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Review article

A brief review of optical polymers in material engineering

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Abstract. Recently, there has been growing interest in materials that combine the advantages of glass and polymer materials. Such a combination results in a kind of hybrid glass-polymer optics that meets the requirements for high-quality imaging in various environmental conditions. So far, the literature on these materials is quite scarce. This article is an attempt to review the most important reports on the topic of available polymers with optical properties, dividing them into groups, *i.e.* synthetic optical polymers (including polymethylmethacrylate, polyethylene terephthalate, polypropylene, cyclic olefin copolymers and polyolefin elastomers) and biopolymers (including polylactide and gelatin). A separate place and chapter is given to transparent CR-39 plastic and the issue of individual dosimetry for radon detection. Moreover, testing methods for measuring the most important optical properties of polymers and their major applications are briefly discussed.

Keywords: *polymer material, optical devices, properties of polymer optics, optical applications of polymers*

1. Introduction

Polymers have now become widely used in optics, electro-optics and photonics. Articles discussing the latest research in this field and/or reviewing the state of research in selected areas are sought. A rich review of the literature on a wide range of polymeric materials and their various properties indicates that research usually focuses on various other polymer properties. Therefore, one of the lesser-known classes of polymers is optical polymers, although they have found many applications in a variety of advanced optical components in the medical, defense, communications and aerospace industries [1–3].

Like many polymer classes, the field of optical polymers encompasses many different materials, but all materials in this category exhibit glass-like properties. Typically, optical polymers are divided into two distinct classes, namely those made from thermosetting resins and those made from thermoplastic resins. As with any polymer, its specific and tailored properties are crucial for each application. They can be manipulated, and so, for example, in terms of optical applications, customization and optimization usually is carried out in terms of density, hardness, stiffness, operating temperature, outgassing, conductivity, as well as water and radiation resistance.

Nevertheless, optical polymers pose several design challenges. These relate to low thermal stability, a limited range of refractive index values and stress birefringence. The combination of polymer and glass materials in hybrid optical devices overcomes these disadvantages. Then, each of the hybrid components fulfills its role, ensuring a measurable effect thanks to its typical characteristics. Taking advantage of the natural quality and formability of plastics, the polymer material is used to recreate unique geometric surfaces in a hybrid combination. It is usually used as a layer on glass. On the other hand, the glass elements in this hybrid combination transmit the optical power. As a result, such systems then combine low

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production costs, a wide thermal range, and better correction of aberrations [4].

In order to realize the possibility of replacing glass in optical devices with a range of polymers or their use in hybrid components, knowledge of their optical properties is required. In particular, to enable the use of polymers in high-precision optics, it is necessary to compare their refractive and dispersive properties with glass. Characterization of optical polymers and comparison of their properties to glasses is usually carried out on the basis of measured refractometric data at a number of wavelengths, transmission spectra and investigation of many dispersive characteristics in the visible (VIS) and near-infrared (NIR) spectra.

For example, the work of Sultanova and colleagues [5] illuminates the issue. The authors examined more than twenty types of optical plastics, including basic, commercial and some newly developed materials, such as polymethyl methacrylate (PMMA), polystyrene (PS), polycarbonate (PC), styrene acrylonitrile (SAN), polyacrylate films or cellulose, just to name a few. The results were compared with catalog data for some analogous types of Schott glass to illustrate the possibility of replacing glass in optical devices with a range of polymers or their use in hybrid components. Thus, a comparison to optical glasses revealed a much narrower range of polymer refractive index values. This fact limits the choice of material in the design and fabrication of all-plastic optical components but can be compensated by using aspherical or other complex geometric surfaces of the optical elements [5].

As a result of the cited studies, a more detailed investigation of the analyzed optical polymer dispersion was also established. Optical polymers differ completely in structure compared to glasses, which determines the interaction of light with matter and, in particular, the specific refractive and absorption properties of the medium. The analysis conducted in the course of the study confirmed that optical plastics are materials with higher dispersion than glasses under the VIS light. However, dispersion generally depends on the type of polymer. For example, acrylic materials had similar normalized curves to glasses. In the NIR region, all materials tested showed lower dispersion compared to VIS [5]. There are some optical plastics, such as acrylic polymers, that are less dispersive than glasses in this part of the spectrum. According to the authors, these plastics appear to be the most suitable materials for night vision applications. Among the polymers tested, samples of polystyrene (PS) and polycarbonate (PC) showed the greatest dispersion throughout the spectral region studied and the cellulose sample turned out to be characterized by the lowest value of the refractive index and the most smoothly falling slope of the dispersion curve with the wavelength [5, 6].

The differences in the dispersion properties of optical polymers compared to glasses, described in the cited papers, confirm theoretical considerations. According to the well-known Kramers-Kronig relationship [7, 8], the refractive index and extinction coefficient are closely related. Both the IR and UV absorption bands of optical materials contribute to the refractive index of visible light. According to Smith *et al.* [9], IR resonance frequencies have less influence on refraction in VIS and are important in the NIR region. If the UV absorption band of a material is shifted toward shorter wavelengths, the dispersion of materials in visible light is lower. In optical materials with high refraction, the UV edge of the transmittance curve is shifted toward longer wavelengths. Therefore, the refractive index in the VIS region has a higher value, and the dispersion curves are more sloped.

Further, the thermal properties of plastics are rather different than glass. The highest operating temperature limits range from 60 to 250 °C depending on the type of polymer [3], while for optical glass, these temperatures can reach 400–700 °C. Thermal expansion coefficients of glass are much lower than those of optical polymers. The most important parameter for optical applications, however, is the variation of refractive index with temperature dn/dT. This temperature gradient is referred to in the literature as a thermo-optic coefficient or a temperature coefficient of refractive index [5, 10].

The absolute values of the thermo-optic (TO) coefficients of polymeric materials are about two orders of magnitude higher than those of optical glasses [5]. It is important to be clear and aware that plastics do not perform well in environments with large temperature fluctuations. Therefore, the temperature instability of the refractive and dispersion properties of optical polymers should be taken into account when designing optical components and devices. On the other hand, the large TO coefficient favors the use of optical polymers for dynamic control of the refractive index in active waveguide elements of photonic

devices, including thermal optical switchers, amplifiers and variable optical attenuators (VOA), controllers and modulators, *etc.* [11–15]. In addition, because polymeric waveguides can be fabricated by spin-coating on virtually any device without any network mismatch constraints, they are promising candidates for integrated optical devices and optical interconnects. Compared to optical fibers, polymer waveguides can be fabricated with sub-micrometer accuracy using state-of-the-art photolithographic technologies. This enables optical delay lines with femtosecond (f_s) accuracy [14, 16].

The effect of temperature on the dispersion properties of optical polymers is also of no less importance, especially in the case of arrayed polymer waveguide gratings. In this case, it is an extremely important dependence since it is known that their wavelength shifts are very sensitive to temperature changes.

The properties of polymers and glass complement each other. Accordingly, proper integration of these materials in the form of hybrid glass-polymer optics can provide the thermal stability of optical systems over a wide temperature range. Ultimately, such a solution creates real opportunities to obtain environmentally stable and low-cost devices with increased optical efficiency, not achievable with optical polymers or glass alone [17].

2. Optical synthetic polymers

2.1. Polymethyl methacrylate (PMMA)

Polymer optical fiber (fiber optics) technologies make extensive use of poly(methyl methacrylate) PMMA due to its favorable optical properties and resistance to aging. Optically transparent and non-aggregated polymer nanocomposites highly filled with a wide range of chemically different nanoparticles, ranging from noble metals (Au, Ag), semiconductors (ZnO, CdSe, PbS), to magnetic nanoparticles (Fe_2O_3), in combination with polymer matrices are described [18]. Nanocomposites consisting of inorganic metal or semiconducting nanoparticles and transparent polymer matrices have been continuously investigated for applications based on selective light absorption in the UV/Vis range, photoluminescence, and high/low refractive index polymeric materials. For example, for nanocomposites used as UV-protective materials, high transparency in the visible range and steep absorption in the near-UV range ($\lambda < 400$ nm) is required. The introduction of inorganic nanoparticles into polymer matrices can result in materials with much greater variations in their refractive index (RI), which would enable applications as lenses, optical filters, reflectors, optical waveguides, optical adhesives, or anti-reflective films. These nanoparticles are preferably incorporated into poly(methyl methacrylate), (PMMA). Using PMMA as a transparent polymer matrix, optically transparent nanocomposites with optical transmittance up to 90% for weight fractions of nanoparticles up to 45 wt% and demonstrating the improved scratch resistance were obtained (Figure 1, Figure 2), which is also important for optical applications.

The requirements for fiber optic technology are constantly increasing due to the rapid development of technologies requiring the transmission of ever-increasing amounts of data, including in the ICT sector. Hence the intensive search for new groups of polymeric materials, characterized by improved optical, thermal and mechanical properties with respect to PMMA, such as by obtaining methyl methacrylate copolymers [19].

Pure PMMA is an amorphous polymer with a glossy surface and high translucency. Known as an excellent optical polymer, is characterized by high optical transparency and visible light transmittance (91–92%), which is higher than that of glass [20–23]. In addition, it has very good strength and dimensional constancy. Polymethyl methacrylate is commonly referred to as organic glass. This thermoplastic material is resistant to ultraviolet radiation, so it does not turn yellow and remains transparent. It can also withstand harsh outdoor conditions [24], so it is an ideal substitute for glass. In addition to its great optical properties, excellent weathering and aging resistance, the material is also distinguished by its good impact strength. It is a hard plastic that is scratch-resistant and rigid. PMMA also remains resistant to biodegradation and is a low-cost, non-toxic, environmentally friendly and recyclable polymer. The structural nature provides PMMA not only with excellent optical transparency but also with good processability. Thus, the material shows no difficulty in processing, has thermo-forming ability and can be modified [23–25].

Due to their high transparency in the visible range, amorphous polymers such as polymethylmethacrylate (PMMA) are used in many optical applications. It is, therefore, the most dominant polymer used to date for optical purposes. For example, it has been shown to be a suitable carrier for some light-generating

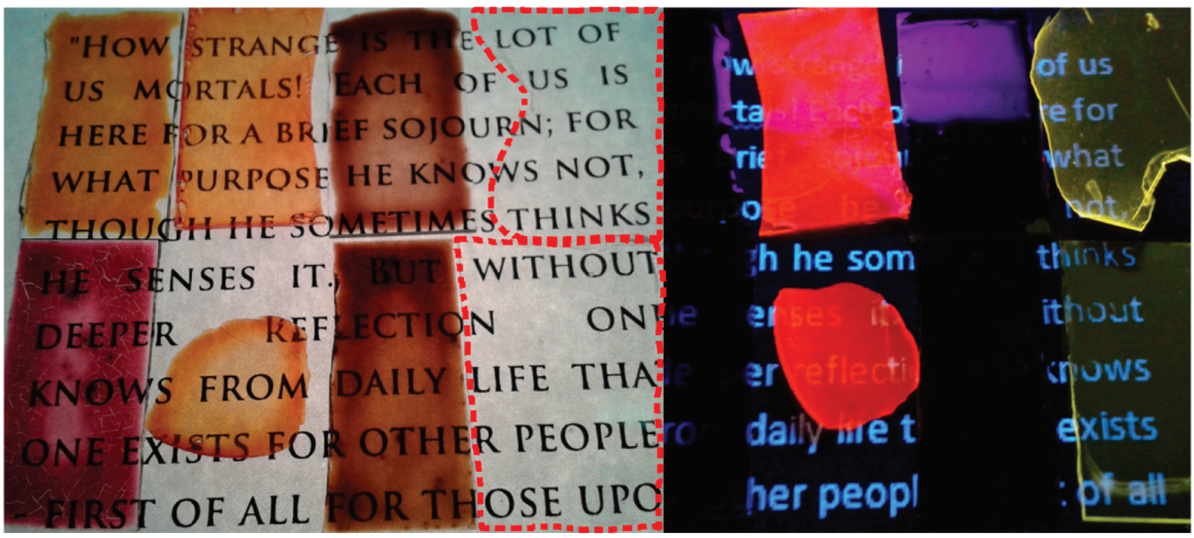

Figure 1. Left panel: photographs of transparent nanocomposite films (150 μm) on glass. Upper row: Ag–PMMA (100 μm, 2 wt%), CdSe–PMMA (200 μm, 10 wt%), PbS–PI (10 wt%), and free-standing ZnO–PMMA (250 μm, 10 wt%). Lower row: Au–PS (100 μm, 2 wt%), free-standing CdSe–PS (100 μm, 29 wt%), Fe_2O_3–P2VP (5 wt%), and ZnO–PS (150 μm, 45 wt%). The dashed red lines indicate the sample positions of the ZnO–PMMA and ZnO–PS films. Right panel: fluorescence of the same nanocomposites at UV illumination [18] (reprinted with permission).

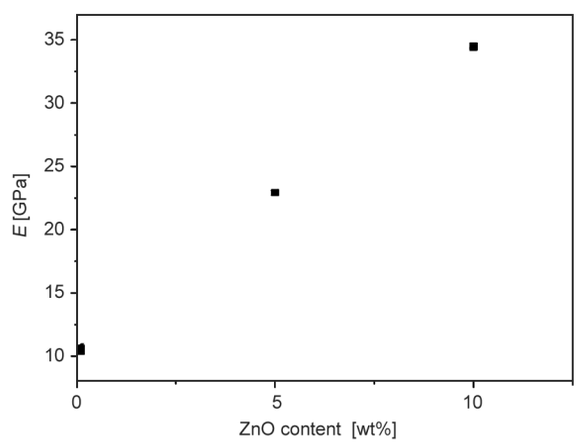

Figure 2. Nanoindentation measurements of ZnO–PMMA composites with different ZnO contents indicating a significantly increasing E-modulus with increasing ZnO content and, thus, considerably improved scratch resistance [18] (reprinted with permission).

rare-earth ion (RE) ligand complexes [26]. While the higher attenuation of polymers compared to inorganic glasses (*e.g.*, silica fibers) limits their use to distances less than about 1 km [27], there are still many applications for light-emitting polymer fibers, films and coatings.

Other published studies show the utility and effectiveness of modifying PMMA to overcome some of the limitations of this plastic [28]. PMMA has a number of methyl (CH_3) and ester methyl (CH_3–O–CO–) side groups that prevent the polymer chains from being tightly packed together, thus creating an amorphous structure [29, 30], which is already known to provide PMMA with excellent optical transparency and good processability. However, the methyl group itself carries some limitations for pure PMMA, as it causes the pure polymer to have a low refractive index and low UV absorption, as well as poor thermal stability.

In the cited work, two comonomers were used for copolymerization with methyl methacrylate (MMA), namely phenyl methacrylate (PhMA) and adamantyl methacrylate (AdMA), resulting in three copolymers [28]. The effects of phenyl and adamantyl substituents on the optical and thermal properties of PMMA were investigated, and it was found that phenyl plays an important role in enhancing the absorption and refraction of PMMA in the deep UV region (190–260 nm). In contrast, the presence of an adamantyl substituent resulted in a greater effect on the glass transition temperature and thermal stability of PMMA than phenyl.

Hence, the cited work provides a valuable description of a method for tuning the optical and thermal properties of PMMA by introducing phenyl and adamantyl substituents into its structure. Thereby, the result was a PMMA material with improved properties, crucial for using the polymer as a photoresist or anti-reflective coating for deep UV lithography [28].

In summary, all these outstanding properties make PMMA widely used in many fields such as aerospace, construction, automotive, advertising, medical

and electronics industries [31, 32]. It is worth noting that PMMA is a versatile lithographic resist for micro and nano production, which can be used as both positive and negative tones under the right circumstances [33, 34]. In addition, copolymerization with comonomers, blending with other polymers or adding some additives are often used to improve the optical as well as thermal and mechanical properties of PMMA.

2.2. Polystyrene (PS)

Polystyrene (PS) is one of the most popular thermoplastic polymers. It is a brittle polymer that is both stiff and simple to produce. It attracts attention because of its excellent properties. It is colorless and transparent in the visible region. In addition, it has good formability, good rigidity, electrical and thermal insulation, long-term stability and easy processing [35–37]. PS is typically a solid thermoplastic at room temperature but can also be melted at a higher temperature for molding or extrusion and then re-solidified. Its main applications are packaging foam, such as in meat trays and egg cartons, insulating foam for use in construction, and biaxially oriented film for use in food packaging. Toys, picnic utensils, audiocassette housings, compact discs and jewel boxes, and are all examples of injection-molded products [38, 39]. The unique properties of polystyrene, such as its low cost and high refractive index of 1.59 at 632 nm, also make it, along with polymethyl methacrylate PMMA, an excellent choice for many optical applications [40].

In optical applications, including lenses, the widely used polystyrene (PS) has not received much attention due to its significant birefringence. Recent research [41] describes an effective method to compensate for the orientation birefringence of PS using bottlebrush polymers with well-controlled PS-grafted chains (PS-BBP). PS-BBP was synthesized by ring-opening metathesis polymerization of norbornene-terminated PS macromonomers produced by atom transfer radical polymerization, and then blend-film samples were prepared by mixing linear PS and PS-BBP (Figure 3).

As a result, the authors of the study obtained the blends of linear PS and PS bottlebrush polymers, revealing excellent low-orientation birefringence of $|\Delta n|$. Especially the blend samples with a specific ratio of linear PS to PS-BBP (30:70) demonstrated extremely low orientation birefringence of $|\Delta n| \sim 3.9 \cdot 10^{-4}$ even under 120% strain, comparable to or even better than those of existing optical polymers. In addition, the blend samples retained almost the same refractive indices as linear PS, possessing the transparency required for optical polymers in the visible wavelength range (Figure 4).

Organic polymer based materials are becoming the workhorse in the area of photonics and optoelectronics. These materials are rapidly replacing their inorganic counterparts due to their flexibility in manufacturing combined with the ease in fabrication and manufacturing. Polystyrene, being a cost-effective commercial plastic, has been utilized as one of the important polymeric materials for various optical devices. For example, recent studies have confirmed the suitability of disposable recycled polystyrene as a host polymer to accommodate active non-linear optical (NLO) guest molecules, through simple

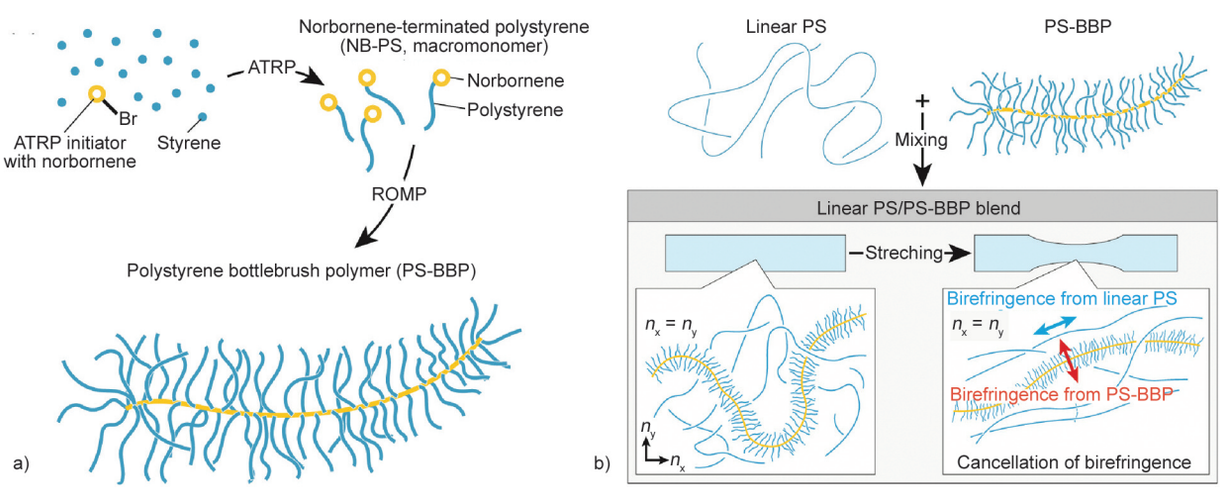

Figure 3. a) PS-BBP synthesis and b) strategy of compensation for orientation birefringence of polystyrene by mixing linear PS and PS-BBP [41] (reprinted with permission).

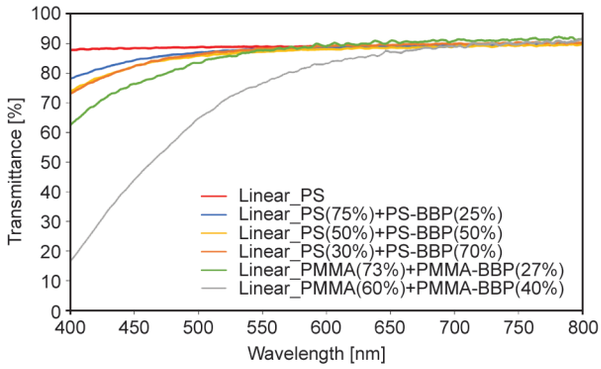

Figure 4. Light transmittance of linear PS, PS/PS-BBP with blending ratios of 75:25, 50:50, and 30:70, and PMMA/PMMA-BBP with blending ratios of 73:27 and 60:40 [41] (reprinted with permission).

modification by solution casting and other processes that can lead to dirt-cheap NLO active device materials [42]. Non-linear optical (NLO) materials are the basis of many next-generation optical defense technologies, as they can be used to shift the wavelength and frequency of laser light, enabling operation in parts of the electromagnetic spectrum that would normally be inaccessible. In particular, NLO materials are also essential for the development of advanced modern technologies ranging from telecommunications, signal processing, data storage, super-resolution lithography, and microscopy to the development of next-generation integrated photonic circuits [43].

Nanocomposites based, for example, on blending polymers with inorganic nanoparticles are also attracting much attention because of their predicted remarkable thermal, electrical and antimicrobial properties, as well as optical properties for optoelectronic applications [44–47]. It has been reported, among other things, that the optical, magnetic and mechanical properties of PS were significantly improved after metal or semiconductor nanoparticles were embedded in the polymer matrix [48–50]. Incorporating noble metals into polystyrene for composite synthesis has potential advantages in optoelectronic, as well as catalysts and chemical sensors [51–53].

According to the literature review, the first study on the preparation and characterization of heterojunction photodetectors based on polystyrene with gold and silver nanoparticles, prepared by laser ablation in liquid, was successfully reported by Ismail and colleagues [54]. The authors of the cited paper obtained optical data, which showed that the optical energy gap of PS decreased when gold and silver nanoparticles were introduced into the polymer matrix, and the electrical and photoelectric response of PS/Si increased significantly. As a result of the study, two response peaks were recorded for the PS composite/Si heterojunction. Based on the results obtained, the described technique can be used to fabricate PS/Si heterojunction photodetectors with high photosensitivity and low cost.

From the recent literature, it is also worth quoting examples of materials for optical applications involving polystyrene in combination with other polymeric materials exhibiting beneficial optical properties. For example, hybrid thin films based on polystyrene (PS) and polymethyl methacrylate (PMMA) doped with different concentrations of cerium dioxide nanoparticles (CeO_2 NPs) have been successfully reported [55]. Cerium oxide nanoparticles have attracted much attention due to their high stability, surface chemistry and biocompatibility [56–58]. They are transparent in the visible region and have a refractive index of 2.2 at a wavelength of 632 nm [59, 60]. Pure CeO_2 exhibits a wide indirect optical band-gap and energy band-gap that works effectively in the ultraviolet (UV) region and, therefore, can be an excellent choice for a variety of optical and electronic applications [61, 62].

The results of the cited work [55] show that the developed composites can be key candidate materials for a wide range of scalable multifunctional smart optical and optoelectronic devices. Introducing CeO_2 nanoparticles into the copolymer matrix (PMMA-PS) reduces the optical band gap, and thus, it is possible to engineer the optical properties of the resulting material.

The novelty of the cited work lies in the modulation of refractive index by using polymer nanocomposites with inorganic fillers since it has been known that performance enhancement of photonic devices can be achieved by engineering the refractive index mismatch of materials used in optical devices. The authors of the study noted an increase in refractive index after the introduction of CeO_2 nanoparticles into the polymer matrix [55]. Therefore, the PMMA-PS/CeO_2 nanocomposite can be used for high-reflectivity coatings and candidates for highly optically constrained applications.

Another recent example involves the development of new composite layers made of polystyrene and metalloporphyrins [63]. Porphyrins and metalloporphyrins are widely used as fillers. Due to the structure

of the porphyrin molecule, aromatic single and double bonds can be arranged in a highly stable manner [64]. A special feature of porphyrin is its ability to incorporate transition metals such as zinc, nickel, manganese, cobalt, copper or iron into its molecular structure [65]. Because of its potential to replace inorganic semiconductors in the creation of cheaper devices, metalloporphyrins are gaining a key function in many areas of technology [66].

By using the ordinary casting procedure, films of PS loaded with various concentrations of tetraphenylporphine manganese (III) chloride (MnTPPCl) were developed. As a result of the published studies, it was discovered that the optical energy gaps for the indirect and direct allowed transition decrease, and the refractive index of PS rises with increasing metalloporphyrin content under normal dispersion [63]. The feasibility of using PS/MnTPPCl composite in optoelectronic devices is due to the reduction of the optical energy gap and the increase in refractive index caused by the addition of MnTPPCl. As a result, PS/MnTPPCl films are favorable for use as environmentally friendly packaging materials for a variety of microelectronic and optoelectronic devices due to the increase in optical properties with increasing the concentration of metalloporphyrin.

2.3. Polyethylene terephthalate (PET) and polypropylene (PP)

Polyethylene terephthalate (PET) is another example of a polymer with optical properties. It is valued primarily for its flexibility, low cost and high transmission in the visible part of the electromagnetic spectrum. It has properties suitable and necessary for packaging applications, especially optical clarity, since it is not only an aesthetical demand but a necessary condition for the quick identification of the product. From the point of view of the packaging industry and the requirements for materials for its needs, PET, therefore, exhibits many favorable and desirable properties for this purpose. These characteristics, combined with others related to its different degrees of crystallinity, give PET a set of properties that make it extremely attractive for use as a material for any packaging, especially for food purposes.

Recently, with greater demand for transparent and deformable electronics, high transmittance and flexibility have also become important characteristics that electrodes should have. However, it is difficult to satisfy desired optical, mechanical, and electrical properties at once. To keep pace with the era of transparent and deformable electronics, electrode functions should be improved. An innovative design has been suggested to overcome the trade-off between optical and electrical properties that commonly arise with transparent electrodes. Flexible organic light-emitting diodes (OLED) and a transparent flexible thin-film transistor (TFT) were successfully fabricated with a double-stacked metal electrode (DME), composed of silver (Ag) and tungsten trioxide (WO_3) deposited by thermal evaporation on a polyethylene terephthalate (PET) substrate [67]. The resulting material showed low sheet resistance of <3 Ω/sq while maintaining a high transmittance (~90%) in the visible range. In addition, flexibility was guaranteed based on the negligibly changed characteristics of the device after a 10 000-cycle bending test with a bending radius of 1 mm (Figure 5).

It seems from the literature review that the optical properties of PET, however, have always been a problem that related studies have tried to overcome. Thus, for example, there has been some improvement in the optical transmittance in the visible region of PET treated with plasma immersion techniques. Surface modification with reactive gases is simple, fast and efficient, and the process rate can be controlled. Plasma treatment causes a number of chemical and physical changes at the plasma-polymer interface that improve the surface properties of the material under study [68–72].

In particular, Plasma Enhanced Chemical Vapor Deposition (PECVD) makes it possible to produce thin films with a wide range of properties by controlling the process parameters. Examples are numerous and of great variety. Noteworthy ones include transparent films suitable for use as optical windows, lenses or sports glasses coatings, anti-reflective layers, or insulating and conductive layers that are used in the manufacture of electronic devices. Examples also include biocompatible films and hydrophobic materials suitable for use in food packaging or solar cells [73]. It is possible to induce and achieve more intense changes in the properties of polymeric materials by exposing a sample to a plasma subjected to polarized pulses of high negative voltage, and thereby attracting positive ions. This process is known as Plasma Immersion Ion Implantation (PIII) and was developed to overcome some of the limitations of conventional ion beam implantation.

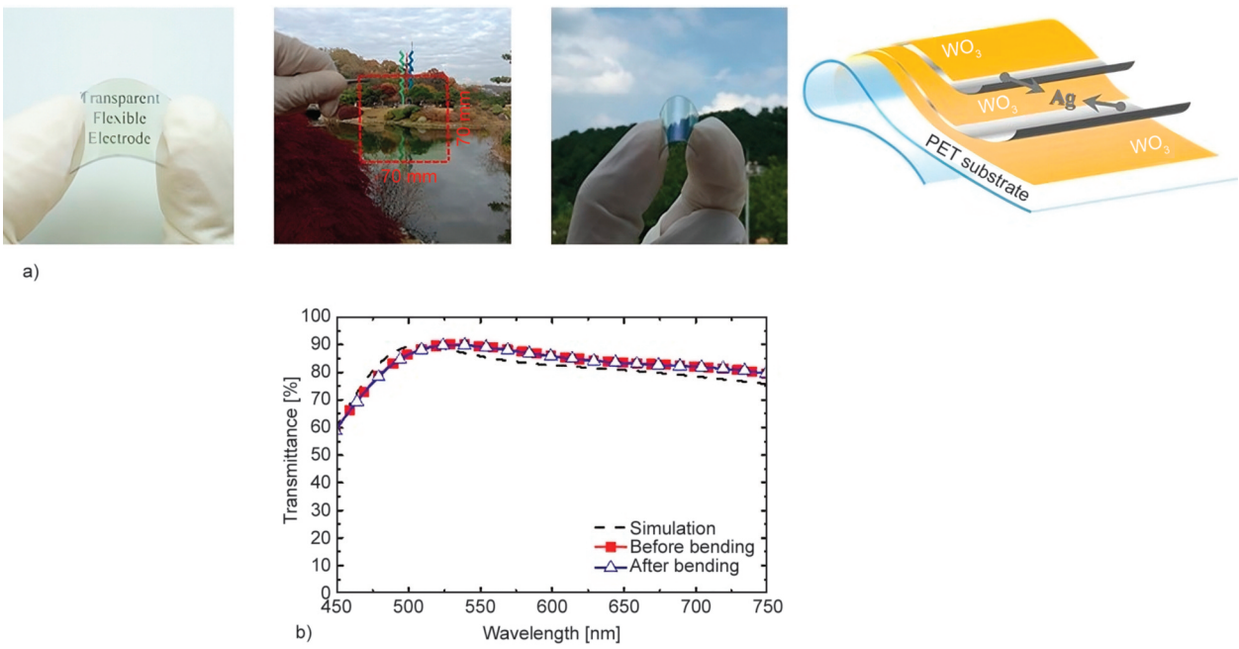

Figure 5. Optical properties of the double-stacked metal electrode (DME). a) Photographs of the realized DMEs and structure. b) Transmittance of the DME with optimized layer thicknesses. The dotted line is the calculated data by the simulation. The red-colored rectangles are experimental data before bending. The blue open triangles are experimental data after 10 000 bending cycles with a 1 mm bending radius [67] (reprinted with permission).

In the cited work [74], the optical transmittance in the visible region of commercial PET samples treated by plasma immersion and PIII was studied since, according to the authors and to the best of their knowledge, at that time there was no known surface treatment capable of improving the optical transmittance of food packaging in the visible region. As a result, they achieved an improvement in optical transmittance up to ~86% in the visible region for treated PET compared to the pristine material. The greatest improvement in transmittance was observed with the treatment of nitrogen plasmas. According to the authors, this improvement could be due to the opening of the polymer structure, the release of hydrogen, the incorporation of more oxygen into the polymer structure, or a combination of these factors [74].

Another more recent example from the literature relates to research aimed at obtaining PET films with excellent optical properties through the effect of the addition of a phosphate antioxidant (PSLDH) on the crystallization properties of polyethylene terephthalate [75]. The relationship between molecular structure and methods for studying the dynamics of crystallization of polymers is considered from the point of view of isothermal crystallization or non-isothermal crystallization. By influencing the crystallization rate and crystallinity of polymers through effective synthesis methods, it is possible to ultimately control their morphology and properties [76]. In the actual production process, usually polymer synthesis and processing are usually carried out by extrusion, injection molding and other methods under non-isothermal and dynamic conditions. Therefore, non-isothermal crystallization kinetics studies are used to obtain polymers with expected performance and to analyze the effects of various additives or polymers on crystallization [77–80]. Thus, usually differential scanning calorimetry (DSC) is used for non-isothermal crystallization analysis.

In the cited studies, the polymeric material, *i.e.* the starting sample and the sample modified with a phosphate antioxidant (PSLDH), was examined by DSC at different cooling rates [75]. The obtained results showed that the addition of phosphate antioxidants in the amount of 0.05 wt% could make PET crystallization smaller and slower, which is the same as the case required for excellent optical properties.

As mentioned above, transparency is closely related to the crystallization and crystalline structure of the polymer. Any effect that influences these factors will also change transparency. Previously, in areas where transparency and optical clarity are basic requirements, amorphous polymers such as polystyrene (PS) were used, because in semi-crystalline polymers, light scattered on different units of their structure made products opaque. Often, the size of the

crystalline units is large enough to interfere with visible light, and this interference causes significant haze [81].

Nonetheless, the favorable price/performance ratio of polypropylene (PP) and developments in both processing and additive technology have led to a breakthrough in its use, also in areas where optical transparency is required. This development is especially important in PP, which usually has quite large spherulites. Several publications indicate, for example, that the introduction of heterogeneous nucleating agents, which reduce the average size of spherulites below the wavelength of visible light, or clarifying agents, such as sorbitol derivatives, into PP homo- and copolymers significantly improves product transparency [82–88]. Low haze materials are usually prepared from random copolymers, and optical properties are further improved by the use of clarifying agents based on various sorbitol derivatives [88]. The latter additives dissolve in the polymer, forming a microcrystalline structure and significantly improving haze (Figure 6). Some time ago, a relatively new family of nucleating agents based on trisamide derivatives also emerged as a competitor to sorbitol-derived clarifying agents [82–85]. However, the effectiveness of a clarifying agent also depends largely on the properties of the polymer used and the processing conditions. Quite a few articles deal with the effect of clarifying agents on the optical properties of PP, but few relate the obtained properties to the structure of the polymer [89].

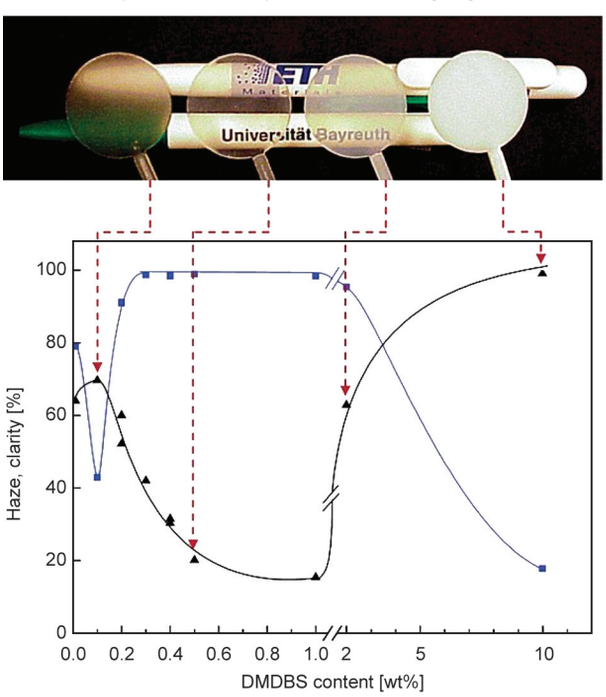

Figure 6. Optical properties of isotactic polypropylene (*i*--P)/1,3:2,4-bis(3,4-dimethyldibenzylidene)sorbitol (DMDBS) for different compositions. Writing instruments viewed through injection-molded plaques containing 0.1, 0.5, 2, and 10 wt% of DMDBS (top) and measured values for haze (▲) and clarity (■, see text) as a function of the DMDBS content (bottom) [86] (reprinted with permission).

The research conducted by Pukánszky and colleagues sheds some light on this issue (Figure 7, and Figure 8). They found a correlation between the molecular structure of homo- and random polypropylene PP copolymers and the optical properties of the products made from them. As a result, they developed a model that quantitatively describes the dependence of nucleation efficiency and haze on the concentration of the nucleating agent. The result achieved in this way was preceded by studies on the effect of two soluble clarifying agents, namely a sorbitol-type additive and a trisamide derivative recently developed and marketed at the time, on the optical properties of nine PP homo- and random copolymers [89]. The analysis showed that lamella thickness and improved crystallinity only slightly affected haze. The model developed in the course of the research assumes that the same factors affect the peak crystallization temperature and optical properties. Chain regularity determines the supramolecular structure and, thus, the dependence of optical properties on nucleation.

The above Figure 7 demonstrates that both the nucleation efficiency and the actual values of various characteristics depend on the molecular structure of the polymer. The absence of a comonomer results in much higher crystallinity, a greater increase in peak crystallization temperature and a much greater improvement in haze in a homopolymer than in a random copolymer. Nevertheless, the latter is more favorable for the purpose discussed in the article [89], as lower haze values can be obtained with it.

The results illustrated in Figure 8 clearly prove that there is no correlation between the average lamella thickness of the polymers containing different types and amounts of nucleating agents and their haze, regardless of ethylene content, as well as other features of the molecular structure.

Some previous research work by other authors indicated that light scattering and reflection/refraction associated with surface roughness have a greater impact on the optical parameter of haze than inhomogeneities

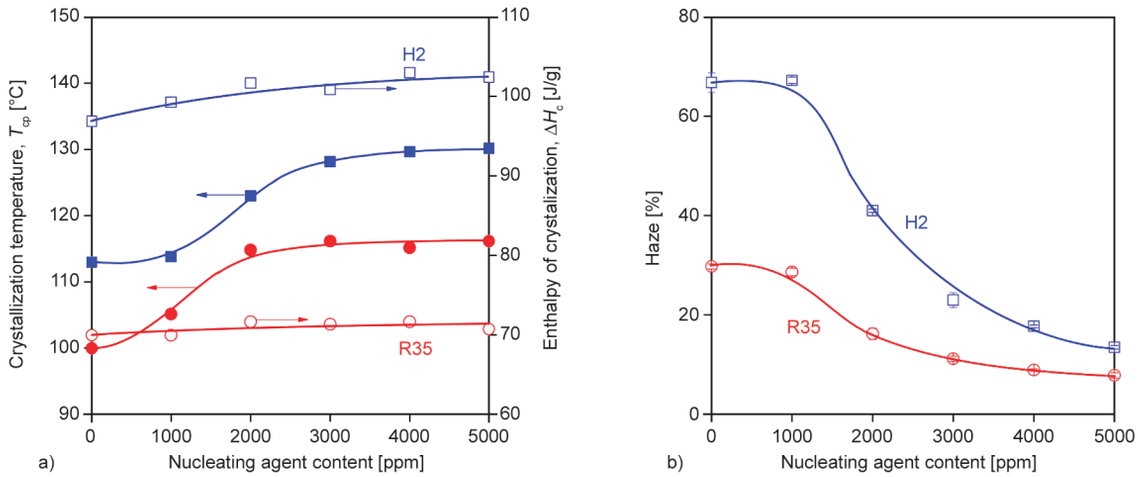

Figure 7. a) Crystallization characteristics of PP polymers plotted against the amount of sorbitol clarifier. Effect of polymer characteristics. Symbols: (○, ●) random copolymer (R35), (□, ■) homopolymer (H2), (○, □) enthalpy of crystallization, and (●, ■) peak temperature of crystallization. b) Effect of nucleation on the haze of the polymers of Figure 7a. Symbols: (○) random copolymer, (□) homopolymer; nucleating agent: sorbitol [89] (reprinted with permission).

attributed to mass. Therefore, at one time, some publications emphasized the analysis of the influence of various processing conditions and material parameters, such as, for example, molecular weight and its distribution, on the formation of surface roughness and structure as a result of extrusion and crystallization [90–93].

Very often, it is precisely in the case of polyolefin films that polymer processing additives, such as slip and anti-blocking agents, are difficult to avoid. These are added to optimize processing or to make handling easier because polyolefin films, in general, tend to stick together. Some publications discuss the

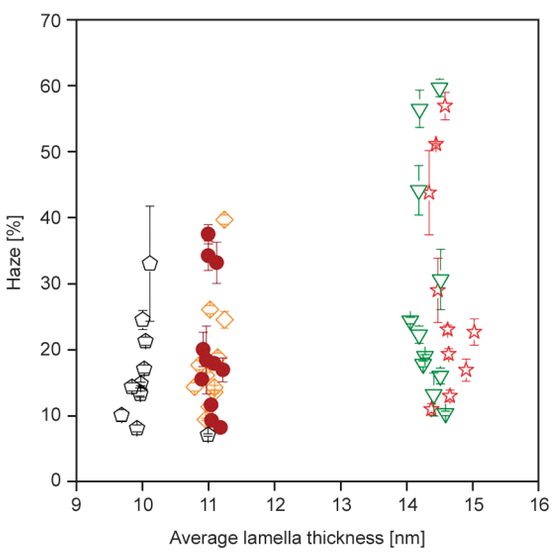

Figure 8. Independence of haze of the average lamella thickness of PP random copolymers. Symbols: (□) R53, (●) R17, (◇) R42, (☆) R21, and (▽) R27 [89] (reprinted with permission).

effect of similar additives on the formation of surface features and optical properties [94–96]. Many of them migrate and accumulate on the surface, thus creating micro-roughness, which, admittedly, has a positive effect on reducing stickiness between film layers. However, on the other hand, increased roughness promotes additional light scattering in the bulk or generates refraction/reflection effects on the surface that are unfavorable from the point of view of good transparency. In contrast, Catino and Gardiner [97] indicated that the enrichment of the surface with additives does not necessarily correlate with vertical roughness parameters, *i.e.* the height of the surface, and thus with its roughness.

Studies, earlier and later supplemented by Resch *et al.* [96], attempt to address this issue. Their earlier work showed the significant effect of polymer processing aids (*i.e.* slip, anti-blocking agents and acid scavengers) on the surface structure and optical properties of highly transparent films cast from homo- and random PP copolymer. Studies by atomic force microscopy (AFM) of the types of films produced without and then with slip and anti-blocking additives revealed either superlamellar crystalline structures or numerous spherical and plate-like structures, respectively. Finally, the best optical properties and the lowest vertical fluctuations in roughness characterized the first type of film, that is, without additives. In contrast, their presence, due to the increase in surface roughness, worsened the optical properties. In the course of the results obtained, a comparison of the degree of haze and roughness was

described with a tendency toward linear correlation. However, it was also found that there was a significant gap between film types developed with and without the analyzed additives [96].

Later studies, following on from the previous ones, were performed on PP materials based on improved formulas and showing haze values between the two separate blocks described in the previous paper. Thus, the completed research focused on a detailed analysis of the process factors for obtaining highly transparent PP films, revealing more in-depth information regarding the effects of material composition and processing conditions on surface structure and optical scattering mechanisms [98]. For example, AFM topographic studies showed, among other things, a significant effect of processing conditions, such as strong vacuum box conditions, on the film's distinct surface scratches, showing a replica of a metal cooling roll. On the other hand, elsewhere on the surface, characteristic octahedral superlamellar crystalline features were observed, whose increased dimension and occurrence were directly related to the increased soft box airflow. Moreover, it was noted that their dimensions decrease with increasing ethylene comonomer content. According to the authors of the study, the formation of plate-like features attributed to the slip agent on the film surfaces is independent of the processing conditions.

In general, polypropylene cast films without additives showed better optical properties. The separation of haze into bulk and surface components showed that total haze is dominated by surface haze. Nevertheless, it was observed that the diffuse scattering, and thus haze, could be influenced by the PP film types produced with polymer processing aids. Indeed, it was found that these parameters were improved, especially with lower porosity anti-blocking agents, as well as with a large amount of acid scavengers.

In addition, films produced with low molecular weight resins and higher ethylene copolymer content had lower haze values. As for the processing conditions, those with low vacuum and high soft box conditions were most beneficial, providing the most transparent polypropylene films with the best optical properties [98].

2.4. Cyclic olefin copolymer COC (TOPAS) and polyolefin elastomer POE (Engage)

TOPAS cyclic olefin copolymers (COCs) are a chemical relative of polyethylene and other polyolefin plastics. These compounds have been recognized as advanced plastic materials that enable product designers and manufacturers to go beyond the ordinary. From insulin delivery to food packaging films to mobile device components, TOPAS polymer is the high-performance material of choice. Cyclic olefin copolymers are ultra-pure, amorphous, crystal-clear engineering materials, based on cyclic olefins and ethylene, with a wide range of unique properties suitable for healthcare, packaging, and electronics applications [99–103].

Key properties and applications of TOPAS COC resins include, first and foremost, purity, which enables applications ranging from direct contact with drugs to food packaging films. Second, barrier properties against moisture, as well as resistance to alcohols, acids and other substances to protect food, medical and electronic products. Finally, glass-like clarity enables their use for sparkling films, glass-like healthcare containers, or high-performance diagnostics with UV transparency [104–108]. All these are very important parameters, for example, for the optimization of microfluidic sensors on the basis of immobilized analytical probes to prepare different biomolecule micropatterns using ultraviolet (UV) photografting methods. The ability to place the immobilized probes in desired locations within the microfluidic chip is an important aspect for making sensors on the basis of immobilized probes. The commodity thermoplastic cyclic olefin copolymer (COC) was selected to build microfluidic chips because of its significant UV transparency and easiness of microfabrication by molding techniques [108]. Once the polyacrylic films were grafted on the COC surface using photomasks, micropatterns of proteins, DNA, and biotinylated conjugates can be readily obtained by surface chemical reactions in one or two subsequent steps. The thickness of the photografted films can be tuned from several nanometers up to several micrometers, depending on the reaction conditions. The micropatterned films can be prepared inside the microfluidic channel (on-chip) or on open COC surfaces (off-chip), as illustrated in Figure 9.

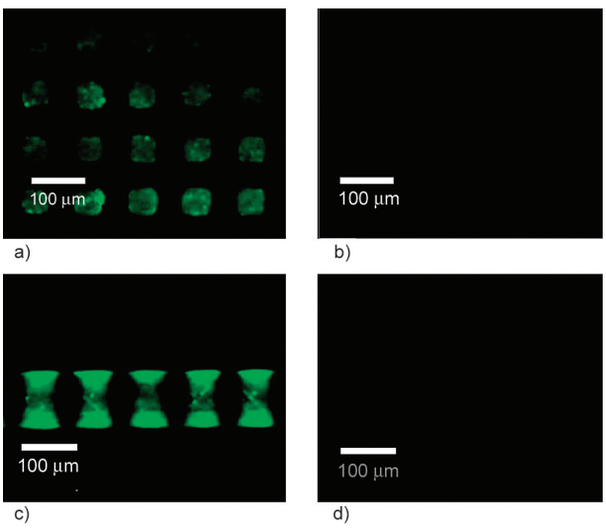

Figure 9. DNA patterns on COC sheets (a), (b) and inside a COC microchannel (c), (d). Images were obtained through hybridization with complementary (a), (c) and random DNA sequences (b), (d); all DNA probes had fluorescent tags [108] (reprinted with permission).

Thanks to the high purity and precision of TOPAS polymer molding, point-of-care tests are more reliable. Advanced assays requiring UV measurement can rely on TOPAS COC with the best UV transmission of all known polymers. For microplates, UV transmission, low autofluorescence and glass-clear optics enable precise analyses. There are even 3D prototyping systems for developing diagnostic devices that have been designed specifically for TOPAS COC [109–112].

It is also worth citing the other strengths of this material, namely that products made from rigid polymers such as TOPAS COC do not need to be so thick. The high stiffness of TOPAS polymer makes it possible to significantly reduce thickness, thereby producing thinner films, for example. Conversely, in molded products such as medical containers, the fracture resistance of TOPAS resin is better than that of glass, resulting in fewer broken containers. Another factor to consider in efforts to reduce consumption and maintain sustainability is the low density of TOPAS polymers, approximately equal to that of water, leading to lightweight products with low energy consumption during transportation. Another positive aspect is the ability to dispose of waste in the safest and most economical way. TOPAS COC is a highly combustion-compatible material with high energy density and halogen-free composition for cleaner and safer incineration [105, 107, 113, 114].

Polyolefin elastomers (POEs) are another that has been recognized as a highly advanced material that enables designers and manufacturers to achieve exceptional performance with an incomparable balance of properties. In a nutshell, POEs combine the chemistry of rubber and plastics. Being resins that can be tough, resilient, and flexible all at the same time, they offer new possibilities. This broad family of polymers provides low density for lightweight parts, outstanding touch and feel, colorability and other significant advantages versus a wide range of other polymers [115–117]. Compared to other polymers, Engage POE has, among other things, extended product life compared to styrene block copolymers, better flexibility and fracture resistance compared to EVA (ethylene vinyl acetate) or EMA (ethylene methyl acrylate) thermoplastics, better processability and better properties compared to flexible PVC (polyvinyl chloride), and greater durability compared to EPDM (EP terpolymer) or EPR (EP copolymer).

Engage POE is designed to enable thermoplastic olefins (TPO) to meet critical performance targets, such as low-temperature impact, melt flow, melt strength, flexibility, and softness [118–120]. The grade includes ethylene octene and ethylene butene copolymers over a wide range of densities and melt flow rates. They are used in both rigid and soft TPO formulations for injection molding, thermoforming, and blow molding applications. They offer exceptional performance and a unique balance of properties when used at various levels in a formulation [121].

Engage POE can be used to modify other materials like polypropylene for impact resistance or improved low-temperature performance. Being compatible with most olefin materials, it offers unique capabilities that can enhance products for automotive applications such as safety systems and body panels, among others [122–124]. It is increasingly preferred for fully polyolefin car interior components and innovative interior designs. Engage polymers also can be used as the sole polymer in molded goods such as toys or household items. It is also used in bedding compounds. In addition to automotive and consumer goods applications, Engage can be cross-linked with peroxide, silane or radiation to create high-performance electrical insulation and jacketing for low- and medium-voltage cable applications [125–127].

Recently, polyolefin elastomer (POE) has also been recognized as an encapsulator for photovoltaic (PV) modules due to its high transmittance, permanent

bonding, and good resistance to creep with low deformation (Figure 10) [128, 129].

So far, ethylene-vinyl acetate copolymer (EVA) is widely used as an encapsulating material for crystalline silicon-based solar cells. The material has had experience in its field for more than 30 years, thanks to its special advantages, such as high flexibility and good optical and mechanical properties [130, 131]. Unfortunately, its weather resistance is poor, prompting the search for new polymers for encapsulating PV modules. This is because the main disadvantage of EVA copolymer is its ability to absorb water molecules, which causes a reaction with the acetate moiety of the polymer backbone. Consequently, the acetic acid generated causes corrosion of the metal connections and failure of the PV module shortening its lifetime [132–134].

Among others, the work of Park and Hwang [135] addresses the feasibility of POE encapsulating material as a replacement for the existing EVA, thus being a design solution for photovoltaic modules in crystalline silicon solar cells. The obtained results show that polyolefin elastomer can be effectively used to adhere to glass in PV modules and the transmittance values of the resulted material were almost similar to those of EVA (90%). The damp-heat test results of the PV modules with the POE blends showed no significant power loss. This means that the performance of PV modules encapsulated with the blends involving POE can be maintained. Considering this result, it can be concluded that the developed blends with POE can play the role of high-quality and long-durability component material for weather-resistant encapsulators of photovoltaic modules.

3. Optical biopolymers (polylactide PLA and gelatin)

In the context of the growing importance of resource efficiency, carbon footprint, and responsible use and disposal, it is reasonable to explore the use of sustainable plastics as alternative materials in optics and lighting technology. One potential alternative could be polylactide (PLA), which is based on renewable raw materials, biodegradable and additionally exhibits excellent optical properties (Figure 11) [136, 137]. Eco-friendly PLA polymers are used in numerous industrial applications in medicine, textiles, packaging, wastewater treatment, and environmental engineering. The global PLA market is predicted to expand significantly over the next decade due to increasing demand for compostable and recyclable materials produced from renewable resources [138]. Accordingly, it is highly desirable to understand the optical properties of this material.

Many of the physical properties of PLA are influenced by the amount and distribution of the R- and S-lactic acid stereocenters in the polymer chain, which reflect its history including the stereochemistry (RR (D-lactide), SS (L-lactide), RS (meso-lactide), or a mixture of equal amounts of D- and L-lactide referred to as racemic or DL-lactide) of the feed composition, polymerization kinetics, and extent of transesterification and racemization [136, 139]. Since this rich variety of structures leads to materials with different characteristics, from fully amorphous to semi-crystalline, a discussion on the optical properties of PLA is valuable so that they can be manipulated to develop materials with desired properties for a specific purpose.

Thus, the structure of PLA is unique in that the polymer can contain enantiomers of both L- and D-lactic acid as repeating units. In general, PLAs are predominantly L- in stereochemical composition. Commercial materials should mentioned here, as they are typically rich in L-stereochemical centers (>90%). However, various levels of the D-stereoisomer may also be present. When optical purity drops

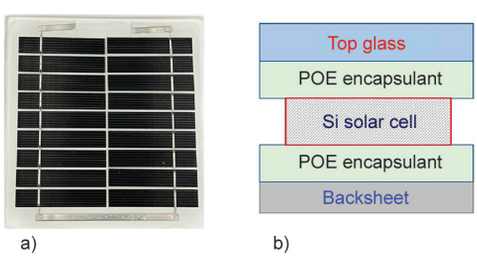

Figure 10. Camera image of the test PV module (a) and Its Laminate Structure Diagram (b) [128] (figure licensed under the Creative Commons Attribution 4.0 International License (CC BY 4.0)).

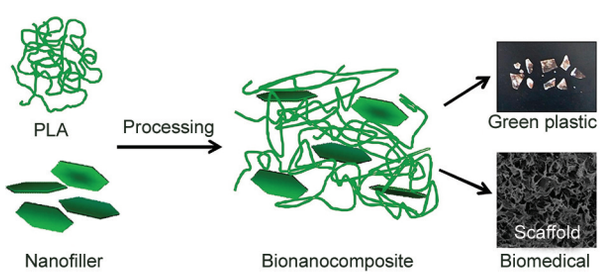

Figure 11. PLA-based bio-nanocomposites for use in applications from green plastics to biomedical applications [137] (reprinted with permission).

below about 80%, PLA becomes fully amorphous rather than semi-crystalline [140, 141].

There are some applications where questions arise regarding the optical properties of PLA, *i.e.* the index of refraction and its dependence on wavelength. Optical properties are therefore important, for example in dyeing operations in textile applications and in various packaging applications where color or transparency is desired. Hutchinson *et al.* [141] found no statistically significant differences in refractive indices between PLA samples of different enantiomeric compositions tested by ellipsometric measurements. Nevertheless, they found that in the light wavelength range from 300 to 1300 nm, the refractive index of PLA decreases from 1499 to 1448. The change in the refractive index with changing wavelength is called dispersion and this quantity is of interest in many technologies. According to the cited work, the dispersion for PLA was calculated by taking the derivative of the well-known Cauchy model [142, 143] with respect to the wavelength. The final valuable result obtained from the study is a useful expression describing the refractive index of PLA as a function of wavelength.

In the food packaging industry, where packaged goods are sensitive to light, the absorption and transmission of light by polymers are extremely important. The irradiation effect of the packaging is another matter, as UV light irradiation is a commonly used method to reduce the microbial population in foods [144]. Hence, the transmission of visible light (400–700 nm) and ultraviolet radiation (100–400 nm) are important parameters in the design of appropriate packaging to store and protect the contents until they reach the consumer. Photochemical degradation of plastics is mainly caused by radiation known as UV-B (315–280 nm) because its high energy content is capable of cleaving some chemical bonds [144].

Auras *et al.* [136], and Lim *et al.* [146] measured the properties of PLA as a barrier to visible and ultraviolet light and compared them with the properties of commercial polymers traditionally used for food packaging. At 225 nm, PLA shows a significant increase in UV light transmission compared to other standard polymers, reaching around 85% at 250 nm and 95% at 300 nm. In this way, most of the UV-B and UV-A radiation passes through the films. In the group of conventional polymers, PS and cellophane transmit less radiation in the UV range where most foods are more sensitive, and PET does not transmit any light in this wavelength range. LDPE is the polymer that shows the highest UV light transmission, followed by PLA [147].

Currently, several important parameters are used to characterize the visible light transmission and color of plastics, such as transparency and degree of yellowness, which are based on the absorbance or transmission of UV-Vis light. PLA, PS and LDPE have the same degree of yellowness, while cellophane and PET have higher values [145]. Since the light yellow color of PLA products can be a disadvantage in their use in the packaging industry, creating the consumer impression that the packaging is old, additives are usually used.

Arguably, PLA is widely recognized as one of the most widely used materials in 3D printing [148, 149]. Nevertheless, it is worth mentioning the work of Gierej *et al*. [150] which describes one of the more interesting optical applications of PLA for medical purposes. The authors obtained poly-DL-lactide (PDLLA) based fibers which they claim show a lower thermo-optical coefficient than those reported for other biocompatible polymeric waveguides at the time. They also studied the in vitro degradation of PDLLA fibers, revealing their rapid degradation during which they show over 84% loss of molecular weight over a 3 month period. The characteristics of the resulting material allow it to be used for *in vivo* light delivery for several hours and left to degrade inside the body for two to three months. Light-based *in vivo* therapies currently require invasive treatments, but the use of biodegradable fiber optics would enable much less invasive therapies, according to the authors [150, 151].

Nevertheless, it is necessary to point out that a significant effort is still required to improve the biodegradability of PLA-containing materials in order to be completely included in a circular economy. Despite being often classified as a biodegradable plastic, PLA, especially with its high molar mass, is hardly biodegradable under ambient conditions, requiring very specific composting conditions (*i.e.*, temperature above T_g, specific microorganisms, adequate humidity, and aerobic environment) for its complete decomposition into CO_2 and H_2O [151, 152].

When writing about biopolymers for optical applications, it is also worth referring to gelatin. This natural biopolymer, obtained through the transformation of collagen, a natural component of connective

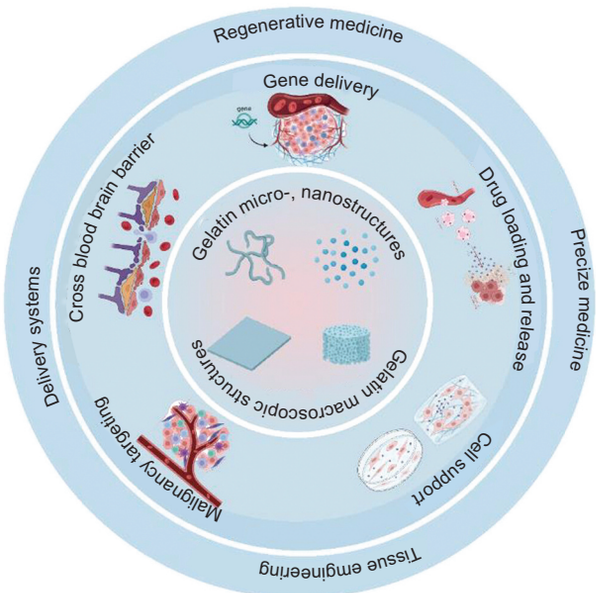

Figure 12. Applications of gelatin and its derivatives in tissue engineering and regenerative medicine [153] (reprinted with permission).

tissue, is not necessarily associated with applications in optics or optoelectronics on a daily basis.

Due to its many advantages, such as swelling capacity, biodegradability, biocompatibility, and commercial availability, gelatin is widely used in the field of pharmacy, medicine, and the food industry (Figure 12) [153–155]. Overall, gelatin has extremely good physical properties, such as jelly force, affinity, high dispersibility, low viscosity characteristics, dispersion stability, and water retention (Figure 13). According to Ramos *et al*. [156], gelatin is an important food additive due to the function of coating, toughness, and reversibility. Gelatin is also safe for consumer consumption.

Gelatin plastics have been used before but primarily as plastic film, not as the main component of a plastic product. The only issue preventing the wide-scale use of gelatin plastic is that its hydrophilic nature makes it non-durable for storing moist food products.

However, it turned out that this biopolymer can be used, for example, in integrated holographic elements. Waveguidings have been observed in thin layers of polymer gelatin on various substrates, including glass and aluminum. A graded index profile can be induced in the gelatin layer and tuned by wet processing. This process enables the formation of waveguides on any smooth surface, and then the integration of single and multiplexed gratings on the same substrate to perform various functions for optical interconnects and signal processing [157].

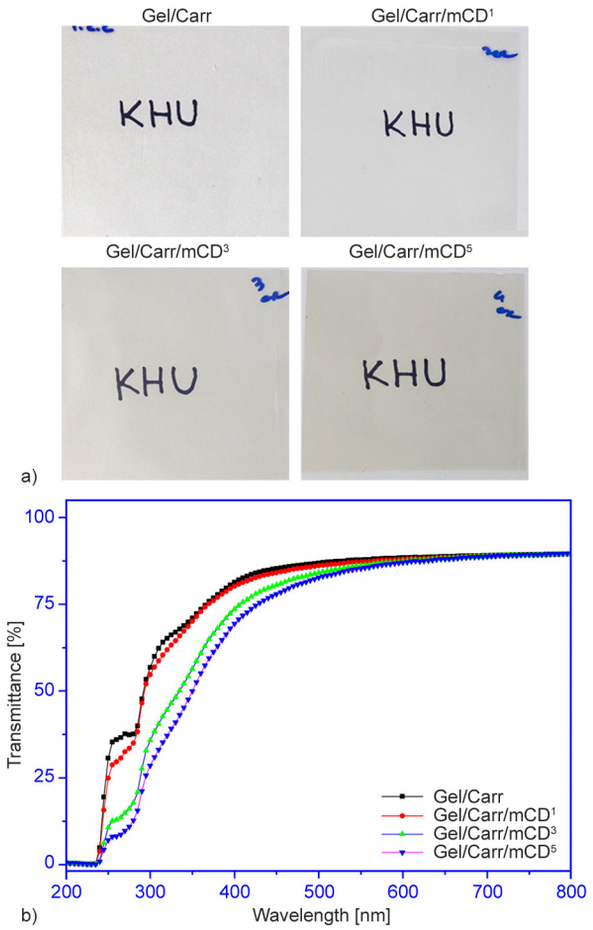

Figure 13. Visual appearance (a) and light transmittance spectra (b) of the gelatin/carrageenan-based active food packaging films [154] (reprinted with permission).

So far, it is the photo-limestone gel that has been gaining attention and becoming more important because of its potential for use in integrated holographic components. However, it was a passive optical element. In response, an electro-optical modulator with nitrophenol and gelatin was constructed and demonstrated for the first time [158]. The transmission spectrum of nitrophenol/gelatin shows an ultra-wide optical bandwidth, from 340 to 2800 nm, and a relatively stable and large electro-optic effect at 632,8 nm. Accordingly, the authors claim that this result indicates that both passive and active integrated optical devices can be fabricated onto the same polymer thin film, forming a fully polymer-based miniature integrated optical circuit [158].

Another interesting example is the use of gelatin in electrochromic devices. The results obtained with gelatin host matrice are very promising. As alternative energy sources are now one of the global challenges that need to be urgently addressed, electrochromic

materials have been in high demand for several decades. Their important applications include such examples as electrochromic windows, rear-view mirrors, electrochromic displays and electronic paper or electrochromic painting [159]. Suffice it to say, that electrochromic windows, for example, which can effectively control heating and cooling loads in buildings, can reduce annual energy costs by as much as 15% if applied correctly. Electrolytes are ubiquitous in all semiconductor devices, which are then transformed into similar multifunctional systems with great potential in such applications [160, 161].

Accordingly, gelatin-based electrolytes were successfully used to assemble prototype electrochromic devices (ECDs) and showed good optical density. The ECD display containing the gelatine I and gelatine II samples presented an average visible transmittance above 68% in the bleached state. After coloration, the structure composed of gelatine I showed an average transmittance in the visible wavelength region above 21 and 36% for gelatin II [162].

There are other similar examples. New gelatin-based polymer electrolytes have been developed, among others, by Leones *et al*. [163]. The cited paper describes the results of characterizing polymer electrolytes using a gelatin matrix with various ionic liquids.

Applications of gelatin-based blends can be expanded. Gelatin is often considered the prototype for most natural polymeric gelling systems. These systems can be modified by blending with synthetic polymers to improve their chemical, physical, mechanical and thermal properties. For example, the effect of ionizing radiation on polymers can cause a variety of effects (*e.g.*, irreversible bond cleavage, cross-linking, chain scission, free radical formation, *etc.*), which can significantly introduce defects inside the polymer [164, 165]. These, in turn, are further responsible for changing their physical and chemical properties, such as the structural and optical properties of the material [166–168]. The issue has been reported, among others, in the paper of Basha and Hassan [169]. The results obtained can expand the range of applications of gelatin-based blends to optoelectronic devices, organic light-emitting devices, solar selective and anti-reflectance bio-coatings, optical organic glass and lenses.

4. Transparent resins; dosimeters used for radon detection (CR-39 resin)

Ionizing radiation has accompanied mankind since the dawn of time. Until the end of the 19th century, it was exclusively natural radiation from radioactive elements contained in the earth's crust and cosmic radiation. The discoveries of Becquerel and Roentgen pioneered the use of ionizing radiation for medical and industrial purposes. It was realized fairly quickly that radiation is, unfortunately, also harmful to living organisms [170–173]. Fortunately, the introduction of protective elements and limits on radiation absorption began fairly quickly.

The situation was completely different for the natural radioactive gas, radon. It has been known for quite a long time that radon, or rather its derivatives forming radioactive aerosol, causes irradiation of lung cells, which can cause lung cancer. However, due to the widespread occurrence of this element in nature, the danger caused by radon was often minimized or even overlooked. In December 2013, The Council of the European Union enacted Council Directive 2013/59/Euratom, establishing basic safety standards to protect against the dangers of exposure to ionizing radiation. The problem presented here also calls for the need to significantly improve the public's knowledge of radon. Among other things, studies conducted by Olszewski and coworkers [174–178] address the problem posed.

Radon concentration in buildings is a very important radiological protection issue. Radon is constantly emitted from the bedrock as a result of the natural radioactive transformation of radium, from where it penetrates the soil and then through basements into buildings. With insufficient ventilation, it can reach high concentrations. The intensity of radon exhalation depends on both local geological factors, as well as the time of day and year, climatic conditions, *etc.* (Figure 14). For example, the chimney effect, which results from differences in air temperature, causes radon to be sucked up from basements and enter the upper floors of the building [174, 175, 178].

In addition, studies have been performed to determine the doses absorbed by the brain, spinal cord, thyroid and eye lens in patients during panoramic radiography, cephalometric radiography and cone beam computed tomography (CBCT). As a result, cone-beam computed tomography was found to provide higher radiation doses to the patients compared

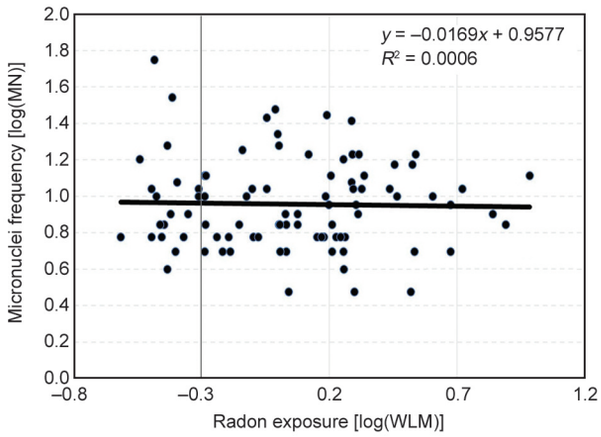

Figure 14. Correlation between micronuclei frequency (MN per 2000 binuclear cells) and radon exposure level in 88 residents of Kowary city. The vertical line indicates the cut-off value of 0.55 WLM corresponding to the whole year of exposure to radon at the activity concentration of 100 Bq/m^3 [175] (figure licensed under the Creative Commons Attribution 1.0 International License (CC BY 1.0)).

to panoramic or cephalometric imaging techniques. The maximum absorbed dose recorded during performed measurements corresponds to the point representing the brainstem and it is 10 mGy (Figure 15) [176].

Various methods are used to measure radon concentrations, one of which is trace detectors. They contain a strip of special CR-39 film in a plastic diffusion chamber with a filter that eliminates solid radon decay products. Radon penetrates the chamber, and

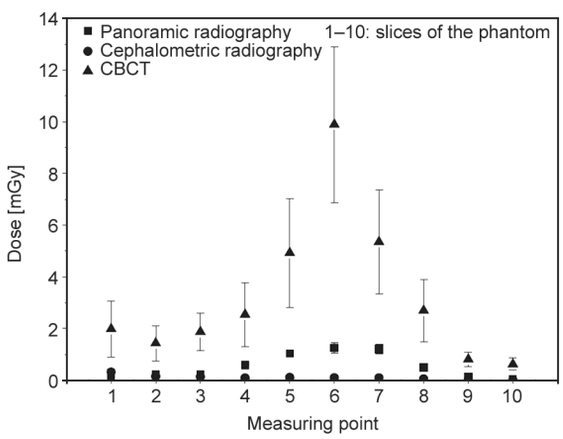

Figure 15. The mean absorbed doses (± standard deviation) to brain and neck structure during panoramic radiography, cephalometric radiography and cone beam computed tomography (CBCT) were measured in anthropomorphic Rando phantom [176] (figure licensed under the Creative Commons Attribution 3.0 International License (CC BY 3.0)).

the emitted alpha particles cause micro-damage to the film. After exposure for a period of 3–6 months, the film is etched in soda lye, making traces of alpha particles visible. The traces can be counted under a microscope or automatically in a special reader that works with a computer. CR-39 films are disposable, as the traces of alpha particles, still magnified by etching, are permanent.

CR-39 is a highly sensitive charged particle detector in current solid-state nuclear track detectors (SSNTDs). Details of the discovery and sensitivity of the CR-39 detector can be found in many previous studies [179–182]. Among them, Rana [183] claim to have authored more than 50 charged particle detection and measurement experiments using CR-39 detectors over the past two decades [182, 184–186]. CR-39 is chemically stable to water and other liquids commonly used in radiation measurement laboratories, and its chemical etching and thermal properties have been described in published studies [187, 188]. Overall, it is a high-quality plastic with very good light transmission, a refractive index close to 1.50 and a density of 1.32 g/cm^3 [189]. It can withstand a temperature of 100 °C continuously. It was observed that CR-39 loses its transparency if heated above 100 °C, and becomes opaque when heated to 200 °C [190]. What is extremely important from the point of view of its use, long-term storage of CR-39 detectors in refrigerators only slightly deteriorates their properties. The response of CR-39 detectors stored for a decade in refrigerators and then used in various charged-particle detection experiments was as good as that of freshly purchased CR-39. Moreover, quantitative measurements of the bulk etch rate of CR-39 stored in a refrigerator for different periods of time show stable values with lower uncertainties compared to those stored in a laboratory atmosphere. Thus, storing CR-39 material in a refrigerator is strongly recommended for its use as precision detectors.

In general, for correct, precise and repeatable measurements with CR-39, or another track detector, knowledge about characteristics of the exposing particles, etchant concentration and temperature along with their stability, and the quantitative response of the trace measurement equipment are important [183].

Certainly, one of the best methods for assessing personnel exposure to ionizing radiation is individual dosimetry. It should be noted, however, that this

method of measuring dose does not always represent the true exposure of a worker in nuclear medicine. As a standard, ring dosimeters are used in nuclear medicine departments, usually placed at the base of the middle finger. The specificity of work in nuclear medicine departments consists of the use of isotopes and procedures that contribute to a significant value of the equivalent dose received, in particular, by the fingertips. In other words, the highly inhomogeneous distribution of dose on the hand means that the ring dosimeter routinely used for measurement provides only approximate values of the dose received by the fingertips, the part of the body most exposed to ionizing radiation. It has been reported, according to Wrzesień *et al*. [191], that the dose recorded by the ring dosimeter is on average five times lower than the dose received by the tips of the thumb, forefinger and middle finger.

Therefore, a wrist dosimeter was developed that could be used as a replacement for the ring dosimeter. The research by Wrzesień and Olszewski [192], among others, is an attempt to answer the question of whether a wrist dosimeter can provide dose information for the most exposed portions of a worker's hand during handling procedures with radiopharmaceuticals. As a result of this research, among other things, correction factors were determined, which represent the correction to be used to go from the dose recorded by the wrist dosimeter to the doses received by the most exposed portions of the hand. As a result, it was noted that the fingertips received, on average, 25 times higher doses compared to the values recorded by the wrist dosimeter. The use of correction factors requires ensuring that the wrist dosimeter is in a stable position during routine procedures.

Summarizing the cited papers and the literature review, they undoubtedly show the validity and importance of the research conducted in the field of protection from ionizing radiation. Since it has been recommended that human exposure to ionizing radiation from all naturally occurring radioactive elements be treated equally, radon exposure must be included in the legislation of EU member states. In the context of the growing importance of the issue, research on the improvement of exemplary medical radiological procedures for maintaining health and safety in workplaces, as well as in the field of protection against exposure to radon from building materials, for example, will certainly not cease.

5. Methods for measuring optical properties of polymers

The optical properties are dependent on the specific polymer or copolymer material, the composition (*i.e.* dyes, fillers, plasticizers and other additives) and the crystallinity of the materials. Also, mechanical and chemical degradation or aging processes and mechanical conditions, as well as thermal treatment applied during processing, affect the optical properties of polymers and polymer formulations [193].

Typically, optical testing includes characterization and analysis of optical components by determining transmission, clarity and haze, refractive index and birefringence, gloss, color and yellowness, as well as surface irregularity and contamination. The transmission of visible light (400–700 nm) and of ultraviolet radiation (100–400 nm) are important parameters in designing, for example, the right packaging to preserve and protect products until they reach the consumer. In general, the practical use of a given material in optical design requires precise data on its refractive index and dispersion behavior [194].

The refractive index and light transmission of transparent materials, such as those used in lenses, optical fibers, large-screen displays or coatings, are relatively easy to measure accurately. UV-visible light transmission is the ability of a plastic material to allow light to pass through it in the UV-visible range, measured by spectroscopy. Objectives here may be different and even totally opposite. For example, in agricultural film, plastics must allow maximum transmission of visible radiation and minimum ultraviolet radiation transmission. In opaque pharmaceutical and cosmetic packaging, the material must ensure minimum radiation transmission. The birefringence is caused by the fact that the refractive index varies with the orientation of the polymer chains at the molecular level [195, 196].

For an imperfectly transparent sample, there are two criteria for evaluating its transparency [197]. First, one can focus on the degree to which the details of the object viewed through it are visible and recognizable. This ability of the sample is known as clarity. And, the second criterion evaluates the degree to which the sample reduces the apparent contrast of the object viewed. This aspect is commonly known as haze or milkiness. Both of these measures must be determined to fully characterize the transparency of a material. At the same time, it should be noted

that they can vary independently of each other, *i.e.* haze can deteriorate while clarity improves [198]. The overall transparency of a sample is determined by the ratio of total transmitted and scattered light.

Haze is the most commonly used to characterize the transparency of a plastic product and is the total scattered light flux in the angular range of 2,5 to 90° and normalized to the total transmitted flux. Haze measurements are most commonly made by the use of a spherical haze meter [199]. However, on the scientific side, spectrophotometric techniques are used that can provide valuable diagnostic data on the origin of haze to investigate a number of issues that result in haze as a symptom (*e.g.*, atmospheric conditions during product and process development). The spectrophotometer fitted with an integrating sphere enables haze *versus* wavelength graphs or percentage transmission versus wavelength to be generated [200].

Less explicit is the determination of clarity, *i.e.* the ability of a sample to convey the fine details of an object. Several quantities are used to characterize it, and unlike haze, there is no standardized, widely accepted technique for its determination [198].

Next, specular gloss is a measure of how reflective a material is at a specified angle based on refractive index [201]. Tests are carried out at different angles of reflection. 60° is the most common angle with lower angles (20°) used for high gloss samples and higher angles (85°) for low gloss samples. This test method helps to determine the impact of external factors on the visual appearance of the optical element. These stresses can include processing, finishing, light and temperature aging, and weathering.

Most polymers are usually gray or yellow in color. White fillers or other optically active color additives can help match the appearance of the application. Color change evaluation may be needed, for example, due to exposure to adverse conditions to match parts molded from different materials, or due to color changes caused by surface texture, molding or processing [202]. Typically, color measurements of polymer materials are then evaluated against the CIE $L^*a^*b^*$ scale, which assigns numerical values to color and thus allows for easy comparison of color and/or color change. More specifically, the L-scale measures brightness relative to darkness, while the a- and b-scales are color coordinates, *i.e.* the a-scale estimates red relative to green, and the b-scale determines the proportion of yellow and blue [203, 204].

Yellowness index is a number calculated from spectrophotometric data that describes the change in color of the test sample from clear or white to yellow.

The number of determining factors and the complexity of the relationship stand in stark contrast to the natural demand in practice to characterize optical properties by a simple number such as transparency, haze, *etc.* Despite these controversies and difficulties in interpreting the dominant factors, the optical properties of a polymer can be determined, reproduced and compared by strict application of appropriate standards.

6. The optical properties and future development prospects of biopolymers

Biopolymers are utilized most frequently in the medical field, which attracts much of interest in comparison with other fields, due to characteristics such as biocompatibility, degradation by microbes into nontoxic end products, maximization of biological activities, lower immunogenicity, ability to support cell proliferation with the proper mechanical properties, *etc.* [205–207]. In addition, because of their physical properties, which allow modification of molecular weight, chemical composition, and production conditions while achieving the desired properties, packaging polymers are also currently in high demand. Biopolymers are thus typically used in applications such as food containers, soil-holding sheets, trash bags, and ordinary packaging materials because of their film-forming and barrier properties [208–210]. It should be also noted that biopolymers have attracted interest from the agriculture industry for their natural degradation and soil-improving properties, with significant potential for developing mulches and plant containers. By retaining moisture, reducing weed growth, maintaining proper soil temperature and, most importantly, being photodegradable, fertilizers containing them contribute to plant growth and eliminate the need for removal and associated costs. They are also finding application in hazardous waste disposal, the paper industry, and even in the development of new building materials, as well as in the production of automotive materials, since most manufacturers are aiming to produce plastic car components from bio-based polymers, such as polyamide, polyester and polypropylene, among others [211–213].

Against the background of the above examples, optical applications of biopolymer-based materials are

limited. Materials used to create optical components must have the ability to modulate or control electromagnetic radiation in the UV, visible and IR spectral ranges. The degree of transparency, refractive index and their dependence on the spectrum are the most important factors when selecting an optical material. Materials with high transparency exhibit relatively low reflection, absorption and scattering of light, which results in minimal optical losses. However, biopolymers largely absorb light at short wavelengths of 250–400 nm, which is typical for many organic compounds. This significantly limits the optical use of materials based on biopolymers [214]. Nevertheless, several fields, including organic electronics, materials chemistry and printed electronics, are now being combined to create new, environmentally friendly electronics. While challenges still remain for real-world applications in the field of biopolymers, there is a strong need to reduce electronic waste and open up creative paths for the development of new electronic devices that are environmentally friendly and sustainably designed. Therefore, future prospects for biopolymer development include the creation of multifunctional electronic devices based on biopolymers [214–216]. In today's culture, where electronic devices are ubiquitous and permeate every aspect of human activity, biodegradable electronics have emerged as the most practical and desirable solution to environmental issues, and biopolymers used in the latest functional electronics applications are being studied in detail for molecular engineering.

The creation of materials with novel functions and programmable properties is made possible by the wealth of functional groups present and the ability to manipulate the supramolecular organization of biopolymers. The prospects for the use of biopolymers are expected to be based on expanding the range of molecular engineering strategies to modify biological molecules for novel optical/electrical properties, functions and applications through non-covalent/covalent bonds with functional groups such as hydroxyl, carboxyl, amine and amino groups. In addition, the abundance of functional groups in biopolymer molecules allows for stable dispersion or high solubility in common liquids, including water, *e.g.* to form soluble electronic inks. Biopolymers also have some unique electrical properties that make them an ideal choice for electronic devices, having good ionic conductivity, high electrical conductivity, as well as versatility and stability, *etc.* [214].

Future predictions for biopolymer applications in optical materials include the growing use of bacterial cellulose (BC). Due to its inherent properties, renewability and abundance, nanocellulose may prove to be one of the most promising green materials, from extraction, fabrication and surface modification, to material creation and applications. The optical properties of nanocellulose provide ample opportunities for design and application in optoelectronics, including solar cells, displays, flexible electronics, and touch screens [217–219]. Because they allow light to pass through, cellulose-based materials are naturally transparent. Since nanocellulose has diameters smaller than visible light wavelengths, the optical transparency of plastic and nanocellulose nanocomposites is increased. The difference between the refractive index (RI) of nanocellulose and plastics is minimized to improve the light transmission of nanocomposites. Chemical processing of nanocellulose changes its refractive index, with acetylation being the most common chemical treatment. It should be emphasized that excessively acetylated nanocellulose will have lower RIs compared with that of plastics. Moreover, nanocomposites containing BCs with a high degree of substitution (DS) show better transmission, since bacterial cellulose exhibits the lower refractive index with increasing DS. Additionally, the nanocellulose (BC) inhibits crack growth in nanocomposites, allowing the material to fold without cracking. The properties of BC-containing nanocomposites are also affected by plasticization methods [214, 220, 221].

The combination of nanocellulose and carbon-based materials, such as graphene, carbon nanotubes and carbon dots, has been identified as a promising approach for the future of renewable electronics. Among the examples in the field of optical electronics, the current literature review shows, for example, high demand for flexible electrically conductive sheets with high surface conductivity, broad optical absorption, and exceptional chemical and thermal stability. Using a facile vacuum filtering technique, silver nanowires (AgNWs) deposited layer-by-layer on the surfaces of hybrid membranes made of cellulose nanofibers (CNFs) and graphene oxide (GO) were developed by Wang *et al.* [222]. As a result, the obtained AgNWs layers are capable of forming fused structures based on the flexible, solid base provided by intermediate CNF/GO layers.

Another example from the current literature would be lightweight, flexible supercapacitors. They can be considered one of the most important potential optical-electronic applications for nanocellulose materials. In this case, nanocellulose combined with a conductive substance (usually a polymer) provides the necessary mechanical support for bendable, freestanding structures and high volumetric capacity. The most commonly used conductive polymers are polypyrrole, polyaniline and polycarbonate. A relevant example of similar materials may be the electroactive composite. For this purpose, polypyrrole was applied to cellulose fibers and a material was obtained that is not only electroactive but also conductive and capable of storing energy. It is anticipated that the latest developments in flexible energy and electronic devices will be pursued with a particular focus on luminescent and conductive materials based on nanocellulose [223–227]. As its industrial-scale production remains relatively expensive, an important issue in this regard will be the development of potential design strategies required to expand their use in commercial applications.

In addition to nanocellulose, other biopolymers identified as ideal for optical applications include poly (limonene carbonate), silk fibroin, chitosan, gelatin, alginate, polylactic acid, and polyhydroxyalkanoates. Silk materials, for example, are creating new opportunities in optics, photonics, and flexible electronics due to their transparency, flexibility, and surface patterning simplicity [228]. These proteins have a unique nanoarchitecture that provides them with additional particular properties such as rigidity, strength, and toughness. Still, integrating the practical application of biopolymers to produce the aforementioned high-performance flexible electronic devices poses various challenges. To offer novel materials with exceptional features (*e.g.*, electronic conductivity, bioactivity, thermostability, 3D conformational properties, and high ion mobility on the skin and curved surfaces), more mechanistic studies and synthetic methodologies need to be developed for innovative biopolymers. Ultimately, progress is needed in surface/interface engineering methodologies, substrate fabrication technologies, and multifunctional integration of flexible electronics based on biopolymers.

Other future applications of biopolymers in optical materials may involve various flat panel display (FPD) technologies, for example, becoming a promising replacement for inorganic light-emitting displays (LEDs). The lack of reliable and stable white light emitting diodes (WLEDs) in the display industry is one of the significant technological obstacles. In addition, organic thin-film transistors (OTFTs), vital parts of electronic displays, are key in regulating pixel resolution. Biopolymers have recently gained much attention as potential building blocks for flexible TFTs. For example, the successful preparation of high-performance OTFTs has been made possible by using biocompatible human hair keratin as a carrier substrate and a high-capacitance dielectric layer [229–233].

Solar cells are another example of the growing interest in biopolymers as optical materials. Biopolymers such as cellulose, chitosan, pectin and silk fibers are increasingly in demand as optical and electronic devices due to their low density and coefficient of thermal expansion, high tensile strength, and elastic modulus that reveal great potential for solar cells. The silk fibroin (SF) film is a breakthrough transparent substrate for solar cells. The high transmittance of SF film is attributed to a motif consisting of a sequence of amino acids that appears to have weak absorption in the 400–1200 nm spectral range. Liu *et al.* [234] prepared a transparent and conductive composite film by embedding ultra-long silver nanowires as the conductive network with silk fibroin as the substrate material for organic solar cells. The ultra-long length can help minimize the number of junctions between the nanowires on the conductive grid, which can reduce greatly the resistance and optical shielding effect of the conductive layer.

The development of high-performance, flexible electronics that can accurately detect external signals has been also observed within the past few years [235–237]. Anticipated development prospects primarily include chemical sensors, biosensors and strain sensors with enhanced performance through molecular modification of biopolymers. The incorporation of functional biopolymers through doping, surface modification and chemical group design, in addition to providing sensors with high flexibility, also enhances charge transfer in the active sensing layer, increasing the sensitivity and detection threshold of the sensors. Biopolymers with multiple functional groups (*e.g.*, such as NH_2, OH, C–N, and C=O) that can accurately detect analytes are suitable for chemical sensing

applications. By converting chemical processes into electrical pulses, chemical sensors are thus sensitive to different substances. This technology is crucial for smart agriculture, food safety, environmental monitoring and medical diagnostics [239]. A potential manufacturing strategy for high-performance biosensors, in turn, is vital for forensic analysis, drug release monitoring and biomarker identification [239–241]. Meanwhile, strain sensors, and wearable strain sensors, in particular, are of great interest because they could play a significant role in future flexible and wearable electronic systems. To ensure long-term monitoring of human health and activity, mechanical stretch has become one of the most important features of strain sensors. However, meeting all practical needs (*e.g.*, higher sensitivity, greater optical resolving power, and more flexible features) without compromising the biocompatibility and performance of the sensors is still a challenge.

Future prospects for biopolymers also include their application in the fields of bioimaging and data storage. The examples of potential directions for the future development of biopolymers in optical materials considered in this chapter are summarized in Table 1.

7. The advantages and disadvantages of optical polymers compared with traditional glass materials

According to reports, the use of plastics as optical materials did not begin until the 1970s and has developed much more slowly than in commodity industries such as packaging, closures, *etc.* [254]. In the past, and to some extent today, plastic components were designed to directly replace components made of traditional engineering materials, leading to poor performance and costly reproduction. In order to effectively replace a material, a designer using plastics must appreciate both their advantages and limitations. Today, designs are being created that are not only unique to plastics but also surpass designs made from traditional materials.

A variety of polymeric materials can be used as optical materials and they mainly include polymethylmethacrylate (PMMA), polystyrene (PS), polycarbonate (PC) and many others described in previous chapters of this publication. Most polymer optical materials have a refractive index between 1.4 and 1.6. Hence, lower optical quality compared to glass materials is cited as one of the disadvantages of polymer optics [254–256]. Generally speaking, the large selection of glass materials allows the designer to choose materials with desirable optical properties to gain better optical performance. This kind of freedom is limited to plastic materials. Indeed, optical glass materials can achieve higher optical transparency and chromatic quality. This is one of the main reasons why glass materials are still used as optical components, despite their higher cost.

Various properties are required for transparent synthetic resins as optical materials, and the refractive index is extremely important among them [257]. A good example is lenses that require a high refractive index, which plays a key role in creating the power and thickness of the lens. For any given lens design, the higher the index, the flatter the curvature of the front and rear surfaces of the lens needed for a given optical power. As a result of these flatter curves, the thickness of the lens is automatically reduced. Therefore, the applications of commonly used resins with

Table 1. Possible future fields with examples of biopolymers for various applications in optical materials.

Field of application	Polymer biomaterial	Literature reference
Displays	Deoxyribose nucleic acid (DNA); chitin nanofibers (CHnF); cellulose nanofibers (CNF), and keratin	[214, 229, 232, 233]
Solar panels	Cellulose, chitosan, pectin, and silk fibroins; DNA and bacterial cellulose (BC)	[214, 218–220, 253]
Sensors	Keratin; chitosan; silk; hyaluronic acid (HA)	[214, 238–241]
Flexible electronics	Silks; cellulose	[214, 215, 242–246]
Bioimaging	Hyaluronic acid (HA); Cellulose derivatives, *e.g.* carboxymethylcellulose (CMC); bio-polymer-based carbon dots	[214, 247–249]
Data storage	DNA; chitosan	[214, 250–252]

refractive indices less than 1.53 are limited in this case. It is reported that the best way to increase the refractive index of optical resins is to introduce the element of sulfur into the polymer structure [258]. Then, sulfur-containing resins reveal high refractive indices, and low dispersion, are light and show good thermal stability.

PMMA and PC are commonly recognized as resins used for optical materials such as plastic lenses. However, the low refractive index of PMMA (1.49 to 1.50) causes a defect during molding in which the center thickness, edge thickness and curvature of the lens become larger compared to inorganic optical glass lenses [254, 259]. Furthermore, although the PC resin exhibits a high refractive index (1.58 to 1.59), it can cause birefringence during molding and, therefore, has a disadvantage in terms of optical uniformity.

It should also be added that PMMA and PC, as thermoplastic resins with a non-cross-linked structure, melt during cutting or grinding. For this reason, they are difficult to be considered satisfactory as materials for use in precision optical machines, optical elements or ophthalmic lenses. Indeed, a method for producing resins with a cross-linked structure using ethylene glycol dimethacrylate as a cross-linking agent is known. However, the resulting resin shows low impact resistance [260, 261]. Hence, there is a need to develop new types of optical resins that would be characterized by a high refractive index and low dispersion (with less chromatic aberration).

When comparing the quality of polymer materials to glass materials, another risk in some situations may also be the sensitivity of plastic optical elements to high temperatures. In some cases, this can be a problem. Glass materials are generally more stable over a wider temperature range and humidity environment than plastics. It should also be noted that plastic optics are softer than glass optics, which means they are susceptible to scratching. As a result, an optical coating may be required in certain situations [262].

However, polymer optics also have advantages over glass optics. They offer other design freedoms that are not achievable or economical with the glass optics. First of all, polymer optics are characterized by low density. Undoubtedly, this aspect is a significant advantage over glass optics since the use of polymers allows the production of light optical components. Moreover, since transparent synthetic resins have excellent impact resistance compared to inorganic optical materials such as glass, they can also be considered excellent in terms of durability [263]. Thus, lighter weight and greater shatter-resistance are very important features, *e.g.* for head-worn optical components such as head-mounted displays.

In general, for example, plastic lenses made from conventional plastics are cheaper and can be produced faster than conventional glass lenses. The manufacturing processes for glass and plastic optics are entirely different. Glass lenses, for example, are made by a grinding and polishing process, whereas precision plastic lenses are made by injection molding [264–266]. Hence, the differences in the manufacturing process provide polymer optics with some unique advantages, such as high-volume production capability and low manufacturing cost. Secondly, the injection molding process makes it feasible and economical to produce more sophisticated optical shapes such as spherical and diffractive surfaces, provided the mold is made correctly. From a design standpoint, the more refined surface shapes provide significantly improved performance in many applications. These advantages determined the superiority of polymer optics over glass optics, hence the wide use of the former in glasses, cameras, telescopes, *etc.*

Finally, the optical properties of polymer optics depend on the specific polymer material or copolymer used. Of course, the composition is also important, taking into account fillers, plasticizers, dyes and other additives. Moreover, the crystallinity of the materials will also have a significant impact on the optical properties [267, 268].

In summary, although glass has been the traditional choice for optical components, the advent of optical polymers transformed and expanded their application potential in modern optics. Polymers have several advantages over glasses and ceramics and have been an excellent replacement for traditional optical materials in many recent applications. Within that wide range of plastic materials, there is a special category that exhibits excellent optical properties, such as high transmission and refractive index comparable to float glass. Such plastics are well suited as substrates in the manufacture of a range of optical components, such as lenses, optical fibers, gratings, *etc.* Nevertheless, to effectively replace the material, the designer must appreciate both its advantages and limitations.

8. Conclusions

This article reviews the most important reports on available polymers with optical properties, dividing them into groups, *i.e.* synthetic optical polymers (including polymethylmethacrylate, polyethylene terephthalate, polypropylene, as well as cyclic olefin copolymers and polyolefin elastomers) and biopolymers (including polylactide and gelatin). A separate place and chapter is given to transparent CR-39 plastic and the issue of individual dosimetry for radon detection.

In addition to this particular application, the article briefly discusses the most important current applications of optical polymers, citing current examples. The examples cited flow from the point of view of the growing demand for high-quality imaging and advanced optical components in a variety of industries, but also healthcare and expanding public awareness of the increasing importance of resource efficiency, carbon footprint, and responsible use and disposal.

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