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Original Research Article

The Influenced Trajectory of The Application of Green Chemistry in The Current Manufacturing of Plastic/Polymer Products

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ABSTRACT

The rapid growth of the plastic/polymer industry and the increasing amount of plastic waste has generated a need for the development of more sustainable alternatives to the production and use of polymer products. Green chemistry provides numerous benefits for the polymer manufacturing process, including energy savings, a smaller ecological footprint, and enhanced product performance. Energy can be saved by reducing the number of steps in the manufacturing process and replacing traditional energy-intensive processes, such as thermal polymerization, with more efficient alternatives when using green chemistry. Green chemistry offers an innovative approach to the production of polymer products through the use of environmentally friendly and sustainable chemical processes. This paper explores the application of green chemistry to the manufacturing of plastic/polymer products, focusing on the production of biodegradable polymers with emphasizes on the advantages of green chemistry principles on plastic productions. Also entailed in this study are some perceived problems associated with functional polymers and plastics.

Keywords: Green chemistry; Polymer; Plastic; Biodegradable

Introduction

For a long time, plastics were considered a gift from science to humanity because they improved people's quality of life, while presenting the development of new technologies. This trend in production generated positive economic impact in many countries. This technology produced inexpensive, lightweight, oxidation-resistant, and highly versatile materials from resultant inherent mechanical and thermal properties [1]. These features account for the success of their application in multiple utility demand areas and, thus, their high production volume

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[1–3]. Due to their importance in our society, their range of benefits, and their role as a large product of many industrial processes, developing sustainable plastics has been a large focus for many green chemists and industrial engineers [3]. By improving the industrial processes of manufacturing plastics, companies can directly reduce environmental pollution at the beginning of the plastic cycle [2]. Much of the innovation has focused on using biologically produced polymers rather than environmentally hazardous processes that use hydrocarbons in oil ("plastics") but biopolymers extracted from biomass [1]. The concept of "green chemistry" emerged in the early 1990s as a novel proposal for a set of principles based on the design of sustainable chemical processes with low environmental impact [4]. In general, the principles of green chemistry are based on the search for the sustainability of our civilization, which will be dependent on our ability to meet and satisfy the demands for food, energy, and raw materials while preserving the environment and supporting a constantly growing population [4-5]. The problem becomes especially difficult when we consider our planet's finiteness in terms of space, capabilities, and resources, as well as the fragility of ecosystem dynamics and balances [5]. In this way, 12 green chemistry principles have been proposed. These are as follows: prevention, renewable raw materials, the atomic economy, reduction of synthetic derivatives, synthesis of less dangerous chemical substances, development and use of catalysts, design of safer chemicals, design of degradable products, the use of safer solvents and auxiliaries, real-time analysis of processes for contamination prevention, the design of processes with high energy efficiency, and intrinsically safe processes [4-5]. As a result, green chemistry has emerged as one of the most appealing philosophies in the field of chemistry for achieving the sustainability of its processes while having a low environmental impact [4]. Through various green chemical research, many private companies have recently been able to create more efficient manufacturing processes [5]. Currently, materials made from biopolymers extracted from biomass have received great attention because they are profitable and economical alternatives for producing materials with added value, and, in principle, because of their origin, they are often considered more environment-friendly materials compared to materials obtained from the oil industry [6]. Typical biopolymers with industrial uses are starch, collagen, chitin, rubber or cis-1,4-polyisoprene, and cellulose [7]. They are used in conjunction with other substances for the production of new materials with a wide spectrum of applications. An important advantage of this type of biopolymer is its biodegradability, which is a property that must be controlled for many applications [8]. The biodegradability of these materials must inevitably be associated with an inherent susceptibility to being colonized by microorganisms

[6-8]. Although in principle this is positive, microbial colonization can also affect the properties of the material, its function, storage, transport, and shell life [6]. Therefore, on many occasions, it is necessary to incorporate additives that allow adequate modulation of its microbial colonization and biodegradation [8]. At the same time, these biopolymers tend to be hydrophilic, so their application in outdoor applications involves their chemical modification, for example, by acetylation of carboxylic or hydroxyl acid groups, or by preparing polymeric composites with other natural or synthetic materials [7-8].

Overview of Green Chemistry

Green chemistry is an emerging field of research that focuses on reducing the use of hazardous substances and minimizing environmental impact during the production of chemical products. It applies principles of sustainable development and environmental protection to the design, synthesis, and use of chemicals and materials [5]. Green chemistry focuses on developing chemical processes and products that reduce or eliminate the use and/or production of hazardous substances, while also reducing energy consumption and waste production [4]. This can include the development of more efficient processes, the use of renewable sources of energy, and the development of more environmentally friendly chemicals. It also seeks to use fewer resources and employ cleaner production methods [6]. Green chemistry has been used to develop safer alternatives to existing chemicals and processes, as well as new products and technologies [4,6]. The ultimate goal is to reduce and eliminate the environmental and health risks associated with the production, use, and disposal of chemicals [6]. It aims to reduce the environmental impact of chemical processes, and to promote the use of sustainable and renewable resources [5]. Green chemistry has been applied in the development of new products and processes. For example, green chemistry has been used to develop processes for the production of polymers from renewable resources, such as biomass. It has been used to develop new catalysts and solvents that are less toxic than their traditional counterparts. Furthermore, green chemistry has been used to develop processes that are more efficient, and that generate less waste [4-6]. Green chemistry uses a set of principles to guide the design of chemical processes and products. These principles include minimizing the use of hazardous substances, using renewable resources, minimizing energy consumption, and minimizing waste [9].

Principles of chemistry

Green chemistry refers to a set of principles and practices aimed at reducing or eliminating the use or generation of hazardous substances in the design, manufacture, and use of chemical products [9]. Green chemistry is increasingly being applied to the development of polymers and plastics, both for their manufacture and for the products themselves. This paper will discuss the application of green chemistry to polymer and plastic products, with an emphasis on how green chemistry can be used to reduce their environmental impact [9]. The principles of green chemistry (Table 2) are based on a set of twelve core principles that guide chemists in designing safer, more efficient, and more economical processes and products [9-11].

Table 2 Principles of green chemistry

S/N	Principles of green chemistry	
1	Prevention	Design processes and products to reduce or eliminate the use and generation of hazardous substances [12].
2	Atom economy	Design chemical syntheses to maximize the incorporation of all materials used in the process into the final product [12-13].
3	Less hazardous chemical syntheses	Design syntheses to use and generate substances with the least possible toxicity to human health and the environment [14-15].
4	Safer solvents and auxiliaries	Design syntheses to use and generate substances with the lowest possible toxicity to human health and the environment [12,15].
5	Design for energy efficiency	Design chemical processes and products to maximize the incorporation of all energy resources used in the process into the final product [12-15].
6	Use of renewable feedstocks	Design syntheses to use renewable feedstocks instead of depleting resources [14].
7	Reduce derivatives	Avoid the use of blocking or protecting groups or any temporary modifications if possible [12,15].
8	Catalysis	Design catalytic syntheses to maximize the incorporation of all materials used in the process into the final product [12-15].
9	Design for degradation:	Design chemical products to degrade after use [14].
10	Real-time analysis for pollution prevention	Design analytical methods to monitor and control the production process in real time to prevent the formation of hazardous substances [13].
11	Inherently safer chemistry for accident prevention	Design syntheses to use and generate substances with the lowest possible hazard in the event of an accident [12,15].

12	Education	Educate chemists about green chemistry and incorporate green chemistry principles into chemistry education [12].

Application of green chemistry principles in polymers processing

Green chemistry offers a number of strategies for reducing the environmental impacts of polymers and plastics. These strategies include the use of renewable resources, the development of more efficient manufacturing processes, and the use of biodegradable polymers [16-21]. The use of renewable resources is one of the key principles of green chemistry. Plant-based polymers and bioplastics are being developed as alternatives to petroleum-based polymers. These polymers have a number of advantages, including reduced energy consumption during production and the potential for biodegradation [20]. The development of more efficient manufacturing processes is also important. Processes such as supercritical fluid extraction and high-pressure homogenization can reduce the energy and chemical inputs required for polymer manufacture, while also reducing waste. Biodegradable polymers are being developed as alternatives to traditional plastics. These polymers are designed to degrade in a range of natural environments, reducing their environmental impact [18-21]. Green chemistry offers numerous advantages for the production of polymers products, including energy savings, reduced environmental impact, and improved product performance. Through the use of green chemistry, energy can be saved by decreasing the number of steps in the manufacturing process and replacing traditional energy-intensive processes, such as thermal polymerization, with more efficient alternatives [17]. This can result in significant cost savings while reducing the environmental impact of the production process. Additionally, green chemistry enables the production of polymers with improved properties and performance, such as increased strength, flexibility, and durability [20]. Green chemistry principles can be applied to polymer processing in various ways, such as designing environmentally friendly solvents, reducing waste and energy consumption, and minimizing the use of hazardous chemicals. Here are some empirical examples of how green chemistry has been applied to polymer processing:

Water-based polymer processing

Green chemistry is an approach to chemistry that seeks to reduce or eliminate the use of hazardous materials in the manufacture of products. It also seeks to reduce the amount of energy and resources used in the production process. In water-based polymer processing, green chemistry can be applied to reduce hazardous chemicals and materials [4-9]. This can be achieved by replacing traditional toxic chemicals with non-toxic or biodegradable alternatives. For example, instead of using hazardous solvents, which are often volatile organic compounds (VOCs), green chemistry techniques can be used to replace these with water-based solvents. In conventional polymer processing, solvents are often used to dissolve and transport polymers. However, many solvents are harmful to human health and the environment [15,22]. Water-based polymer processing has emerged as an alternative that uses water as a solvent [23]. This approach has been applied to various polymer processing techniques, including electrospinning, injection molding, and 3D printing. For example, researchers have used water as a solvent for electrospinning chitosan/polyethylene oxide nanofibers [22-23]. This technique can be applied in the synthesis of various polymers such as polyvinyl alcohol, polyacrylamide, and polyethylene glycol [23]. In addition, green chemistry can be used to reduce energy consumption by optimizing the process parameters and equipment used in the production process [22]. This can be done by reducing the temperature and pressure of the process, as well as improving the efficiency of the equipment used [15, 22]. Finally, green chemistry can be used to reduce the environmental impact of water-based polymer processing. This can be done by reducing the amount of wastewater generated in the process, and by reducing the energy and resources needed for the production process. Green chemistry can also be used to reduce the amount of hazardous chemicals and materials used in the process [12].

Supercritical fluid processing

Supercritical fluid processing is a type of green chemistry that uses supercritical fluids to extract, purify, and process materials [24]. Supercritical fluids have properties between liquids and gases, so they can be used to separate materials by extracting desired components while leaving other unwanted materials behind [25]. This process is both efficient and environmentally friendly, requiring fewer resources and producing less waste than traditional methods. Supercritical fluid processing is used in a variety of industries, including pharmaceuticals, food processing and energy production. It is also used to create new materials and products, as well as to improve existing ones [26]. Green chemistry principles are applied to optimize the process, such as reducing toxic chemicals, minimizing energy consumption, and utilizing renewable energy sources. Additionally, the process can produce higher-quality products with fewer contaminants, making it an attractive option for many industries. Supercritical fluids, such as carbon dioxide, have become increasingly popular solvents for polymer processing because they are non-toxic, non-flammable, and can be easily removed from the final product [25-26]. Supercritical fluid processing has been applied to various polymers, including polycaprolactone, polyesters, and polyurethanes. Researchers have used supercritical carbon dioxide to prepare poly(lactic acid) microspheres for drug delivery [25].

Microwave-assisted polymer processing

Green chemistry has been applied to microwave-assisted polymer processing in order to reduce the energy and material costs associated with traditional processing methods [27]. Microwave-assisted polymer processing uses microwaves to quickly heat up polymeric materials, allowing them to be shaped and finished faster than with conventional methods [27-29]. The use of green chemistry in this process reduces the amount of hazardous chemicals used, as well as energy and material costs. Additionally, green chemistry can be used to reduce the amount of waste generated during the processing. By using green chemistry, manufacturers can reduce their environmental impact, while still producing high-quality products [28]. Microwave heating has been used as an alternative to conventional heating methods in polymer processing. Microwave heating is a green technology that can reduce energy consumption and processing time. Microwave-assisted polymer processing has been applied to various polymers, including polyesters, polycarbonate, and polypropylene. Researchers have used microwave heating to prepare poly(caprolactone) microspheres for drug delivery [29]

Biodegradable polymers processing

Green chemistry has revolutionized the biodegradable polymer processing industry. It has enabled more efficient and sustainable methods of production, which make use of renewable resources and minimize the environmental impacts of waste [5]. The use of green chemistry in the production of biodegradable polymers can reduce the energy required for production, as well as the amount of waste that is produced. For example, it can be used to create polymers from plant-based sources, such as corn, wheat, and soy. The use of these materials can reduce the amount of energy needed to produce the polymer, as well as the amount of non-biodegradable waste that is created [7]. Green chemistry also enables more efficient production processes. For example, it can be used to catalyze reactions that break down polymers into smaller components. This can reduce the amount of energy and time required to produce the polymer. Additionally, green chemistry can be used to modify the properties of the polymer, such as its flexibility, strength, and durability [6]. The use of green chemistry in biodegradable polymer processing can help to reduce the environmental impact of production. By using renewable resources and more efficient production processes, the industry can reduce its reliance on fossil fuels and minimize the amount of waste that is created [5,8]. Biodegradable polymers, on the other hand, can be decomposed by microorganisms into harmless substances. Several biodegradable polymers have been developed, such as poly(lactic acid) (PLA), polyhydroxyalkanoates (PHA), and polycaprolactone (PCL). These polymers have been used in various applications, including packaging, textiles, and medical devices [6].

Biodegradable polymers a reflection of green chemistry

Biodegradable plastics are those that can be broken down by living organisms, typically microbes, into water, carbon dioxide, and biomass. [1] According to the International Union of Pure and Applied Chemistry (IUPAC), these are materials that are susceptible to degradation by biological activity, leading to a reduction in molecular mass [8]. According to ASTM D883, a polymer is biodegradable when it can be deteriorated by microorganisms such as fungi, bacteria, and algae [30]. However, these definitions do not take into account that the biodegradation process is also aided by oxidation reactions, photodegradation, hydrolysis, and so on. As a result, a biodegradable polymer should be defined as material whose physical and chemical properties deteriorate due to the cleavage of their structure as a result of environmental factors [30-33]. According to international standards such as ASTM6400, EN13432, AS 4736, ISO 17088, and Green Pla, a material can be certified as biodegradable if it decomposes by 90% in 6 months [31]. Natural materials, also known as biopolymers, and synthetic materials are the two main types of biodegradable polymers. Biopolymers, which include polysaccharides like cellulose or chitin, proteins like collagen or albumin, and even lipids and nucleic acids, are the result of nature's evolutionary process. These materials also have biocompatibility and non-toxicity properties, making them appealing for use in the pharmaceutical, cosmetic, food, and biomedical industries [34]. Synthetic biodegradable polymers, on the other hand, have been developed to create materials with specific morphological and mechanical properties, as well as optimal reproducibility [34] In contrast, synthetic biodegradable polymers have been developed to produce materials with specific morphological and mechanical properties, as well as optimal reproducibility. Poly (lactic acid) (PLA), poly(e-caprolactone) (PCL), poly (glycolic acid) (PGA), poly (butylene succinate) (PBS), polyhydroxyalkanoates (PHAs), and other synthetic biodegradable polymers are examples [6]. Although synthetic biodegradable polymers are being developed, they account for less than 2% of non-degradable polymer production because these environmentally friendly materials are generally more expensive, even today, and thus are not an economically viable option for many industries and consumers [6,34]. In recent years, research into the development of inexpensive biodegradable polymers with optimal mechanical properties has been ongoing, but it is a growing topic of interest due to its environmental benefits [34].

Polymer biodegradability

In most cases, degradation of these biodegradable polymers occurs in two stages. The first is the excision of the polymer to produce low molecular weight molecules via abiotic (e.g., hydrolysis, oxidation, photodegradation, etc.) or biotic processes (i.e., by the enzymatic action of microorganisms). In the second step, the fragments generated are bio-assimilated for subsequent mineralization into simple molecules such as CH_4, CO_2, H_2O, and biomass [33]. The biodegradability of polymers is determined by chemical and physical properties associated with structural and morphological features, in addition to environmental factors. These characteristics are discussed further below.

Chemical properties

The presence of specific functional groups, bonds, aggregation structures, and so on will determine how easily fragmentation can occur [33]. Thus, a material has greater biodegradability when cleavage occurs easily; thus, it is important to understand the structural and morphological properties that have a relevant impact on this property, such as the presence of heteroatoms in the polymer's main chain, the presence of easily oxidizable groups, and side chains composed of bulky groups that provide less chain packing [35-36].

Physical properties

Aside from the chemical properties mentioned above, biodegradable polymers are distinguished by physical properties associated with structural features [37-41]. These properties include the glass transition temperature (T_g), melting temperature (T_m), density (D), Young's modulus (E), tensile strength (T_S), and so on. The following are the effects of these properties:

Tensile strength (T_S), Young’s modulus and Density

Tensile properties will be best in the most crystalline and dense materials. Tensile strength and E are parameters used as mechanical failure criteria, so they are fundamental properties for polymers that will be used in construction [38]. In a recent review, Laycock et al. [30]

established that when tensile strength drops by 5% of its initial value, the polymer has lost its strength. This property is influenced by the forces between the chains as well as the crystallinity of the material: the more crystalline regions there are in the polymer structure, the stiffer it will be [38-41]. This can be a disadvantage because rigid materials exhibit localized tension that is much higher than the tensile strength in some cases, resulting in crack formation [30,40]. The functional groups in the polymeric structure influence crystallinity and thus the mechanical properties of the material because if hydrogen bonding and polar interactions are encouraged, crystal packing is also encouraged [38, 40-43]. A high hydrophilicity, resulting from the functional groups of the chains, will influence mechanical properties because the polymer will absorb water, causing swelling and loss of material strength [41]. Density is also closely related to mechanical resistance; thus, a higher density material is related to greater mechanical strength [43].

Melting Temperature (T_m)

Tm is an important parameter to consider because it is at this temperature that thermal degradation of biodegradable thermoplastic materials occurs, as chain mobility occurs, reducing the rigidity of the material and making the bulk of the material more accessible to external factors. As a result, polymers with lower T_m are more prone to degradation [44]. Thermal degradation may limit the use of these materials in various applications. For example, PCL, a polyester exhibiting optimal thermal processability, however, its useful life is limited by its low T_m, as a consequence, PCL is mixed with other polymers, such as cellulose, to increase the scope of its applications [44].

Transition Temperature

Biodegradable polymers with low T_g, on the other hand, have poor mechanical properties because the flexibility of the chains is reduced at room temperature, preventing movement because they are vulnerable to traction or tension. T_g has also been identified as a temperature limit beyond which the polymer degrades dramatically at higher temperatures t [45-46]. Difference scanning calorimetry (DSC) and thermogravimetric analysis can be used to calculate T_g and T_m (TGA) [47]. The thermal properties of these materials are evaluated at room temperature (25℃), storage temperature (around 23℃), and high temperatures (close to 30℃) for applications in the packaging area, as the polymer must be stable under these conditions [46]. Thermal properties are important because they are related to the structural characteristics of the material and, as a result, its ability to be biodegraded. Aliphatic polyesters, for example, have a low T_g while a high Tm, which contributes to their biodegradability while also limiting their applications due to poor performance. Starch, on the other hand, has a high T_g and a low Tm, requiring the addition of plasticizers such as glycerin, sorbitol, or urea in conjunction with shear forces and high temperatures to improve plasticity and produce a thermoplastic material [48].

Structural feature

A material's capacity and degradation mechanism are primarily controlled by its molecular structure. In a review of decomposition mechanisms, Kanwal *et al*. [49] discovered that polymer biodegradation occurred in the following order of functional groups: aliphatic ester, peptide bond > carbamate > aliphatic ether > methylene [49]. This makes sense because hydrolyzable groups in the chain are susceptible to hydrolytic enzyme degradation, such as ester, urea, urethane, amide, and enamine bonds. Furthermore, it is consistent with the fact that biopolymers like proteins and polysaccharides degrade in biological systems [50]. Due to their low reactivity, conjugated systems, such as aromatic groups, were previously thought to be more biodegradable than their aliphatic counterparts, whereas conjugated systems would cleave their C-H bonds when exposed to sunlight or ultraviolet light. However, aromatic groups give the material high rigidity and radical elimination properties, so this theory is no longer valid. It is currently known that incorporating aliphatic esters into polymeric structures improves polymer materials' biodegradability [51].

Morphological feature

The shape of the polymer has been shown to be a characteristic that affects biodegradability because enzymes degrade linear polymers more easily than branched polymers [52]. Another important factor in promoting degradation by enzymatic catalysis is the material's flexibility, which allows it to be more accessible to the active site of enzymes [52-55]. This explains why aromatic polyesters, such as PET, are not biodegradable due to their structure, which is made up of rigid aromatic rings, whereas aliphatic polyesters are highly biodegradable. Polymer flexibility is related to the degree of crystallization of the macromolecule and, as a result, to their molecular ordering. Heteropolymers, such as proteins, are less likely to crystallize due to irregularities in their repetitive units and are more biodegradable [53]. This is one of the most difficult challenges in the synthesis of biodegradable polymers because they are typically composed of short, uniform, repetitive units that contribute to crystallization, negatively affecting their biodegradability due to hydrolysable groups that are inaccessible to hydrolytic enzymes. Semicrystalline and amorphous polymers, on the other hand, are more biodegradable than crystalline polymers [54]. However, by first breaking down the amorphous and semicrystalline regions, a crystalline material is produced, which prevents enzymatic degradation [30, 56]. It has been demonstrated that increasing the number of chiral centers increases enzyme specificity and, as a result, polymer biodegradability. As a result, it is common to incorporate hydroxyl, benzyl, methyl, carboxyl, and other substituents during the design and synthesis of biodegradable polymeric materials with the goal of generating chiral carbons close to the hydrolysable regions of the polymer chain and increasing their biodegradability [55].

Application of biodegradable polymer to plastic products

Biodegradable polymers are used in a wide range of applications, from medical implants to packaging material. Table 1 below show gives a summary of some selected relevant applications for biodegradable polymer.

Medicine

Materials used in medicine and biomedicine must be biodegradable, biocompatible, and bio-adsorbent in many cases. In this regard, biopolymers such as polysaccharides and proteins have been appealing because they typically exhibit these attributes [57-58]. Because proteins are components of tissues in various organisms, including skin, vascular, pulmonary, and musculoskeletal tissues, they are used as materials in drug-delivery systems, scaffolding in tissue engineering, and even suture development [58]. Polysaccharides such as chitin and cellulose have also been designed as biomedical and pharmaceutical materials [59]. Polyesters have also been ideal candidates within the group of biodegradable synthetic polymers due to their superior mechanical properties and the ability to control their biodegradation rate. Polyurethanes also have excellent biodegradability and biocompatibility, making them promising candidates for the development of medical implants and biomedical materials in contact with tissue and biological fluids [60]. Because of their excellent mechanical properties, PHAs are also appealing biodegradable materials that have been used as medical scaffolding such as screws, pins, and so on [58,64]. Although biodegradable polymers were developed to replace conventional non-degradable materials, they also have potential applications in medicine, technology, and other fields [61-64]. Nanomedicine, for example, has a promising future that could improve the quality of life for many people, and biodegradable polymers have been evaluated as drug nanocarrier systems in this regard [65]. To that end, in addition to in vivo toxicity studies, the physicochemical properties of these materials, such as polymeric composition, tacticity, molecular weight, colloidal stability, hydrophilic/hydrophobic ratio, and so on, are being investigated and evaluated on a continuous basis [63-64]. In a recent review, Narancic *et al.* [66] highlighted current research in this field, where PHAs such as PHB are the protagonists, exhibiting optimal cell adhesion and good immune response [66]. Although promising, this field of medicine is still in its early stages and is being researched today. Other biodegradable polymers, such as alginate, quitosane, and PLA, have the potential to be used in the development of non-toxic carrier systems, allowing oral vaccines to achieve the desired immune response without the need for a booster dose [62-63,67]. PLA nanofiber biocomposites with electro-threaded polyethylene glycol have the potential to be used as bone regeneration scaffolding because they demonstrated excellent mechanical properties, similar to polyethylene glycol, in combination with PLA's biodegradability [62,67]. When compared to conventional bone grafts, bone fillers based on biodegradable polymers such as soybeans resulted in better tissue regeneration. Bacterial nanocellulose tubes have also been proposed as biomedical prostheses such as artificial blood vessels, the urethra, and the esophagus [68-69]. Although research in the field of tissue engineering is still in its early stages, with only a few in vivo studies, biodegradable biopolymers are appealing materials because they could replace materials that induce immune responses [69-70]. As a result, polyesters such as PLA are widely studied for their optimal properties. They do, however, produce acid residues during hydrolysis, which may have a negative impact on cellular physiology [66,69-70].

Packaging

Packaging materials, such as containers, are one of the most important plastic industries, accounting for 40.1% of total plastic production. They must have a good seal and air permeability, be easy to process and shape, be inexpensive for commonly used applications, and be safe when in contact with food or other products [71]. Poly (ethylene) is the most commonly used polymer for packing a wide range of liquids, powders, and solids. Biodegradable polymers were designed to gradually replace this material in order to reduce the residues of conventional polymers [71-74]. PLA, on the other hand, has acceptable levels of oxygen permeability and water vapour, making it widely used in storage systems; however, its cost is relatively higher than polyethylene (ethylene) [66]. PLA materials are estimated to replace 86.9% of PET-based packaging [75]. PHAs, such as PHB, have also demonstrated excellent mechanical properties when used as packaging materials. PHA has been proposed as a packaging material to replace PE and PP; however, its use in food packaging is limited due to odour issues and the subsequent addition of additives [71]. Furthermore, nanocomposites based on starch and PLA with clay had excellent mechanical properties with little water penetration, helping to advance packaging technology [71–74]. The preservation of a packaged food product is dependent on intrinsic mass transfer procedures which take place between the food, the container or coating, and the exterior, in addition to external conditions such as temperature, pressure, relative humidity, and asepsis [71,76-78]. According to this dynamic and depending on the type of food, mass transfer processes involving the exchange of water, CO_2, O_2, volatile and nonvolatile organic compounds, microorganisms, and so on may occur between the phases involved [72,78]. As a result, the packaging material must have the chemical and structural characteristics, as well as sufficient properties, to allow for the extension of the useful life of the food by controlling these processes appropriately [77]. When preserving fresh fruits or dry foods, for example, water barriers should be used to avoid hydration or dehydration. Similarly, the barrier material can regulate the permeability of gases such as oxygen or the loss of organic vapours, which allows, through packaging or coating, to control the ripening of fruits, the oxidation of components (fats, pigments), browning reactions, the retention of organoleptic properties, the penetration of solvents or toxic components, the entry or proliferation of microorganisms, and other functions [76,78]. Edible films and coatings are defined as thin layers arranged on the surface of food to form a container or primary barrier that, in addition to performing specific functions of containment, conservation, and/or protection, is completely biodegradable and/or can be eaten with food [79-81]. Coatings, on the other hand, are applied directly to the surface of the food and are an integral part of the food [80]. Films are preformed, self-contained materials that are commonly used to manufacture bags, capsules, wrappers, and casings [79]. In terms of mechanical properties, the packaging material, on the other hand, must be strong enough to maintain its integrity during use [82]. Furthermore, sensory compatibility between the food and the coating or packaging material should not be overlooked, as aesthetic appearance, taste, and smell are important factors in consumer perception [82]. The polymeric container material's composition will be determined by the food in which it is used, the processing conditions required, and the functions that the container must perform [82]. The melting and glass transition temperatures must be known depending on the material's structural properties, use, and storage method, as the material's stability is dependent on these [83]. It is necessary to prepare a film-forming solution or emulsion from the solubilization or dispersion of the raw materials in water, ethanol, or a mixture of both for both films and coatings. The desired food additives (e.g., plasticizers, antimicrobial agents, colouring, or flavouring) are introduced here, and pH or temperature conditions are adjusted after homogenization [80, 82-83]. As previously stated, incorporating multiple materials in the film-forming solution to form edible polymer composites is an alternative approach to enhancing the functional properties of coatings and films (e.g., polysaccharides, polypeptides, lipids, fibers, nanoparticles, nano systems, and so on) [81]. In the case of coatings, the prepared solution is applied to the surface of the food in liquid form, either by immersion or by direct spraying followed by drying. In this case, it is essential that you consider the characteristics of the edible material to be coated since there must be compatibility between its surface properties (wettability, contact angle, surface tension) and those of the coating material [81]. On food, single or bilayers are commonly used, with the latter achieved through layer-by-layer coating (LbL), in which the food is alternately coated in different film-forming solutions to improve the functional properties of the coating [82, 85]. A bilayer coating can be made of various materials; for example, to improve the barrier properties to water vapour, a first layer of polysaccharides or proteins can be used, followed by a second layer of lipids [80]. Another example of a two-layer coating is provided by Bilbao-Sainz et al., [86], who formed an electrostatic LbL to coat fruit bars enriched with ascorbic acid using two solutions prepared with oppositely charged polyelectrolytes, chitosan (polycation) obtained from mushroom (Agaricus bisporus) by-products, and alginate (polyanion) obtained from brown algae; the authors demonstrated that, despite the advantages that have been demonstrated in the industry, the use of bilayers is less common due to the fact that two stages of coating and drying are necessary to obtain them, which implies more time and operational control of the process [86]. The incorporation of these active compounds can be done on the external surface of the food after coating, between polymeric multilayers, at the food-edible polymer interface, or dispersed between the film [86]. Some of these active and bioactive compounds, however, are sensitive to light, heat, humidity, and the presence of oxygen, or are unstable to the conditions of preparation of the film-forming solution or the storage conditions; this results in a degradation or loss of functionalities, which can also influence the taste, smell, and colour of the food that comes into direct contact with it [87]. To overcome these challenges, nanoencapsulation and microencapsulation are options that seek to protect these components by acting as reservoirs or physicochemical barriers against moisture, gases, or pro-oxidant agents such as free radicals, oxygen, and UV radiation [81]. Controlling the release of active and bioactive components into food is possible in addition to improving stability. Encapsulation systems come in a variety of shapes and sizes, including capsules, spheres, and liposomes, and are made from a variety of wall materials. Spray drying, coacervation, liposomes, co-crystallization, nano-emulsions, solid lipid nanoparticles (SLNs), nanoprecipitation, electrospinning, spray drying, and other techniques are used to prepare micro- and nano-encapsulates [88]. Nano-emulsions have been used in coatings based on chitosan, pectin, sodium alginate, or methylcellulose to encapsulate antimicrobial agents and antioxidants such as carvacrol, cinnamaldehyde, a-tocopherol, or essential oils of garlic, clove, oregano, basil, mandarin, lemongrass, or resveratrol [89]. Li et al. [90] developed a hydrophobic interface film based on gum arabic, gelatin, and beeswax that can be used at the packaging interface to reduce the loss of residual liquid foods like milk, yoghurt, and honey. Deposition of a polymeric film-forming solution on the surface of a solid substrate was followed by spraying of a beeswax microemulsion. The superhydrophobic interface demonstrated high contact angles (150 degrees) for the various liquids tested; additionally, it demonstrated reasonable mechanical durability by retaining its structure and functionality after repeated folding and washing [90]. Cui et al. [91] used the ionic gelling method to create active zein films doped with chitosan polymeric nanoparticles and encapsulated pomegranate peel extracts [91]. In this case, in addition to the antimicrobial effect of the chitosan nanoparticles, pomegranate extracts, which are high in polyphenols, have been shown to have the same capacity because their hydroxyl groups can interact with the cell membrane of bacteria via hydrogen bonds or other mechanisms, causing changes in the structure and permeability of the membrane, as well as causing the loss of cellular content and subsequent death of the microorganism [92]. The authors reported uniform distribution of nanoparticles in the film with improved thermal stability, and the controlled release of polyphenols to meat samples was confirmed, demonstrating strong antimicrobial activity against L. monocytogenes. Other applications include clove essential oil, zinc oxide rods, and gelatin in shrimp [93], and clove essential oil, soy protein, and montmorillonite in bluefin tuna (Thunnus thynnus) muscle fillets [94]. Lysozyme nanofibers-pullulan and lactoferrin-cellulose have been used as antimicrobial films in fresh sausages; additionally, most have antioxidant properties.

Agriculture

The use of biodegradable plant protection materials is critical in agriculture. Other biodegradability characteristics required of these polymers include the ability to conserve moisture and raise soil temperature [95]. Biopolymers such as cellulose, starch, and lignin, as well as synthetic polymers such as sorbitol, citric acid, glucamine, and others, are used for this purpose, and are degraded in soil by organic manure, contributing to silver growth and soil viability [96-97]. Biodegradable polyesters are also appealing for agricultural applications [98-99]. PLA, in particular, has been used as an agricultural mulch with the goal of replacing poly(ethylene) and achieving optimal crop yield while avoiding negative effects such as soil contamination [98]. Because of their ability to inhibit weed growth and soil evaporation, PHAs are also used as mulch. Furthermore, these biodegradable polymers promote nitrogen fixation and act as a bacterial inoculant [100]. Functional polyurethanes have also been developed for intelligent crop fertilization [100].

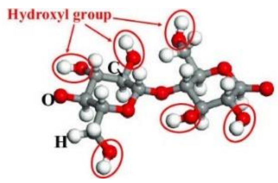
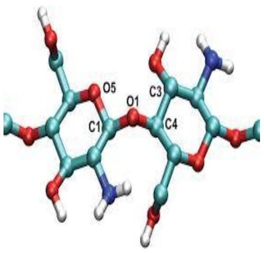
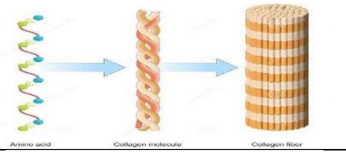
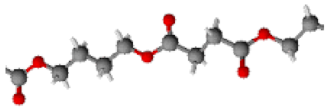
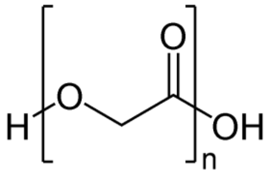
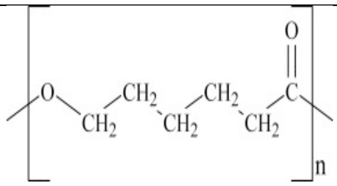
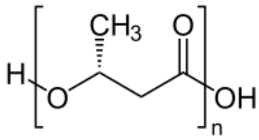
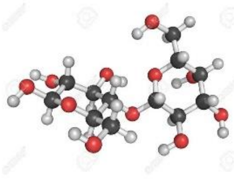
Technological

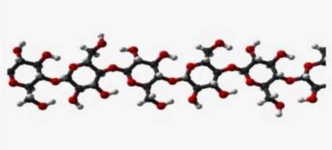
The technological revolution has resulted in the development of devices that improve communication and information access while also polluting the environment. As a result, efforts have been made to develop environmentally sustainable electronics [100]. One of the most important works is that of Gao et al.,[100] who created an electret nanogenerator out of cellulose and PLA, thereby providing new knowledge for the development of ecological energy [98]. Because of their high ion conductivity, mechanical resistance, and ease of manufacture, highly ion-conductive polymeric electrolytes are also appealing for use in ion batteries, supercapacitors, solar cells, and other applications [101-102]. As a result of its renewal capacity and biodegradability, PCL has been proposed as an electrode material, contributing to the generation of sustainable energies [103]. Other biodegradable polymers, such as cellulose, have been proposed for use in the development of light-emitting diodes, solar cells, and field-effect transistors [104-106]. However, the use of biodegradable polymers in electronics is still being researched because the electrical and mechanical properties of these materials need to be improved [105-106].

Environmental purifier

In addition to preserving the environment, biodegradable polymers have the potential to reduce or eliminate toxic waste discharged into the environment as a result of industrialization [108]. PCLs, for example, have been proposed as a groundwater absorber of endosulfan, a toxic pesticide. The results demonstrated a high retention capacity, making it a promising material for use in contaminant removal [109].

Table 1: Summary of the most Relevant Applications of some Biodegradable Polymers

Polymer	Structure	Chemical formula	Application
Cellulose		$(C_6H_{10}O_5)_n$	Controlled released of pesticides, nutrients and fertilizers. Material for the development of controlled drug-delivery system and scaffolding for the regenerations of tissues [53].
Chitin and Chitosan		$(C_8H_{13}O_5)_n$	Products with antioxidant activity and radical elimination. Carriers of drugs, antitumor products, anticoagulant, antibacterial agents and immune-adjuvants.
Collagen		$C_{57}H_{91}N_{19}O_{16}$	Wound dressing, bone graft and tissue repair
PBS		$(C_8H_{12}O_4)_n$	Medical suppliers, packaging, Bottles and biomedical applications
PGA		$(C_2H_2O_2)_n$	Internal fixation devices for bones, absorbable sutures and scaffolding for tissues regeneration
PCL		$(C_6H_{10}O_2)_n$	Materials for the development-controlled drug-delivery systems, scaffolding for the regenerations of tissues and support materials for agricultural planting
PHB		$(C_4H_6O_2)_n$	Disposable products, food packaging and medical scaffolding like screws [54]
PLA		$(C_3H_4O_2)_n$	Waste bags, packaging systems, development of agricultural mulch films and fertilizers bags

Starch		$(C_6H_{10}O_5)_n$	Food packaging development of agricultural mulch films [38]

The current problems associated with functional polymers and plastics

Plastic production in the world is estimated to have reached 348 metric tonnes in 2017 [110]. Unfortunately, many commercially used polymers are derived from nonrenewable sources, and as a result, they are environmentally hazardous due to their low biodegradability and high accumulation rate, making them a global problem [110]. As a result of the foregoing, various government policies based on comprehensive waste management have been put in place. However, the implementation of these programs is often inefficient due to a lack of coverage, infrastructure, resources, or community interest in waste management [111]. Simultaneously, physical and chemical processes for the transformation and utilization of polymer waste have been developed. Thus, mechanical recycling is commonly used in thermoplastic polymers to produce the raw materials to manufacture new products through the selection, washing, compaction, and palletization of plastic waste; however, after several cycles of recycling, the mechanical properties of the polymers can be altered to the point of losing practical applicability, and the reuse of material is limited depending on the initial type of application. For example, recycled food packaging should not be used in other applications for health reasons; the same is true for biomedical packages used to collect biological samples, etc. [112]. According to the foregoing, it is clear that there is an urgent need to develop and promote actions and legislation to ensure maximum environmental preservation [112]. However, it is clear that this required a high level of awareness on the part of humanity about its role in the environment, as well as a clear understanding of the vulnerability of everything that supports us as a species on a planet with finite resources. The concept of "green chemistry" has been successfully applied in a variety of industries, including automobile, cosmetic, energy, and pharmaceutical, to name a few [112]. And it is clear that its success in its foray into the industrial field is due to a confluence of factors such as the recognition of the possibility of extinction, the association of the adjective "environmentally friendly" as a positive characteristic of products, and a population increasingly identifying with the importance of preserving the environment. Furthermore, increasingly stringent regulations have an impact on the productive sectors. Thus, from a market and economic standpoint, "environmentally friendly" is unquestionably a commercial label for positive product promotion. Faced with the threat to our species' survival, the concept of green chemistry has undoubtedly served as a tool to stimulate governmental and private participation through the formation of pacts and alliances, educational initiatives, and research centers [113].

Conclusion

The application of green chemistry to the production of plastic/polymer products offers numerous advantages, including energy savings, reduced environmental impact, and improved product performance. Green chemistry is currently being used in the production of plastic packaging, conventional plastic products, and bioplastics, and is expected to be used in the production of advanced materials such as nanocomposites and biopolymer composites in the future. As green chemistry continues to evolve, it is likely that the application of green chemistry to the production of plastic/polymer products will become increasingly widespread.

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