber (smaller size)	70 GPa	700 MPa
Mechanical/chemical dissolving	Crystal structure	130–250 GPa	800–10000 MPa

Table 1 Interrelation among structure, disintegration process, obtained component, modulus of elasticity, and tensile strength of natural fibers [22]

5. Conclusions

Sustainable polymers and composites have the potential to reduce negative impacts on the environment and future generations through (1) recycling post-consumer plastic products,(2) using biodegradable polymers made from renewable resources, and(3) reducing the materials used by making either foamed parts or stronger polymer composites. Using natural cellulose fibers as fillers for biodegradable polymers can also result in fully biodegradable green composites and help to reduce the matrix polymer material used. It is hoped that these approaches will help to accelerate and facilitate recycling and the reduction of polymers, as well as promote an increased adoption of polymers and composites from renewable resources.

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