Sustainability in polymeric materials: A review on basic concepts, socioeconomic challenges, and innovations in the field of nanotechnology

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ABSTRACT
This text was prepared collaboratively by the students of the undergraduate course in Nanotechnology at the Federal University of Rio de Janeiro (UFRJ), under the mediation and guidance of professors Lizandra Maurat and Ana Catarina Gomes, as part of the summative and formative evaluation processes of the discipline "Sustainability Applied to Polymeric Materials". The use of this active methodology intended to fix and summarize the topics covered in class, in addition to disseminating and discussing the theme, through an integrative review of fundamental concepts, socioeconomic challenges and advances related to the context. The growing need for research, study and basic knowledge of the physical chemistry of polymers was highlighted here, in order to conceive classifications and discussions in terms of sustainability, considering the complexity of the interactions between polymeric materials, society and the environment. This paper highlights the ecological and socioeconomic complications associated with these materials, as well as discusses emerging innovations in nanotechnology as potential solutions. It was possible, by integrating all the subjects, to link a comprehensive understanding of the topic, highlighting the importance of innovative approaches to overcome the challenges of the application and evaluation of polymeric materials, nanostructured or not.

Keywords: Sustainability, Polymers, Nanotechnology, Active Methodologies, Materials Science Teaching.

1 INTRODUCTION

1.1 POLYMERIC MATERIALS - INTRODUCTION, HISTORY & CLASSIFICATIONS

In 1823, Mackintosh, an English researcher, made an important discovery when he realized that rubber could be dissolved in coal naphtha. This solution allowed the use of rubber, after solvent evaporation, to coat fabrics and make them waterproof [1]. Between the years 1820 and 1824, Thomas Hancock pioneered the development of the first polymer blends, combining natural rubber with gutta-percha [2]. But the first registration of the term "polymeric" occurred between 1832 and 1833, with the Swedish-German chemist Jöns Jacob Berzelius, who attributed this classification to substances formed by repeated molecular units, in particular, compounds with high and multiple molecular weights.

However, the term "polymer" only became better known and began to be widely used after 1922. The word, chosen according to the structural characteristic of the material, is of Greek origin (*Polus+Groupers*) and means "many parts" [3, 4, 5]. Charles Goodyear's contribution, in 1839 in the United States, was fundamental. He found that natural rubber acquires elasticity when mixed with sulfur and subjected to heating, a process known as vulcanization. This discovery revolutionized the rubber industry, giving it desirable properties such as increased strength and durability [6]. Over the years, other significant milestones in the evolution of polymers stand out, starting in 1846 with the patent for gutta-percha insulated conductor cables. The emergence of plasticized cellulose nitrate by the Hyatt brothers in 1870-1872 and the development of the first inflatable tire by Dunlop in 1888 marked notable advances. The year 1907 witnessed the creation of Bakelite, the first thermosetting synthetic polymer, by Leo Baekeland. The 1920s, as already mentioned, brought fundamental concepts, such as Staudinger's proposal on polymer molecular chains. Subsequent discoveries included the synthesis of PVC in 1912, polyethylene in 1933, and nylon in 1934. Notable advances continued in the following decades, culminating in the discovery of stereospecific polymerization by Ziegler and Natta in 1954. Evolution persists, with the current emphasis on the development of new engineering materials through blending, compatibilization, and the creation of new polymers [7].

Professor Eloisa Biasotto Mano played a fundamental role in the history of Polymer Science and Technology in Brazil, dedicating her career to the pioneering development of this area in our country. His impact can be traced back to the early years of his academic training at the National School of Chemistry of the University of Brazil, where he graduated in Industrial Chemistry and Chemical Engineering. Professor Eloisa's entry into the field of polymers occurred in 1954, when she assumed the position of Chemist-Technologist at the Rubber and Plastics Laboratory of the National Institute of Technology. Recognizing the need to enhance her knowledge, she pursued training in Polymer Science at the University of Illinois, USA, under the guidance of the renowned Professor Carl S. Marvel. This international experience was crucial to enriching his understanding of polymers. Back in Brazil, Professor Eloisa, now Full Professor of Organic Chemistry, introduced polymerization practices in laboratory classes, arousing students' interest in the universe of plastics and rubbers. In 1968, he led the creation of the Polymers Group, which became the embryo of the Institute of Macromolecules of the Federal University of Rio de Janeiro (IMA), being a pioneering initiative in the country [8].

The IMA, conceived by Professor Eloisa, has become a multidisciplinary center of excellence in polymer studies, with researchers from different areas. His tireless effort to overcome financial and bureaucratic challenges resulted in the construction of the institute's building in 1978, marking the beginning of a new phase. In addition to consolidating the IMA as an international reference, Professor

Eloisa promoted international meetings, such as the IUPAC International Symposium on Macromolecules, and the Polymer Seminars (SEMPOL), strengthening ties between Brazilian and foreign researchers. His legacy also includes an impressive scientific production, with more than 200 published works, 6 invention patents and the supervision of more than fifty theses. His impact on polymer science has been recognized with national and international awards, culminating in the Grand Cross of the National Order of Scientific Merit awarded by President Fernando Henrique Cardoso in 2000. The Professor Eloisa Mano Award, created by the Brazilian Polymer Association in her honor, highlights the enduring legacy of this remarkable scientist and educator [8, 9].

Once the history of these materials is understood, it is possible to deepen the chemical-theoretical knowledge: polymers are macromolecules obtained by the addition or condensation of monomers - micromolecules of low molecular weight with the ability to react and unite with identical or similar molecules. Paraphrasing the late Professor Eloisa Mano, it is highlighted: "all polymers are macromolecules, but not all macromolecules are polymers". The union of one or more types of monomers (polymerization) results in long chains, formed by repetitive portions, covalently linked to each other, which are called "meros" - fundamental structural units of polymers. The number of associated groupers (degree of polymerization of the molecule) is quantified numerically as the polymeric molar mass, to which the most diverse physicochemical and mechanical properties are associated. These materials are popularly known as plastics, rubbers, and fibers. Resins are very viscous polymeric liquids, of intermediate molecular weight; and oligomers are very low molecular weight polymers [5, 10,11].

The distinguishing characteristics of polymers begin to manifest themselves in the order of 10^3 and become more noticeable as the molar mass increases, and can reach the order of millions. Most polymers used in industry have a molar mass in the tens or hundreds of thousands. In the literature, three main types of molar mass are commonly mentioned - the numerical mean (Mn), the ponderal mean (Mw) and the visvimetric mean (Mv). The discrepancies in the values of the average molecular weights, Mn, Mw and Mv, result from the processes used to obtain them, since they are influenced by the polymolecular nature of the polymers. Several methods are employed in the determination of molar mass. These include terminal group analysis, cryoscopy, ebullioscopy, vapor pressure osmometry, membrane osmometry, gel permeation chromatography, light scattering, ultracentrifugation, and viscometry. Each approach offers a unique perspective, exploring different properties and behaviors of the substance to provide an estimate of its molar mass [5].

The complex integration of information on chemical structure, properties, applications, and manufacturing conditions shows a range of possibilities for this type of material, justifying its extensive use and emphasizing the constant need for evolution and expansion of its study [5, 11].

Polymers can be obtained through different media and various precursor sources. They can be found in nature (such as elastin, collagen, proteins in general, polysaccharides and nucleic acids) or obtained in laboratories (such as polyethylene, polypropylene, polystyrene and polyurethanes), thus being divided into two major groups: natural or synthetic. Depending on the organisms involved in the synthesis or the raw materials used, they can also be distinguished into subgroups such as: fossil, vegetable, animal, bacterial, fungal polymers, etc. Listed below are some criteria and types of polymer classification [5, 11, 12, 13, 14 , 15].

a) origin
  - Natural Polymer
  - Synthetic Polymer
b) Number of Types of Monomers
  - Homopolymer
  - Copolymer (2 or more different types of groupers)
    - alternate
    - random
    - en bloc
    - Grafted
c) Chain Interaction Type
  - Linear Chain
  - Branched Chain
  - Cross-linked chain
  - cross-linked chain
d) Method of preparation
  - Addition polymer
  - Condensing Polymer
  - polymer obtained by modification
e) Chaining Type
  - head-tail polymer
  - Head-to-head polymer
  - Cauda-Cauda Polymer
f) Configuration of the atoms in the chain
  - CIS Polymer
  - polimero trans
g) Tactility of the chain
  - isotatic polymer

- Syndiostatic polymer
- Atative polymer

h) functional group present in the structure

- polyesters
- polyamides
- polyalcohols etc.

i) fusibility and/or solubility

- thermoplastic polymer (softening occurs by increasing temperature and solidification, through cooling, in a reversible procedure)
- thermoset polymer (they are not moldable, but degraded by the action of temperature)

j) Mechanical behavior

- Plastic (rigid or flexible)
- Elastomer (rubber)
- fiber (flexible, cylindrical body, with small cross-section and high aspect ratio; it is formed by linear, longitudinally oriented macromolecules and resists temperature variations between without a substantial change in mechanical properties)

k) degradability

- Biodegradable
- they do not degrade at an observable rate under environmental conditions.

Polymerization processes present the most diverse technical possibilities, in terms of materials and methods, which makes their variables responsible for the final properties of the polymeric material. The conditions for obtaining polymers are of great importance, not only with regard to the molecular characteristics, which interfere in their daily and industrial application, but also with regard to the peculiarities of the process of synthesis, processing and reuse or recycling, which reflect on the final destination, viability and socioeconomic competitiveness of the material [5, 11].

Generally speaking, polymer preparation methods vary in terms of reaction type or mechanism, formation of micromolecular byproducts, and chain growth velocity. Polyaddition is, as the name suggests, the direct union of monomers, forming covalently linked carbon chains, from 3 blocks of reactions (initiation, propagation and termination), which occur successively or simultaneously, without the formation of by-products. In this type of polymerization, the degree of polymerization and the reaction rate are high, with the immediate formation of polymers, as observed for polyethylene, polystyrene and polymethyl methacrylate. Condensation polymers differ from addition polymers in that they incorporate atoms of diverse elements, such as oxygen, nitrogen, sulfur, and phosphorus, into the main chain. In addition, polycondensation consists of a single reaction, but given in stages, in which there is no distinction between the beginning of polymer formation and macromolecular growth; The conversion is high, but the growth of the chain is slow and statistical, reaching a significant molecular weight after intercondensation of the smaller segments. The resulting molecular weight is usually an order of magnitude lower than that obtained in polyaddition. Examples of condensation polymers include polyethylene terephthalate - PET, polyvinyl acetate - PVAc and PA-6.6, polyhexamethylene-adipamide. In cases of aldehydic monomers or lactamas, polymerization occurs by the carbonyl or opening of the lactam ring, introducing heteroatoms into the chain, as in polyoxymethylene and polycaprolactam. Some polymers, such as polyurethanes, combine characteristics of both reactions. In addition, there are polymers (such as polyvinyl alcohol - PVAl) whose production is only possible through the modification of a pre-existing polymer (PVAc, in the case of PVAl), without a combination of monomers for its formation. And, in terms of polymerization techniques, there is the possibility of obtaining polymers in homogeneous medium (mass or solution polymerization) or heterogeneous (in slurry, suspension, emulsion or interfacial polymerization) [5, 7, 10, 16].

Although there are widely exploited industrial polymeric materials such as natural rubber, an excellent elastomer obtained by bleeding rubber tree latex, most of the polymers with sufficiently satisfactory properties to be commercialized on a large scale are produced from petroleum derivatives. Seeking a more sustainable way to obtain polymers, there are "green" alternatives to the use of fossil polymers - using modified or improved natural polymers (such as nanocomposites) or even adapting the route of obtaining a fossil polymer to make it less aggressive, with less toxic intermediates, using less energy or generating less waste for the environment [11, 17].

1.2 INDUSTRIAL & EVERYDAY POLYMERS

Due to the breadth of the concept of polymers and the varied properties they can possess, human society has sought them out and adapted to their presence. The application of materials to human development, in any area whatsoever, has been limited by a few classes of materials for most of human existence, until recently, with the production of human-made polymers altering the scales of what is possible and practicable. Nature offered polymers of use long before we started synthesizing anything, however. Disregarding the polymeric aspect of proteins and DNA itself, we still have starch, cellulose and natural rubber as polymers used by humans over the years to facilitate life. [1, 2, 4].

Our understanding of natural polymers was essential to a technological breakthrough. In the nineteenth century, vulcanized rubber allowed scientific achievements and advances in convenience and urban mobility. To this day, vulcanized rubber is one of the most common polymers in the routine of most human beings [1, 5, 6].

Looking at the human synthesis of polymers, their introduction into society has taken an accelerated momentum, with their presence becoming more and more pronounced as we approach the point of analysis of the current moment. The appearance of synthetic fibers in the textile industry was well marked by the successful application of Nylon®, producing clothes by the end of the 30s, and soon being absorbed in other areas, such as the military and industrial. This pattern of development followed by application in multiple areas is repeated over the decades for various polymers that are still used today [4, 18].

Modern life as it is understood by the majority of the global population is unthinkable if we remove the action of polymers on it, as their participation is denoted in the most important and diverse areas of application: packaging, automotive industry, electronics industry, health sector, civil construction, textile industry, aerospace sector, food industry, energy production and storage, recycling, sanitary engineering, among others. Some examples of the most commonly used polymers include polyethylene (PE), polypropylene (PP), polystyrene (PS), polyvinyl chloride (PVC), Teflon (PTFE), polyethylene terephthalate (PET) and nylon (polyamides in general) [2, 12, [19, 20, 21 , 22, 23].

1.3 POLYMER CHARACTERIZATION

Polymer analysis encompasses a diverse set of analytical techniques and methods employed to identify the physical, chemical, and mechanical properties of a specific material. Characterization involves the evaluation of several properties that delineate their structure, behavior, and applicability; and aims to evaluate these materials in relation to: chemical structure, viscosity, microstructure, color and opacity, thermal resistance and response, mechanical properties, average size and distribution - chain and particle, surface charge, morphology and surface, solubility in water, biological compatibility, degradability in various media, pharmacokinetic and pharmacodynamic evaluation, antimicrobial, antioxidant and gas and vapor barrier activity [[23, 24, 25, 26 , 27].

Molecular weight determination, or molar mass, can be performed by methods such as size exclusion chromatography (SEC or SEC/HPLC), mass spectrometry (MS) and viscosimetry, while particle size analysis is performed via SEC or dynamic light scattering (DLS). To identify the chemical composition and structure of polymers, which are crucial aspects for their properties, techniques such as carbon or hydrogen nuclear magnetic resonance (C13 or H1 NMR) and Fourier transform infrared spectroscopy (FTIR) are used. Morphology and surface analysis can be conducted using microscopy techniques, including scanning electron microscopy (SEM), transmission electron microscopy (TEM), and atomic force microscopy (AFM). Mechanical properties such as tensile strength, bending, hardness, and toughness are evaluated through specific tests, guided by the standards of the American Society for Testing and Materials (ASTM), while thermal properties are investigated by techniques such as thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC). The electrical or insulating performance is tested through the dielectric constant and dielectric resistivity. The rheological behavior, which highlights the response of the polymer to flow under tension, is analyzed by techniques such as capillary rheometry and Torke, Haake. Optical properties, such as light transmittance, reflection, and absorption, are evaluated using UV-vis spectroscopy and near-infrared absorption spectroscopy. In packaging applications, the ability to block gases and liquids is examined through permeability and diffusion techniques to characterize barrier properties. Analysis of crystal microstructure and surface chemical composition, relevant in adhesion and coating applications, is conducted using X-ray photoelectron spectroscopy (XPS) and X-ray diffraction (XRD) [28, 29, 30].

These approaches provide a thorough understanding of the properties of polymers, contributing to their effective application in a variety of areas. The characterization results from the combination of several of these techniques, depending on the specifications of the material with which one works, the time and apparatus available, as well as the proposed application and final destination, which, in turn, will delimit the specific properties that are desired to be obtained and that are, therefore, necessary to be evaluated. From this, it is possible to design the properties and behavior of the material under different conditions.

1.4 (BIO)DEGRADABILITY OF POLYMERS

Biodegradation is the organic conversion of polymer into biomass, water, carbon dioxide and other gases. Biodegradable polymers are a contribution to a sustainable future. Concern about environmental pollution and the negative impacts of plastic waste on our planet, especially in the oceans, has led to an increase in research and development of new materials. Biodegradable polymers are materials capable of being broken down by living microorganisms into natural by-products that are harmless to the environment. They are an alternative that has received prominence as an approach to reduce environmental problems associated with traditional polymers, which can persist in the environment and other living things for several years. Even synthetics are designed to meet the needs of consumers and industry while maintaining the desired properties, but with a shorter life cycle, being more environmentally friendly. There are several classes of biodegradable polymers, which can be obtained from renewable sources, such as starch, cellulose, proteins, PLA and PHA, or from non-renewable sources, such as synthetic polymers designed or modified to be biodegradable [12, 14, 15, 17, 31].

The biodegradability of a material is influenced by several factors, including its chemical structure, the environment to which it is subjected, and the conditions of the microbiota around it. Biodegradable polymeric materials degrade faster under specific conditions of humidity, temperature, pH, and the presence and amount of certain gases, metals, and microorganisms. Thus, biodegradable polymers end up becoming more suitable for applications in which their final disposal occurs in natural environments, which is the case of various bags and packaging, especially food [32, 33, 34].

Taking into account the information presented, it is important to emphasize that biodegradable polymers cannot be listed as the solution to all problems related to "plastics", because biodegradation depends on a number of factors, such as the polymeric structure required (such as aliphatic chains with tertiary carbon, unsaturation between carbons and hydrolyzable functional groups - ester bond, amide, acetal), maintenance of balance in the composting ecosystem, the availability of suitable microorganisms and the condition of the polymer in question. In some cases, biodegradation may not occur, with the obstruction of the process in the initial fragmentation stage, resulting in the formation of microplastics, which can have severe environmental impacts, with damage of unknown size [35, 36, 37, 38, 39 , 40].

The most important thing when it comes to this topic is to educate consumers about the benefits and limitations of biodegradable polymers, so that the possibility of degradation is not lost or this concept is confused with that of recyclability, which does not imply biodegradability or vice versa. Recycling, on the other hand, consists of transforming discarded materials into new products or raw materials. Awareness is key to preventing materials from being wrongly disposed of, contaminating recycling and composting systems, while they should be properly disposed of at the end of their useful life, reducing waste, saving natural resources, and minimizing socioeconomic and environmental impacts [35 - 40].

It is worth mentioning market factors that hinder or even make polymeric biodegradation difficult or even impossible: soiling with impermeable or toxic materials, the presence of other polymers with a non-degradable chain in the matrix and the insertion of additives in its composition, such as vulcanizing agent, accelerator, catalyst, activator, antioxidant, filler (reinforcing or inert), plasticizer, stabilizer, dye, lubricant, etc. curing agent or sponge agent [12, 15, 39].

As the demand for sustainable solutions for single-use polymeric materials (such as masks, cups, straws, cutlery, plates) grows, there are continuous advancements in research and industry that make biodegradable polymers play a significant role in reducing the environmental impact caused by plastic materials. However, the most effective approach to polymer-related environmental challenges is a combination of reducing the rampant use of disposables, effective recycling, and ultimately responsible adoption of biodegradable polymers where possible and appropriate. Biodegradability represents a step towards a more sustainable future, but it requires a collective commitment from society, industry and governments, to ensure that costs are affordable for all and thus social and environmental benefits are achieved and maintained.

The evaluation of polymeric degradation can be conducted by monitoring the growth of microorganisms, following the consumption of the substrate, gauging the consumption of O2 and the release of CO2, observing and measuring the changes in properties (physical/chemical/structural) or even employing mathematical modeling to make predictions that contribute to the study of degradation kinetics [12, 35, 40].

1.5 POLYMER RECYCLABILITY

Given the global increase in the improper disposal of polymers, especially plastics, recycling emerges as another promising way to address this problem. However, it is imperative to recognize that the conventional recycling process, adopted on a large scale, proves to be ineffective. Even when implemented at a scale below its maximum capacity, it faces significant challenges in the economic and logistical spheres, highlighting the pressing need for more robust and comprehensive strategies [38, 41].

The recyclability of a polymer is determined by the possibility and ease with which it can be reintroduced into the processing cycle, either with simple thermomechanical changes (formation of pellets and the like for new production), with the reuse of the chemical structure, with the reacquisition of a valuable product used in the polymer, or simply with the recovery of part of the energy spent to achieve the final product [18, 36, 38].

In general, fusibility is the crucial factor for the thermomechanical recyclability of a polymer. Thermoplastics, for example, can be thermally remodeled without significant loss of properties, making it possible to reuse them. The difficulties of thermo-mechanical recycling tend to be the industrial additives that compromise the process and prevent the use of a polymer in an application that requires higher purity; as well as the misuse or sloppiness in the disposal of the material (with lack of cleaning or incorrect direction), adding impurities and affecting the entire process. An additional obstacle in polymer recycling is the establishment of a well-defined upper limit for the amount of recycled material allowed in certain products. In some cases, the use of recycled material is even prohibited due to the specific nature of some articles made with polymers (such as in hospital materials), which imposes significant restrictions in certain areas [42, 43, 44].

Other forms of recycling, however, rely on the use of parts (monomers, additives, raw materials), rather than considering the final chemical structure of the polymer. Among these, chemical recycling seeks to transform polymers into basic production materials, generally for a subsequent polymeric synthesis, or for the reacquisition of other products (usually petrochemicals). The determining factor of this process comes from the vulnerability of the polymer to the most common techniques, such as hydrolysis [41, 45, 46].

Energy recycling of polymers involves the controlled burning of plastic waste to generate heat or electricity. This process includes collecting, sorting, and pre-treating the plastics before burning or pyrolysis, where thermal decomposition occurs. The heat generated is then used to produce steam, which powers turbines to generate electricity. Although it is an alternative to plastics that are difficult to recycle mechanically, energy recycling faces criticism due to the possible emission of pollutants, highlighting the importance of emission control technologies. This approach is seen as secondary, and it is preferable to prioritize reducing the use of plastics and promoting more sustainable recycling methods [47, 48, 49].

1.6 POLYMERS - HEALTH & TOXICITY

The duality of polymers is evident, since these materials are frequently mentioned in the scientific literature and in the mass media, sometimes as executioners, sometimes as the ideal artifice for various purposes. When disposed of quickly and improperly, polymers can accumulate, persist in nature for many years, generate microplastics, disperse, or even become carriers of toxic agents, contributing to environmental pollution and posing threats to human health and biodiversity. However, this same class of materials exhibits remarkable potential when applied responsibly - they are increasingly used as a matrix for food packaging, cosmetics, and biocompatible bases for implants, prostheses, medicines, contact lenses, dressings, sutures, utensils for clinical management (tweezers, pouches, masks, gloves, drains, *etc*) and diagnostic devices. Their versatility in terms of properties make them fundamental in the creation of increasingly innovative and efficient products [2, 4, 5, 27, 34, 35, 37, 50].

In today's landscape of urban populations, efficient time management is crucial, driving the steady growth of the market for ready-to-eat products with single-use packaging. Strict sanitary standards in some areas, such as food and health, for example, favor the adoption of single-use plastics that minimize risks to the consumer. Despite some unfavorable aspects, polymers emerge as a very advantageous and versatile economic solution, justifying their wide use, especially in single-use disposable products or limited reuse. The polymers in this group are classified as *commodities* - such as low-density polyethylene (LDPE), high-density polyethylene (HDPE), polypropylene (PP), polystyrene (PS) and polyethylene terephthalate (PET). Manufactured on a large scale, with low individual added value, but high socioeconomic importance since they are consumed in significant quantities; Commodities are intended for generic uses, without lacking high technology or advanced and distinctive properties [4, 5, 51, 52, 53].

The prevalence of polymers in the form of bags, films and containers based on mixtures, blends and composites for food transport, handling and storage raises investigations on the migration of compounds to food, with emphasis on the study of microplastics, monomers and oligomers that can detach from the packaging structure and interact with its content and the environment. Global regulatory authorities such as the Food and Drug Administration (FDA) in the United States, the European Medicines Agency (EMA) in the European Union, the National Health Surveillance Agency (ANVISA) in Brazil, and the National Administration of Drugs, Food and Medical Technology (ANMAT) in Argentina, set migration limits to ensure safety in this context. Still, punctual and extreme conditions of temperature, pH, and humidity can lead to accelerated fragmentation and degradation of polymers, impacting the environment and human health more directly. The release of toxic substances can also occur in certain circumstances, such as during the burning of plastics, resulting in emissions of gases that are harmful to fauna and flora. In addition, when plastic degradation leads to the formation of microparticles and nanoparticles that are ingested by living organisms, this issue represents a major environmental and public health challenge. Widely used polymers, such as polyethylene and polypropylene, exhibit low intrinsic toxicity when isolated and not subjected to extreme heat, but the presence of dyes, fillers, and monomer residues can introduce fatal elements into their risk equation, especially when the mode of use and disposal are not properly managed [18, 35, 51, 52].

It is understood, therefore, that the possible toxicity of polymer-based materials is influenced not only by the composition of the matrix and the additives used during manufacturing. The assessment of the risk intrinsic to each material and the prediction of the possible risks associated with its use also depends on the specific application conditions - such as time, mode and intensity of use - in addition to the disposal environment. Namely, plastic products such as baby bottles, toys, bottles, and even food can coatings based on polycarbonates and epoxy resins present a primary risk related to their improper use and disposal (mainly involving burning or exposure to radiation and excessive heat). The release of substances used as plasticizers or intermediates in the production of artifacts, such as phthalates (BBPs) and bisphenol A (BPA) is a dilemma since these represent potential endocrine disruptors, also related to obesity, asthma, type II diabetes, cardiovascular diseases, and have been associated with adverse effects on the reproductive health of adults and impacts on the neurological and behavioral development of children and adolescents (such as attention deficit, hyperactivity and disorders within the autism spectrum), posing risks to both human health and the environment, especially marine beings [54, 55, 56].

Therefore, while most other *commodity* polymers are considered inert (i.e., they do not react spontaneously with a range of everyday materials) and even the ingestion of microplastics can be considered harmless, this relative inertia definitely does not imply the total absence of possible unwanted effects, especially after the improper disposal of plastic waste into complex ecosystems such as rivers, lakes, oceans, and landfills. In addition, environmental pollution from the dispersion and accumulation of tons of plastic waste is increasingly becoming a global concern, with potential negative impacts on aquatic and terrestrial ecosystems. Polymers from a biological synthesis or from a natural and renewable source are a more viable option when thinking about sustainability and possible toxicity. However, its mechanical properties and high cost often lead to technical and economic unfeasibility. Thus, it is necessary to rethink and balance their use in everyday life, considering the reconciliation of good management of *commodity* polymers, reuse and recycling, because even though many biopolymers and biodegradable polymers seem to present a lower risk to ecosystems, if their management and disposal are not done correctly, their degradation is affected (or even impossible) and there can still be human and environmental contamination. especially due to the other components added in its formulation [12, 18, 36, 38, 57].

Thus, although many studies are underway to understand globally and specifically the impacts associated with polymers, it is evident that the topic is dynamic and subject to constant revisions. Continued research and implementation of effective regulations are crucial to minimize the risks and harms associated with these materials. Proper management of polymers, from their production to their disposal, is crucial to mitigate their possible negative impacts and optimize their beneficial applications, seeking a sustainable balance between the benefits and challenges associated with these materials.

1.7 SOCIAL IMPLICATIONS AND ECONOMIC ASPECTS AROUND "PLASTIC"

The presence of plastic materials in human society has reached a very high level in recent years and is already significantly altering the way society and the economy develop. The consumerist cultural model currently disseminated is constantly related to the massive global production of waste, resulting from the continuous search for the consumption of futile and rapidly obsolete objects, causing a serious and accelerated loss of natural resources, in addition to the accumulation of garbage, especially of a polymeric nature, in inappropriate places. This indicates that, despite the role of plastic waste in the environmental problem, the cultural aspect is the main motivator for this reality, associated with the excessive and unnecessary application of packaging and other disposables [38, 58, 59].

Plastic lifecycle management requires a comprehensive approach that encompasses education and awareness. Society needs to understand not only the negative impacts of rampant plastic use, but also the importance of responsible disposal and recycling. And governments play a crucial role in implementing public policies aimed at this issue. Educational programs and campaigns are vital to promote awareness from childhood, emphasizing the need for reduced consumption, proper disposal practices, and valuing recycling as an effective means of reducing the environmental footprint. In addition, governments have a role to establish more effective regulations and incentives, which in fact favor sustainable business practices and the promotion of extended producer responsibility [18, 36, 59, 60].

In general, world leaders have been escaping the discourse that blames the action of consumers for companies and have been seeking to impose greater action and responsibility on them, with the proposal of applying reverse logistics so that, armed with the knowledge of processing their materials, they can properly dispose of the products, through the application of a domestic return network. Such policies do not exempt society from the need for greater education on the subject, because regardless of the quality of the reverse logistics network, the active cooperation of the population will always be necessary [59, 60, 61].

The work of garbage collectors in developing countries reveals a situation of social disparity that stimulates informal recycling work, mitigating the impacts of plastic waste, since it not only redirects the material, leading it to the recycling chain to which it should have already been inserted, but also transforms it into a source of income and subsidy for less affluent people. Currently, many countries have been seeking to organize and refine the actions of these individuals, in order to provide them with better living conditions and so that they can make an even greater positive impact on the issue of the absorption of reusable resources unfortunately trivialized as common waste [36, 38, 42].

The global recycling rate of plastics reached levels of less than 10% in 2022, highlighting the need for additional efforts to promote sustainable practices and reduce the environmental impact of improper disposal. An increase in the total volume of recycled material in the current socio-economic conditions, however, has its strength reduced by the reality of the cost-benefit of recycling. In most industries that use a base material that can be replaced by recycled material, the difference in acquisition costs and process adequacy does not tend to be significant enough for the transition to be seen as favorable. Thus, the socioeconomic weight of polymers does not allow recycling to be consolidated as a viable alternative in a comprehensive way, in addition to recycling on a domestic scale. The challenge lies in the need to develop economic strategies that make the adoption of recycled material more attractive to large industries, promoting the reduction of environmental impacts without compromising efficiency and competitiveness in the market. Therefore, it is imperative to invest in research and innovation aimed not only at improving recycling technologies, in order to reduce associated costs, aligning environmental benefits with economic demands, and thus enabling an effective transition to more sustainable practices [36, 47, 49, 60, 62, 63, 64].

The development of biodegradable plastic materials, nanosized particles and composites based on nanotechnology represents a promising frontier in the biomedical, textile, electronics, food safety and everyday products in general, seeking multifaceted alternatives, with more effective and ecologically friendly applications compared to conventional polymers. However, the cost associated with these materials with innovation and a higher degree of aggregate technology is still a challenge, hindering their large-scale adoption and sometimes making them inaccessible to certain sectors of the population until their sale is cheaper[12, 15, 32, 33, 34, 65, 66, 67].

From a social point of view, the poorest communities in particular face challenges related to polymers with greater gravity, such as the lack of access to advanced resources for public health and food security; and environmental pollution resulting from the inappropriate use and disposal of already popularized materials, which are deposited in dumps and landfills, most of the time strategically positioned in suburbs and marginalized areas. Homeless people and the poorest individuals are the most affected by health issues related to the plastic sector - diseases arising from the accumulation of garbage and lack of access to basic plastic materials (clothes, masks, sanitary pads, diapers, disposable dishes, *etc*.), especially living in precarious conditions of basic sanitation. Therefore, the implementation of public policies that encourage sustainable practices, as well as the creation of infrastructure for the popularization of basic and advanced plastic materials, selective collection, and recycling, are key to addressing these social issues [37, 44, 52, 59, 61].

In short, the issue of plastic involves a complex interconnection between economic, social and environmental factors. The search for effective solutions requires a holistic approach, integrating technological innovations, education, and public policies that aim at a balance between social well-being, economic development, and environmental preservation.

1.8 STANDARDS AND CERTIFICATIONS IN "GREENER" POLYMERS

The definition of "green polymer" is not taken as a consensus, but in general, a material is termed "green" comparatively - when it is considered more sustainable than an analogous material, in relation to one or more aspects - raw materials, adjuvants used in synthesis and processing, energy expenditure associated with production, recycling or degradability [68]. Therefore, even if a polymer is today named "green" by an author, it is still liable to generate waste and pollution throughout its entire life cycle and can probably still be optimized.

Biodegradable polymers can be considered green because they do not persist in nature; ideally, they are broken down by living beings, reducing them to simpler substances, such as water, carbon dioxide and biomass, which are reintegrated into the environment. The adhesion, blending, and gradual transition to biodegradable polymers raises challenges in terms of regulation and standardization. Establishing consistent standards is essential to ensure that biodegradable polymers meet expectations regarding their application, degradation, and safety [12, 15, 32, 68].

The technical standards of the Brazilian Association of Technical Standards (ABNT) evolve and adapt over time. In addition, local standards can be developed to complement national rules and meet specific environmental and industrial needs. However, among the current standards related to sustainability in polymers, applied in the national territory, the following stand out:

a) ISO 14001: defines the requirements for environmental management systems and can be applied to companies that produce sustainable polymers.
b) ABNT NBR ISO 14044: deals with the assessment of the life cycle of products, including polymers, to assess their environmental impact.
c) ABNT NBR 15575: specifies the requirements for the performance of residential buildings and may be relevant for the construction of buildings that incorporate sustainable polymeric materials.
d) ABNT NBR 15448: defines the requirements for the environmental labeling of products, which may be relevant for sustainable polymers that wish to obtain eco-label certifications.

e) ABNT NBR 16173: establishes guidelines for the management of social responsibility in organizations and can be applied to companies that produce sustainable polymers.

The international standard generically used to evaluate the biodegradability of various products and materials is ISO 14855, also known as "Determination of the ultimate aerobic biodegradability of plastic materials in an aqueous medium - Method by analysis of evolved carbon dioxide." This standard specifies methods for evaluating the aerobic biodegradability of plastic materials in aqueous media. It addresses procedures for determining the amount of carbon dioxide released during the biodegradation of samples under controlled conditions. There is not yet a single, unanimously accepted international guideline exclusively for biodegradable polymers and their final products. Entrepreneurs and authors of polymeric studies and innovations use biodegradability standards according to their context and needs, selecting specific points or combining topics of greater relevance from several standards in order to fully address all the necessary aspects of the topic. The following are some of the most relevant international standards and certifications:

f) EN 13432 (Europe) - sets out the requirements for compostable and biodegradable packaging. It defines criteria for the biodegradation, disintegration, compost quality, and environmental impact of compostable products.

g) ASTM D6400 and ASTM D6868 (United States) - address the requirements for biodegradable and compostable plastic products.

h) ISO 17088 - provides guidelines for the determination of the biodegradability and disintegration of polymers under controlled composting conditions.

i) OKCompost certification (awarded by TÜV Austria) - indicates the compostability of products and packaging, including biodegradable polymers.

j) Seedling certification (granted by Din Certco) - indicates that a product is compostable according to EN 13432.

Notable examples of green polymers include PLA (poly(lactic acid)), obtained from corn starch or sugarcane, which is biodegradable and commonly used in packaging and disposable products. PHAs (polyhydroxyalkanoates), produced by bacteria through the fermentation of sugars, are fully biodegradable and find application in a variety of plastic products. PBS (Polybutyric Acid) is another biodegradable green polymer, often sourced from renewable sources such as sugarcane and used in packaging. PEF (Polyethylene Furanoate), derived from plant biomass, is considered a more sustainable alternative to PET and used in beverage packaging. These examples represent the diversity of green polymers that seek to reduce the environmental footprint of the traditional polymer industry [12, [15, 32, 68]].

1.9 LIFE CYCLE ANALYSIS OF POLYMERS

The life cycle shows the stages that the product or material goes through throughout its process, from obtaining the raw material to its production, final application and disposal, evaluating the impact that each phase has and making it possible to evaluate and make decisions about sustainability related to that product [69].

Life Cycle Analysis (LCA) emerges as a fundamental tool in the evaluation of polymers, standing out as a systematic approach to measure environmental impacts throughout all phases of a product's life cycle. In the context of polymers, which play an essential role in modern industry, LCA offers a holistic perspective, from the extraction of raw materials to the final disposal of the product, taking into account factors such as quantitative and energy demand, source of production, biodegradability and recyclability. This comprehensive approach allows the identification of critical points in the polymer life cycle, contributing to process optimization and the reduction of environmental impacts [60, 69].

The LCA process comprises four key steps. In the first stage - definition of objectives and scope - the purposes of the analysis are established, outlining the extent of the study and identifying the limits of the system, as well as the main functions of the product under analysis. Next, the life cycle inventory stage involves a thorough compilation of all inputs and emissions associated with the product life cycle. This phase encompasses the collection of data related to raw materials, energy, transportation, and industrial processes, providing a comprehensive view of the system's inputs and outputs. The third stage, environmental impact assessment, translates inventory data into environmental impacts, considering several categories, such as natural resource consumption, greenhouse gas emissions, and air and water pollution. The use of mathematical models and specific indicators helps to quantify these impacts. Finally, the results interpretation stage aims to analyze the results in light of the defined objectives and scope, highlighting critical areas and identifying opportunities for improvement. This interpretation guides decision-making aimed at mitigating environmental impacts throughout the product's life cycle, contributing to more sustainable practices [60, 62, 63, 69].

The LCA of polymers therefore considers important aspects such as the energy embodied in the different stages of production, greenhouse gas emissions, the generation of solid and liquid waste, as well as other relevant environmental indicators. The comparison between different polymers through LCA provides a solid basis for sustainable decision-making in the selection and development of these materials, considering not only the physical and mechanical properties, but also the associated impacts. This proactive approach is essential in the search for solutions that minimize the environmental footprint of polymer production, promoting the transition to more sustainable practices [62, 69].

However, persistent challenges in polymer LCA include the complexity of global supply chains and the variation in production practices between different regions. In addition, the incorporation of social factors in the evaluation is still an area under development, aiming at a more complete view of the sustainability of polymers. Overcoming these challenges requires collaboration between industry, researchers, and policymakers to develop guidelines and standards that promote robust and equitable LCA for polymers [60, 62, 63, 69].

1.10 CHALLENGES IN THE USE OF POLYMERS

The use of polymers is a great challenge, as it is necessary to evaluate the entire production process in order to always aim for better efficiency with low environmental impact, as well as an awareness for the people who use them [60, 63].

For better efficiency, evaluating and improving stages of your production process is essential, as it is possible to minimize effects such as waste, use of toxic components, reduce energy expenditure and greenhouse gas emissions and thus mitigate the environmental impact associated with these practices. And all this becomes possible with studies on technologies and process optimization, developing more sustainable ways for their production or even in relation to their raw material, finding more eco-efficient alternatives [60, 63, 69].

Although the improvement of processes is a big step that we are getting closer to the path of sustainability, just optimizing production and disposal in an industrial way is not enough, it is also necessary to make people aware as a whole that it is necessary to have better environmental education. Promoting practices such as responsible use, correct disposal, conscious consumption and reuse makes it more possible to make the life cycle of this material more sustainable [70].

The combination of this process optimization, the awareness of a better use for this material and the implementation of the necessary recycling infrastructure is an extremely important step to deal with the challenges in the use of polymers. Collaboration between these pillars becomes essential to significantly change usage practices, making them more sustainable and ensuring human and environmental preservation.

In addition, nanotechnology is also emerging as a promising tool to drive sustainability in the field of polymers. By adding particles at nanometer scales, it is possible to achieve controlled modification of the properties of polymers, giving them improved performance and sustainability characteristics. The use of nanoparticles in polymers can improve their mechanical strength, durability, and even make them lighter, thereby reducing resource consumption. In addition, nanotechnology offers opportunities for the creation of more efficient biodegradable polymers, contributing to mitigating the problem of persistent plastic waste. The ability to develop more energy- and resource-efficient nanomaterials opens doors to more sustainable production processes while enhancing the properties of polymers, providing innovative and environmentally friendly solutions to the challenges faced by the polymer industry [50, 52, 65, 67, 71].

1.11 CIRCULAR ECONOMY AND POLYMERIC MATERIALS

In times of social changes in the search for sustainability, the concept of circular economy has been employed as a way to assist in the issues of polymeric materials. The term circular economy is usually attributed to Pearce and Turner (1990), in a publication where they expose the idea of an economic model that challenges the current linear model, one that takes concepts of conservation of physics and seeks to apply them in the socioeconomic sphere, so that, in short, circular economy is a system in which each end of the process is the beginning of a next process. extending the application of what is produced to the maximum possible, integrating acts and social awareness for the maintenance of the system, thus reducing the exploitation of natural resources and the volume of waste [37, 44].

When we bring the scope of the concept to polymeric materials, the challenges already exposed regarding environmental education are again relevant, considering the need for adequate socio-environmental integration and proper disposal. And, even if the social issue were properly applied, there is a need to create adequate processes and materials for the maintenance of this type of model. This need has been addressed with a new way of thinking about the polymer research and development process. With their *design* being done with the circular economy in mind, advances such as the production of virgin polymers from renewable or recyclable materials coordinate with the preference for energy with a lower carbon footprint, as well as the possibility of reinserting the product into the economic cycle with recycling [37, 38, 61].

Other approaches to the issue try to alter the production processes already known for the acquisition of sustainable qualities to the final product, such as the proposal for catalytic alteration of polyethylene that seeks to maintain its mechanical properties as much as possible, but allow an easier degradation to monomers. In the face of these innovations, it is hoped that polymers in general will be adequately reimagined, or that their techniques of use, recycling, processing, use and disposal will be renewed to compose an eventual sustainable condition [32, 40, 72].

1.12 NANOTECHNOLOGICAL INNOVATIONS FOR SUSTAINABLE DEVELOPMENT

As already mentioned, nanotechnology can provide great advances to help preserve the environment, bypassing several challenges in the use of polymers. The following are some of the main potential benefits of nanotechnology for sustainable development [22, 23, 24, 25, 50, 52, 65, 67, 73, 74]:

a) Prevention of pollution or indirect damage to the environment: catalytic nanomaterials can be used to increase efficiency and selectivity in industrial processes, which results in greater use of raw materials, lower energy consumption and less waste.

b) Treatment of pollutants: due to their large surface area, nanoparticles have adsorption properties of metals and organic substances. Therefore, these particles can be used to remove such substances. Redox or semiconductor properties can be used in the treatment of water and industrial effluents, based on the chemical or photochemical degradation property of organic pollutants.

c) Pollutant detection and monitoring: Nanosensors are more selective and more sensitive for the detection and monitoring of organic and inorganic pollutants in the environment. These advances provide better control of industrial processes and earlier and more accurate detection of contamination in the environment, in food and other products for human use.

d) Use of nanocomposites: the creation of nanocomposites is used to modify characteristics of existing materials, for example, incorporating fillers to increase the stiffness and strength of biodegradable polymers, opening the possibility for these to be used in place of conventional polymers.

Careful consideration of the use of nanomaterials, in accordance with the principles of nanotoxicology, is imperative to ensure that the benefits of nanotechnology are not compromised by potential risks to human health and the environment. Nanotoxicology is a discipline that investigates the adverse effects of nanomaterials, and in this context, their application in polymers requires a cautious approach. When using nanocomposites in polymers for various applications, it is crucial to evaluate the potential toxic effects that nanoparticles may have. Nano-sized particles have unique characteristics that can influence their interaction with biological systems, raising concerns about potential impacts on health and the environment. Therefore, it is essential to carry out specific nanotoxicity studies for nanomaterials incorporated into polymers, considering aspects such as size, shape, chemical composition, and solubility [71, 75, 76].

Nanotoxicology research provides valuable insights into the mechanisms of interaction between nanomaterials and living organisms, enabling the development of risk mitigation strategies. Potential toxicity should be carefully assessed, with the underlying mechanisms clarified. To this end, different approaches can be used. Firstly, experimental toxicology, which consists of conducting in vitro or in vivo experiments (including clinical studies). However, the respective advantages and limitations of in vitro and in vivo models are discussed, as well as some issues associated with experimental nanotoxicology. Perspectives for future developments in the field are also proposed. Secondly, computational nanotoxicology can be used to predict the toxicity of nanomaterials. Establishing stringent regulatory guidelines and safety standards is critical to ensure the safe application of nanotechnology in polymers. Thus, careful consideration of the use of nanomaterials, coupled with a proactive approach in identifying and mitigating potential risks, is essential to promote the safe and sustainable advancement of nanotechnology in the field of polymers [71, 75, 76, 77].

2 FINAL THOUGHTS

The present review addresses a wide range of topics related to sustainability in polymer materials, highlighting key concepts, socio-economic challenges, and notable contributions in the field of nanotechnology. By exploring the history and classifications of polymeric materials, the crucial role of these materials in our society, both in the industry and in our daily lives, became evident. Considerations on polymer biodegradability and recyclability underscored the importance of sustainable approaches to address the environmental impacts of plastic.

The social and economic implications surrounding the use of plastic have highlighted the need for a holistic approach, which includes education, awareness, and public policy to promote more sustainable practices. The discussion on standards and certifications in more sustainable polymers emphasized the role of regulations in guiding more environmentally friendly solutions. The discussion on life cycle analysis provided a comprehensive understanding of the environmental impacts throughout the life cycle of polymers, underscoring the importance of informed decisions and waste management strategies. The challenges in the use of polymers have been recognized, encouraging the continued search for more sustainable alternatives.

When addressing the circular economy and its relationship with polymeric materials, it became clear that the transition to circular practices is essential to reduce dependence on non-renewable resources. Finally, nanotechnological innovations have been highlighted as promising catalysts for sustainable development, providing significant advances in the efficiency and properties of polymeric materials.

It is highlighted that the application of nanotechnology in polymers plays a crucial role in water and wastewater treatment, offering innovative solutions to optimize process efficiency. The creation of nanocomposites, resulting from the incorporation of nanoparticles into polymeric matrices, emerges as a promising approach to reduce the demand for materials, minimize costs and modulate general properties, including those related to the degradation of these materials. The presence of nanoparticles in polymers used in water treatment systems can improve the adsorption of contaminants, increasing the efficiency in the removal of pollutants and contributing to more effective purification processes. In addition, the mechanical strength and durability of polymers are improved, extending the life of materials used in water treatment equipment and wastewater management systems. Thus, the synergy between nanotechnology and polymers opens up innovative perspectives to address environmental challenges, promoting more sustainable and efficient practices in the treatment of water resources.

And, in a global landscape that demands environmentally conscious solutions, the convergence of historical knowledge, stringent regulations, technological innovations, and societal efforts is imperative to shape a more sustainable future for polymer materials.

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