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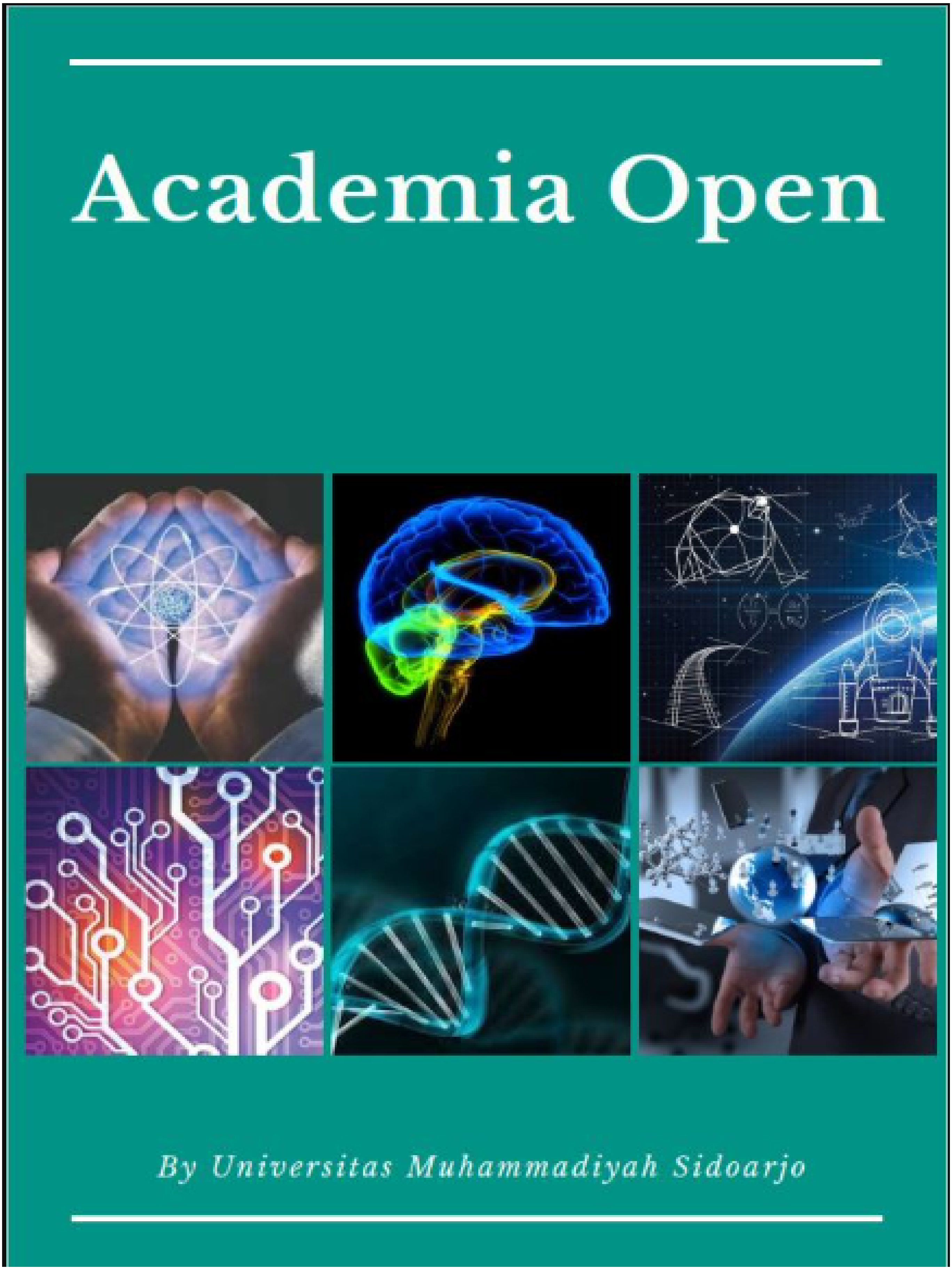

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Polymer Science: From Basics to Nanotechnology Applications: Ilmu Polimer: Dari Dasar hingga Nanoteknologi Aplikasi

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Abstract

General Background: Polymer materials have become essential components in modern technology due to their lightweight structure, chemical stability, and adaptable physical characteristics.**Specific Background:** Advances in polymer science have enabled the modification of molecular structures and the integration of nanoparticles, allowing polymers to perform functions beyond traditional insulating and structural roles. **Knowledge Gap:** Despite extensive use in industrial and technological fields, a comprehensive conceptual synthesis linking polymer structure, classification, properties, and emerging nanotechnology applications remains necessary to clarify their functional relationships. **Aims:** This study analyzes the fundamental principles of polymer science, including structural composition, polymerization mechanisms, classifications, and key physical and chemical properties, while highlighting emerging nanopolymer applications. **Results:** The analysis demonstrates that polymer performance is strongly related to molecular structure, degree of polymerization, and intermolecular interactions. The integration of metal and oxide nanoparticles within polymer matrices introduces additional optical, electrical, and catalytic functionalities. **Novelty:** The work provides an integrated conceptual overview connecting classical polymer theory with modern nanocomposite developments in materials science. **Implications:** Understanding the structure–property relationship of polymers supports the development of advanced materials for applications in electronics, renewable energy systems, biosensors, and biomedical technologies, while also emphasizing the importance of sustainable polymer research.

Keywords: Polymer Science, Nanopolymer Materials, Polymer Structure, Polymer Nanocomposites, Materials Engineering

Key Findings Highlights

1. Polymer molecular structure determines mechanical, thermal, and electrical material behavior.
2. Nanoparticle integration introduces new optical and electronic functionalities in polymer systems.
3. Polymer nanocomposites support emerging technologies in energy systems, sensing devices, and biomedical materials.

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Introduction

Modern technologies require many properties not found in other materials [1] and polymers have played a very distinctive role in many areas of daily life due to their unique properties compared to traditional materials [2-3]. Today, engineers and designers are working to easily transform the properties of polymers because They have a number of qualities not found In other types of materials. Polymers are unique in their resistance to corrosion, flexibility, colorfastness Flexibility in treatment and light weight. [4-5]. The science of polymers has advanced significantly in recent years, and scientists are working to produce inexpensive, flexible, and versatile polymers [6-7]. Polymers have become a substitute for metals in most applications due to their chemical stability and resistance to corrosion and deterioration. Currently, most polymers are produced as lightweight solids or porous sponges and are used as insulating materials because of their poor thermal and electrical conductivity. Although traditional polymers have virtually no free electrons modern scientific and technological advancements have allowed for minor modifications, resulting in a new generation of polymers that combine electrical properties similar to conductors and semiconductors while retaining the original mechanical and chemical properties of polymers. [7-8]. Research and studies on these materials continued, especially during World War II when research was conducted continuously and rapidly. Countries began competing to produce various types of synthetic polymers and composites made from them. Due to the distinctive physical and mechanical properties of these materials polymer technology flourished rapidly, thanks to the high degree of modifiability and control. Consequently various technological properties surpassed those of some traditional materials leading to significant applications across different fields. Polymers were used in numerous industrial products ranging from children's toys to the structures of cars and aircraft [9]. Furthermore these materials were used in electrical applications, making the study of their electrical properties one of the most attractive and active areas. Their ability to provide complete electrical insulation was used to protect electrical currents in conductors from leakage and to protect the electrical field from breakdown [10]. These materials were classified as semiconductors and conductors. Communication networks were among the first prominent scientific applications of polymers. For example polystyrene (PS) is characterized by its high electrical insulation and ease of molding. Polyurethane (PU) is distinguished by its good electrical insulation durability and resistance to weather fluctuations. Polyethylene (PE) was characterized by good electrical insulation and flexibility a desirable property in insulators used in the manufacture of coaxial cables for radar and television equipment. Thin polymer films were chosen after their development and expansion in the capacitor industry. These materials fall under the category of semiconductors where some insulating polymers are transformed into conductive ones by doping with impurities sometimes referred to as metallic plastics. Furthermore, polymers can become superconductors at relatively low temperatures, as demonstrated in studies by several researchers the earliest of whom [11]Polymers have been adopted in optics to manufacture lenses used in the latest optical devices due to their light weight polymers weigh half as much as glass. Furthermore they possess high resistance to breakage. Polymers have also been used to reduce the impact of sunlight on aircraft instruments and pilots eyes and to mitigate multiple reflections within the material [12-13]. Additionally they were used to coat metal sheets for attenuation in stealth technology and to prevent rust and oxidation [14].

2 History of Polymers

The history of polymers dates back to the early 19th century, when Henri Bracono conducted groundbreaking research on cellulose-derived compounds, considered among the foundational studies in the field.The discovery of vulcanization in the late 19th century marked a pivotal turning point in the history of materials. This technique radically enhanced the mechanical properties and thermal stability of natural rubber. This fundamental shift paved the way for the widespread use of the first semi-synthetic polymers. This was followed by another significant scientific achievement at the beginning of the 20th century: Leo Baekeland's success in 1907 in synthesizing the first fully synthetic polymer in the laboratory, later known as Bakelite. This innovation relied on a controlled chemical reaction between phenol and formaldehyde, subjected to precise conditions of temperature and pressure to achieve the desired result. This revolutionary product entered the commercial market just two years after its discovery, in 1909 [15]. Nor can we overlook the pioneering role played by two other prominent scientists in establishing and developing the science of synthetic polymer chemistry: the Italian Giulio Natta and the German Karl Ziegler, who made substantial research contributions that laid the methodological foundations for this broad scientific field. Ziegler received the Nobel Prize in Chemistry in 1963 for his invention of the Ziegler-Nattah catalyst. The global interest in this field was further demonstrated by the awarding of the Nobel Prize in Chemistry in 1974 to Paul Florey. Synthetic organic polymers (such as wax and lacquer) have been used for centuries. Cellulose—a plant polymer—formed the basis for the strength of natural fibers and ropes. In the early 19th century, natural rubber (derived from rubber trees) became widely used in medical applications. When compared to vulcanized Goodyear rubber, untreated natural rubber offered greater abrasion resistance, higher strength, better elasticity, and greater tolerance to temperature variations, electrical and gas insulation, and chemical resistance [16].

3 Basic Concepts and Foundational Definitions

3.1 Definition of Polymer

Polymer science was defined as the study of macromolecules, which are composed of repeating simple chemical units called monomers. Each monomer is a fundamental building block of the polymer, as illustrated in the structural table of some important polymers. These basic units were linked together by chemical bonds, forming long molecular chains. Because of this, polymers typically have a high molecular mass compared to other compounds [18-17] .The number of monomer units that make up the polymer chain was called the degree of polymerization [17] .

The term polymer was derived from a Greek root composed of two parts: "poly," meaning many, and "mer," meaning part or unit, indicating that a polymer consists of many repeating units in its molecular chain. The bonds that hold polymer molecules together are generally covalent, and there are intermolecular forces known as secondary forces or van der Waals forces. These forces are usually generated between adjacent polymer chains or between parts of the same chain and have a significant impact on most of the physical and mechanical properties of polymers [19].

Table (1) provides an overview of the basic structure of a number of major polymers along with the basic molecular units (monomers) that they are made of.

Monomers.	Structure.	Polymer name.
Ethylene- $CH_2=CH_2$	$(CH_2\text{-}CH_2)_n$	(Polyethylene - PE)
Propene- $CH_2=CH\text{-}CH_3$	$(CH_2\text{-}CH(CH_3))_n$	(Polypropylene - PP)
Chloroethene- $CH_2=CHCl$	$(CH_2\text{-}CHCl)_n$	(Polyvinyl Chloride - PVC)
Phenylethene- $CH_2=CH\text{-}\ C_6H_5$	$(CH_2\text{-}CH(C_6H_5))_n$	(Polystyrene - PS)
Acrylonitrile-$CH_2=CH\text{-}CN$	$CH_2\text{-}CH(CN))_2$	(Polyacrylonitrile-PAN)

Table 1.

3.2 Degree of Polymerization, Molecular Weight

The behavior and properties of a polymer depend fundamentally on its degree of polymerization, abbreviated as Dp, which is defined as the number of repeating building blocks within the polymer chain. If the degree of polymerization is low, or falls between 10 and 20, the polymer was classified as an oligomer. In contrast, commonly used synthetic polymers were characterized by high degrees of polymerization. Dp values range around 100 in materials such as glues and paste-like adhesives, while reaching 1000 or more in the case of synthetic rubbers and rigid plastics. Therefore, the degree of polymerization is a direct measure of the molecular weight of a polymer, as the molecular weight can be deduced from the degree of polymerization (Dp) and the repeating unit weight [18].

4. Polymer structure

The spatial structure (shape) of polymer chains is determined based on the type of chemical bonds that link the chain atoms. Because single bonds can rotate around their axis—especially when the polymer is in solution or molten—polymer chains can assume multiple and varied three-dimensional configurations [20]. The local mobility of specific parts of the polymer chain, and the resulting different three-dimensional configurations, is the primary factor controlling the physical and mechanical properties of polymers, such as the elasticity of rubber and the rigidity of some other polymers. The process of strengthening rubber (vulcanization), which aims to increase its rigidity and decrease its elasticity is just one example of restricting the free movement of these chains. The local mobility of polymer chains is entirely temperature-dependent. Molten polymers are in a viscous, flowing liquid state because their chains move relatively freely. This property was exploited in polymer manufacturing processes by melting the polymer and then pressing it into molds of specific shapes. This technique was known as casting. During the cooling process of a molten polymer mass, the material takes the shape of the container or mold in which it is placed. The decrease in temperature restricts the movement of long polymer molecules causing them to lose their ability to move freely and limiting their movement to small localized vibrations. These vibrations involve the movement of molecular ends and some functional groups attached to the main chains [21]. This molecular transformation is accompanied by a radical change in the mechanical and macroscopic properties of the material as it transitions from a highly viscous liquid phase to a cohesive solid phase. The critical point at which this transition occurs is known as the glass transition temperature (Tg). When the temperature of the medium drops below Tg, even the minute localized movements of the polymer chains and their side branches freeze transforming the material into a brittle solid. Conversely if the material's temperature is maintained above this critical threshold (Tg) the chains retain some internal movement, which gives the polymer its elastic and ductile properties [20]. Figure (2) shows an illustrative representation of the relationship between the basic molecular structure of the polymer and the resulting physical properties [22].

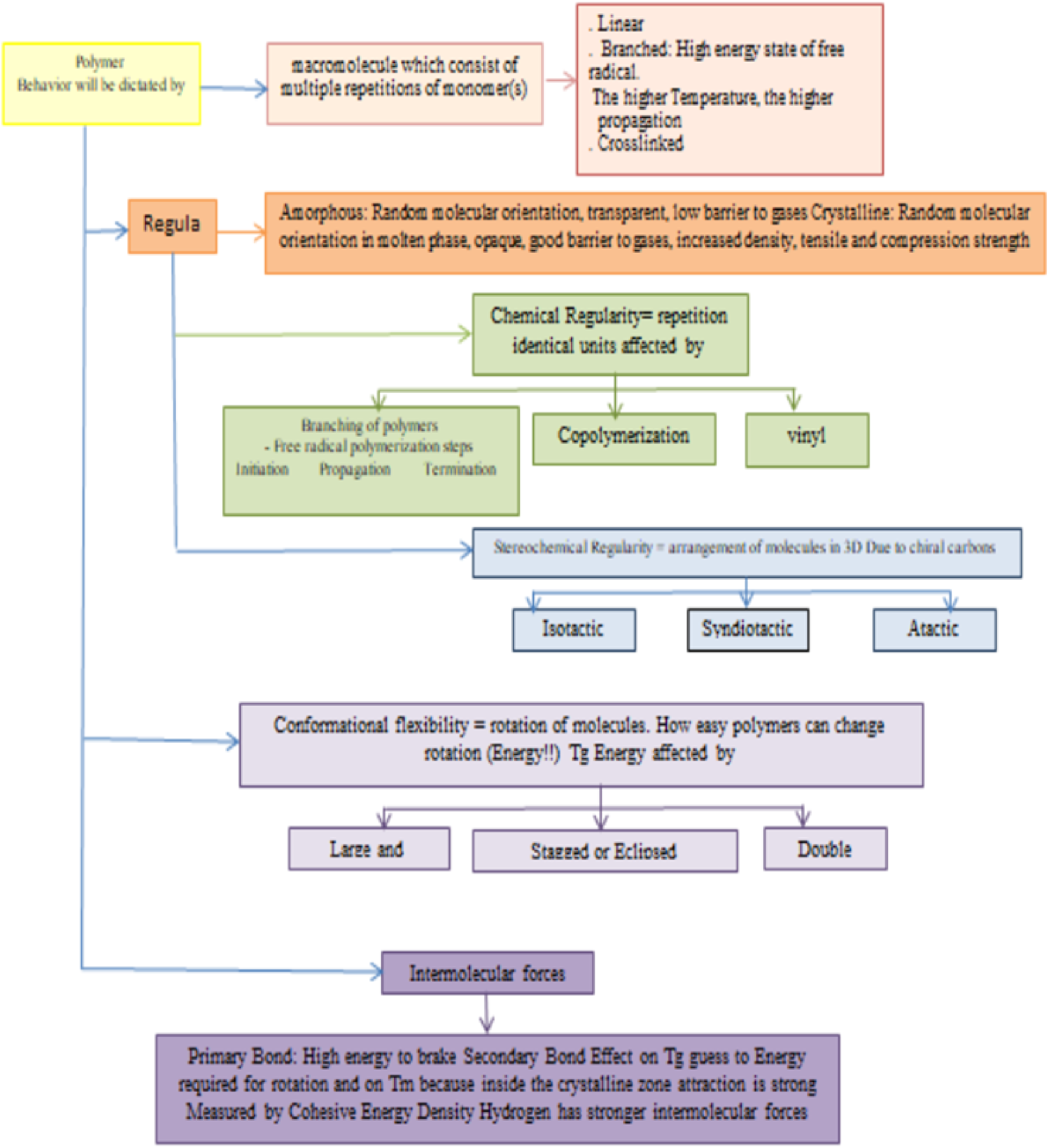


Figure 1.

Figure (1): Shows the relationship between the basic molecular structure of polymer materials and their performance characteristics.

5. Classification of Polymers

Polymer materials can be classified and categorized according to multiple approaches based on various criteria. The following is a presentation of the most prominent classifications:

5.1 Classification by Origin

Polymers are divided into three main categories based on their origin and primary source [20]:

5.1.1 Natural Polymers

This group is further classified into two main categories organic polymers and inorganic polymers.

A. Natural Organic Polymers: These polymers are obtained from plant or animal sources. Examples include cellulose, starch, gum arabic, cotton fibers, natural rubber, silk, leather, and others. These materials are usually relatively expensive due to their scarcity and the difficulty of their extraction processes, which limits the range of their industrial applications.

B. Natural inorganic polymers: These polymers are extracted from mineral sources or inorganic materials such as diamond sand and graphite [20].

5.1.2 Modified Natural Polymers:

This category includes natural polymers whose chemical structure has been altered through deliberate modification processes. These modifications include the addition of new functional groups, modification of the structure of existing functional groups, or cross-linking between a natural and a synthetic polymer or vice versa [21]. Examples include semi-synthetic fibers (such as rayon) cotton cross-linked with acrylic fibers, and cellulose derivatives such as cellulose acetate and its esters among others [23].

5.1.3 Synthetic Polymers

This category is defined as polymers manufactured in laboratories through controlled chemical reactions using simple precursor compounds. They constitute the largest and most important share in the industrial field. This classification includes diverse materials such as synthetic fibers, dyes, various types of plastics, and other industrial products [21].

5.2 Classification Based on Thermal Behavior

5.2.1 Thermoplastics

This group includes polymers whose physical state and properties change when exposed to heat. They soften and become flowable when heated. When the temperature approaches the glass transition threshold (Tg), the material transforms into a malleable and ductile state. As the temperature continues to rise, the fluidity increases, eventually transforming into a molten, viscous mass.

This behavior is attributed to the polymer chains acquiring the ability to move and slide relatively smoothly in the molten phase. During the cooling process, the polymer undergoes the opposite behavior. The chains lose their ability to move and their movement becomes confined to a narrow local range, returning them to their solid state [24]. Generally, the properties of thermoplastics after solidification are determined by several factors, including the molecular length and geometry of the chain, the nature of the side functional groups, the presence of rings in the main structure, and the strength of the van der Waals forces between the molecules. These latter forces contribute to raising the melting point. Representative examples of this class include polymethyl methacrylate (PMMA), polyethylene, polypropylene, and polystyrene [25].

5.2.2 Thermosetting Polymers

These are polymers that undergo irreversible chemical reactions when exposed to heat.

Therefore, crosslinking of the polymer resin and results in thermosetting. Consequently, the resin cannot be reversibly returned to its original state, whether by heating or cooling [26]. In this type of polymer, the molecules are linked by strong covalent bonds through crosslinking, leading to the formation of polymer chains with a three-dimensional network structure. These chains are interconnected and intertwined at multiple locations, and the crosslinking process results in the formation of branched molecules that are initially soluble. However, as the reaction continues for a longer period, the polymer gradually begins to harden [27]. Examples of this type of polymer include unsaturated polyester resins, phenol-formaldehyde (PF) resins (both novolac and resol), and epoxy resin [28]

4.2.3 Elastomers

These are elastic materials that can be stretched to twice their original length and then return to their original length. Examples include natural rubber and polyurethane [29-30].

5.3 Classification by Structure:

5.3.1 Linear Polymers:

In these polymers, the structural units are linked together in a continuous linear fashion, and there are van der Waals forces between the chains, as shown in Figure (2-a).

Examples include polystyrene, polyvinyl chloride, nylon, and polyethylene.

5.3.2 Branched Polymers:

Branched polymers are formed either by the use of monomers with multiple functional groups or by side reactions. The polymer molecule takes on a branched shape, and the branching varies in terms of the length of the lateral branch and its position on the polymer chain. These branches may be arranged cross-linked on the main chain, comb-like, or ladder-like, as shown in Figure (2-b). Example: Low-density polyethylene (LDPE) and high-density polyethylene (HDPE) [31].

5.3.3 Cross-linked Polymers:

In this type, the chains are connected by covalent bonds, often achieved by the addition of molecules or atoms that form covalent bonds between the chains, as shown in Figure (2-c). Many types of rubber have this structure.

5.3.4 Network Polymers:

As shown in Figure (2-d) [33-32].

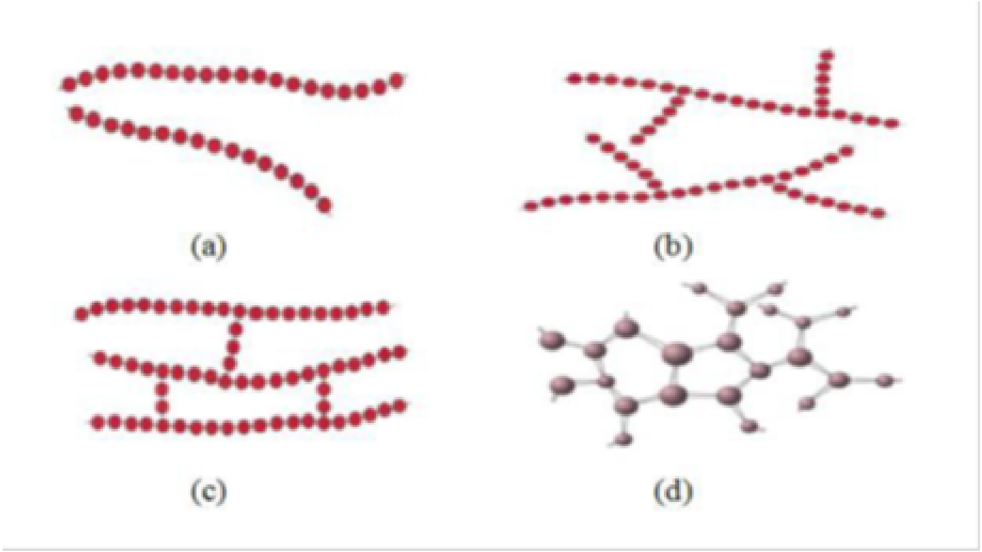


Figure 2.

Figure (2): Schematic representations of (a) (linear), (b) (branching), (c) (intersecting), and (d) (circles defining individual repeating units [34].

5.4 Polymers were classified into three types based on their structural composition [20]:

A. **Organic Polymers:**

These polymers are prepared from organic compounds containing hydrogen, nitrogen, oxygen, sulfur, and halogen atoms, as well as carbon atoms. These atoms are an essential component of the polymers. They are among the most important polymers in industry [35].

B. **Inorganic Polymers:**

These polymers are typically composed of inorganic compounds and do not contain carbon atoms. Their polymer chains are usually composed of silicon alone, nitrogen, phosphorus and nitrogen together, or boron and nitrogen. They were characterized by their high heat resistance [36]. These compounds also possess a three-dimensional network structure. An example of this type is magnesium oxide (MgO) [37].

C. **Organic-inorganic polymers:**

This type of polymer contains atoms of other elements in addition to carbon in its main chain or the main chain may consist of inorganic atoms, but its side branches contain carbon atoms directly attached to the main chain [38]. These polymers are characterized by their good heat resistance and polysulfone fibers are an example [19].

6 Polymerization Mechanisms and Production Techniques

Polymerization is a fundamental chemical process defined as the conversion of low molecular weight molecules (monomers) into high molecular weight substances without altering the basic structure of the molecules [21]. During this process monomer units are linked together to form a polymer. Flory (1953) and Carothers (1940) divided polymerization processes into two main groups[23- 39]:

6.1 Condensation Polymerization:

The condensation reaction occurs between two molecules containing multiple functional groups, resulting in the addition of one molecule and the loss of a small molecule (such as water). These reactions continue until one of the reactants is completely exhausted[23]. Condensation polymerization is characterized by the loss of a small molecule at each step of the reaction. The reaction rate in this type of polymer is highest at the beginning of the reaction due to the highest concentration of reactants, then the rate decreases over time as in the case of polyester polymers [40].

6.2 Addition Polymerization

Also called chain-growth polymerization, this involves the successive linkages of monomer molecules. The chain growth process goes through three different stages:

Initiation In this stage the active center is generated, which may be an ion or a free radical carrying an unpaired electron [21-41]. Propagation The active center grows through a series of symmetric reactions, forming the growing polymer chain. Termination Chain growth stops when two free radicals react one terminating the other [20]. The reaction rate in this type of polymer increases from zero to a maximum rate after a short period of time then stabilizes at a steady state, as in the case of low-density polyethylene (LDPE) [17 -35].

7 Properties of Polymers

Polymers possess distinctive properties that have led to their widespread use, such as their high mechanical, electronic, and optical efficiency, as well as their light weight. Their superior thermal, electrical, and structural properties have also attracted considerable attention recently. Polymers are used in the manufacture of optical waveguides and as information storage materials [42]. The properties of polymers were classified into several categories according to the standard used to measure the physical property the type of building blocks (monomers) that compose them and the set of internal structures of the polymer itself [43].

7.1 Physical Properties:

Polymers are characterized by physical properties including molar volume, density, molecular weight, crystal structure and polymerization level. These properties also include physical characteristics (such as glass transition temperature and viscosity) as well as mechanical properties. (such as strength, resistance, and hardness) are related to the polymers molecular weight, viscosity, and transition temperature. Mechanical properties deteriorate as molecular weight decreases. Due to the increased cross-linking of polymer chains with increasing molecular weight the polymer acquires a higher viscosity in its molten state making its manufacturing processes more complex. Crystalline Structure Polymers with a crystalline structure exhibit two main types lamellar and amorphous. Highly crystalline solid polymers are characterized by high melting points and high crystallinity along with low impact resistance. In contrast soft polymers are usually amorphous and have low melting points, as seen in the case of polyethylene terephthalate (PET) when it crystallizes [44].

7.2 Chemical Properties

Many of the distinctive properties of polymers are attributed to the intermolecular forces between their long molecular chains. Due to the large length of these chains the effect of these forces is amplified, far exceeding the intermolecular forces in materials with smaller molecules. The polarity of the constituent monomer units (i.e., their dipole nature) also directly affects the strength of the intermolecular forces within the polymer. For example the presence of carbonyl or amide groups in the polymer structure can create strong hydrogen bonds between adjacent chains, resulting in high tensile strength and a high melting point which are characteristic features of polymers containing groups such as carbamates, urethanes, or ureas.[45].

7.3 Thermal Properties

Polymer molecules exist in a solid state at low temperatures. Although they possess vibrational energy, they lack the ability to undergo significant spatial displacement. This state is known as the glassy state where the polymer is rigid and brittle similar to glass. As the temperature increases the polymer transitions to a softer more elastic state similar to rubber known as the elastic state. The temperature at which the transition from the glassy to the elastic state occurs is called the glass transition temperature (Tg). This property defines the amorphous regions of the polymer while the crystalline regions are defined by their melting point. These properties are measured using thermal analysis techniques which are essential tools in polymer characterization, most notably differential thermal scanning (DSC) [44].

7.4 Optical Properties

Laser polymers are used as a carrier medium (array) in dye lasers. These polymers are characterized by high transparency superior surface quality and chiral properties where the properties of the laser dye used override those of the polymeric carrier. The refractive index of the polymer changes with temperature [45]. Molecular sensing and catalytic activity are key structural determinants responsible for the functional properties of polymers [46- 47]. Iron oxide nanoparticles are widely used in sensing applications due to their unique structural and optical properties [48].

7.5 Mechanical Properties

Determining the basic mechanical properties of a polymer, such as its modulus of elasticity and tensile strength, is a crucial step before employing it in any application. For molecular weight, tensile strength increases with increasing molecular weight until it reaches a stable point at a specific critical value. Polymer crosslinking restricts chain movement and increases the material's stiffness because, in the crystalline state, intermolecular interactions become more effective potentially leading to polymer deformation with increased strength [44, 49].

7.6 Electrical and Electronic Properties

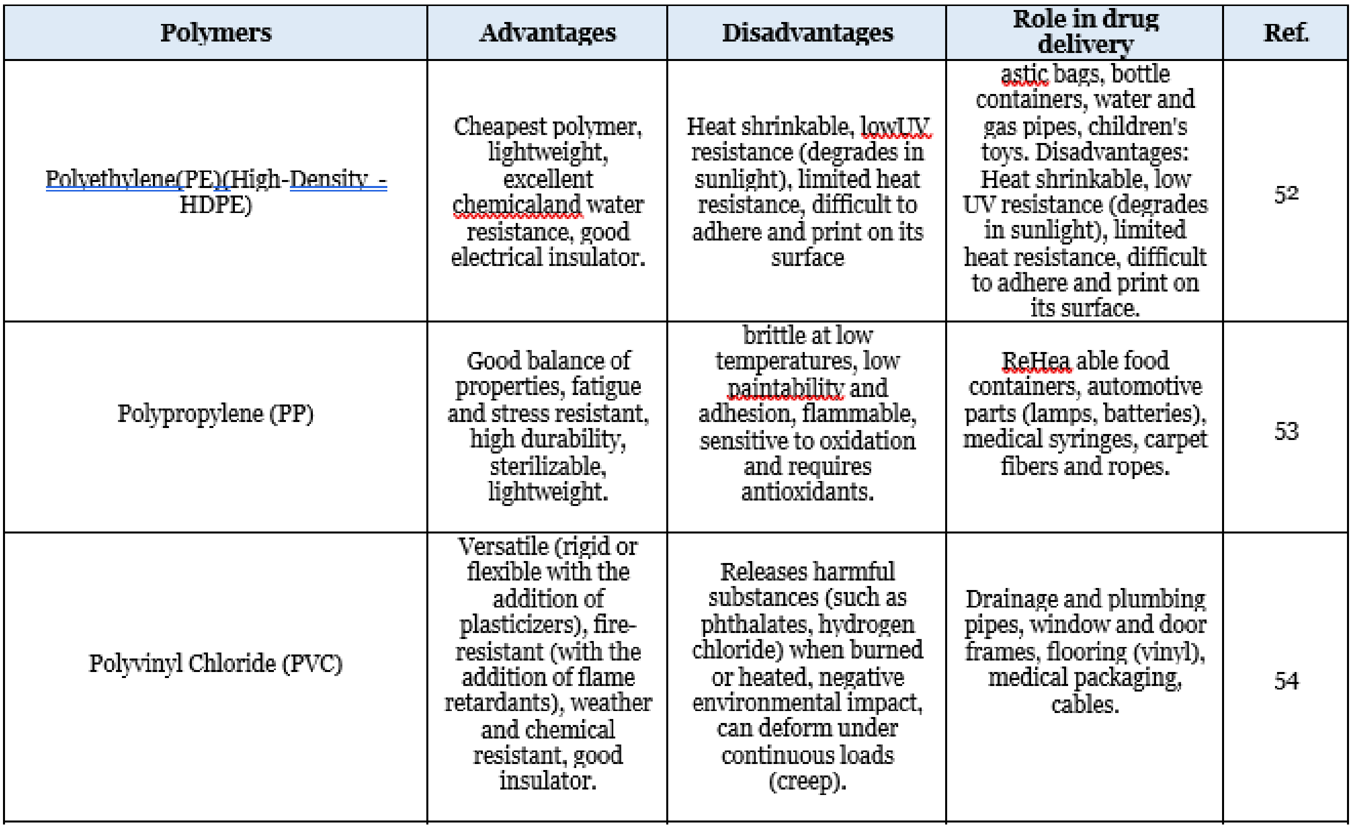
All electrically conductive polymers share a system of conjugated bonds in their basic structure, where single and double bonds (π bonds) alternate. These polymers act as insulators or semiconductors and their electrical conductivity increases with increasing concentration of impurities added through oxidation-reduction processes [50].

7.7 Solubility Properties

When studying polymers it is essential to determine their solubility, especially in the case of unstable polymers, because their solubility mechanism differs significantly from that of low molecular weight materials.

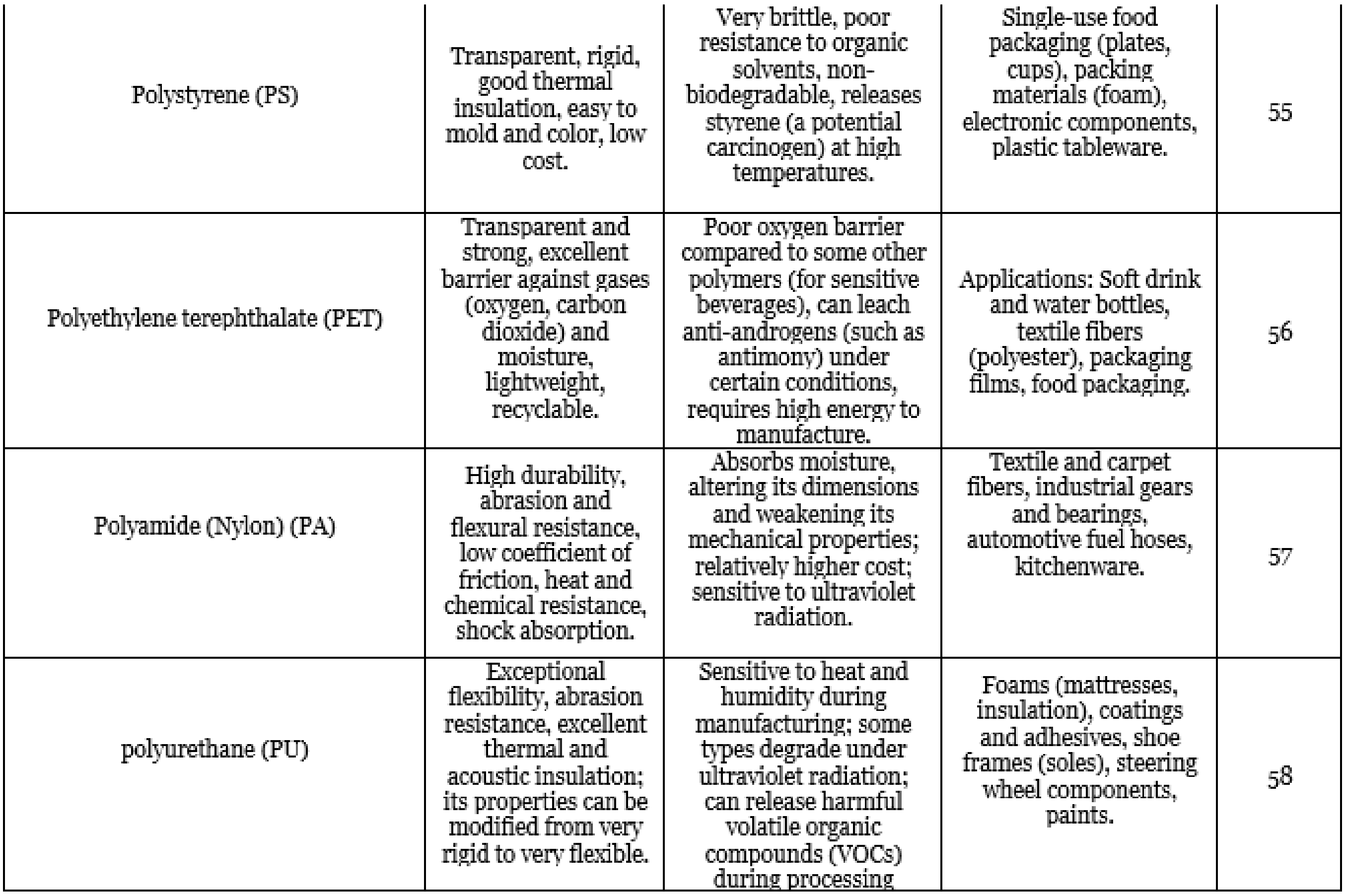
Dissolution occurs in two stages first the polymer swells because of solvent molecules penetrating between its polymer chains. Then these chains detach from the swollen state to form a true solution [51].

Table 2 shows the advantages, disadvantages, and applications of the most important polymers used in all fields.



Polymers	Advantages	Disadvantages	Role in drug delivery	Ref.
Polyethylene(PE)(High-Density - HDPE)	Cheapest polymer, lightweight, excellent chemicaland water resistance, good electrical insulator.	Heat shrinkable, lowUV resistance (degrades in sunlight), limited heat resistance, difficult to adhere and print on its surface	astic bags, bottle containers, water and gas pipes, children's toys. Disadvantages: Heat shrinkable, low UV resistance (degrades in sunlight), limited heat resistance, difficult to adhere and print on its surface.	52
Polypropylene (PP)	Good balance of properties, fatigue and stress resistant, high durability, sterilizable, lightweight.	brittle at low temperatures, low paintability and adhesion, flammable, sensitive to oxidation and requires antioxidants.	ReHea able food containers, automotive parts (lamps, batteries), medical syringes, carpet fibers and ropes.	53
Polyvinyl Chloride (PVC)	Versatile (rigid or flexible with the addition of plasticizers), fire-resistant (with the addition of flame retardants), weather and chemical resistant, good insulator.	Releases harmful substances (such as phthalates, hydrogen chloride) when burned or heated, negative environmental impact, can deform under continuous loads (creep).	Drainage and plumbing pipes, window and door frames, flooring (vinyl), medical packaging, cables.	54

Figure 3.



Polystyrene (PS)	Transparent, rigid, good thermal insulation, easy to mold and color, low cost.	Very brittle, poor resistance to organic solvents, non-biodegradable, releases styrene (a potential carcinogen) at high temperatures.	Single-use food packaging (plates, cups), packing materials (foam), electronic components, plastic tableware.	55
Polyethylene terephthalate (PET)	Transparent and strong, excellent barrier against gases (oxygen, carbon dioxide) and moisture, lightweight, recyclable.	Poor oxygen barrier compared to some other polymers (for sensitive beverages), can leach anti-androgens (such as antimony) under certain conditions, requires high energy to manufacture.	Applications: Soft drink and water bottles, textile fibers (polyester), packaging films, food packaging.	56
Polyamide (Nylon) (PA)	High durability, abrasion and flexural resistance, low coefficient of friction, heat and chemical resistance, shock absorption.	Absorbs moisture, altering its dimensions and weakening its mechanical properties; relatively higher cost; sensitive to ultraviolet radiation.	Textile and carpet fibers, industrial gears and bearings, automotive fuel hoses, kitchenware.	57
polyurethane (PU)	Exceptional flexibility, abrasion resistance, excellent thermal and acoustic insulation; its properties can be modified from very rigid to very flexible.	Sensitive to heat and humidity during manufacturing; some types degrade under ultraviolet radiation; can release harmful volatile organic compounds (VOCs) during processing	Foams (mattresses, insulation), coatings and adhesives, shoe frames (soles), steering wheel components, paints.	58

Figure 4.

8 Polymer Applications

Based on their diverse properties and malleable nature, polymers find wide-ranging applications across multiple sectors and key application areas. In healthcare, they are used in the manufacture of pharmaceuticals and their delivery systems, biomaterials for medical devices, and pharmaceutical packaging. In manufacturing, they are used in the production of plastics, advanced adhesives, and corrosion-resistant tanks and equipment. Packaging is used in the manufacture of various packaging materials to protect food and consumer products. In infrastructure and construction, they are used in piping systems (for sewage and water), composite building materials that replace wood, and in aircraft canopies. Advanced industries play a vital role in the aerospace, automotive, and electronics sectors, where they are used as lightweight materials, insulators, and structural components. Engineering and technical applications are widely used in various engineering disciplines[59-60]. Specialized applications include their use as corrosion inhibitors, in the fiber and textile industry, in agricultural applications (such as membranes and bioplastics), and in water and wastewater treatment as filters and adsorbents[61] For example, this work presents a methodology for preparing hybrid composite materials based on PVA and PVP polymers as a matrix, combined with zinc oxide (ZnO) and iron oxide (Fe_2O_3) nanoparticles, while exploring the range of their potential applications in the fields of photocatalysis, antibacterial properties, electronics, and the delivery of active agents [63-62].Some of the most important and distinctive applications of nanopolymers include:

A. Solar cells: Renewable energy sources are gaining increasing importance due to the significant rise in energy consumption and the gradual depletion of traditional non-renewable resources such as fossil fuels. Nanotechnology is emerging as a rapidly developing and widely applied field in this context. Composite nanopolymer materials demonstrate promising potential due to their unique properties and their applications are diverse. In the field of solar cells efficiency can be enhanced by coating polymers with metallic nanoparticles thus improving their ability to absorb solar energy. Plasmonial metallic nanoparticles have a quantum yield greater than one making them the preferred choice for this type of cell. These metallic polymer composites act as metallic insulators resulting in what is known as surface plasmon resonance a collective oscillation of conduction electrons occurring at the interface between the metallic nanoparticles and the insulating material arising from the interaction of incident light with these metallic particles. [64]

B. Sensors: Sensors are used to monitor changes in the environment, and therefore their applications extend beyond environmental ones to include biological uses. Polymer nanomaterials play a crucial role as sensors due to their high sensitivity, selectivity, and adaptability to various conditions. their surface Plasmon resonance excitation [65]. Surface

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Plasmon resonance is one of the most important properties of metallic nanoparticles. Combining the properties of metals with polymers enables multi-field applications. Metal-polymer composites can improve the efficiency of sensors. Surface Plasmon resonance vibrations add detection properties to the device. Thus These materials are used as detectors for viruses and malignant tumor particles in biosensors [66]. Polymer nanocomposites are also used in sensing applications to study and analyze biological and environmental issues.

C. Thin Films: Currently multiple methodologies are employed for thin-film production, and fabricating such films from metallic nanoparticles using a single material is a complex process. The polymer plays a pivotal role in forming thin films that are coated and support the metallic nanoparticles. Polymers incorporating metallic nanoparticles are of paramount importance in the design and fabrication of nanodevices. Integrating metallic nanoparticles into the polymer results in films of significantly higher quality than those made from metallic nanoparticles alone. These films create a precise phase boundary between the metallic nanoparticles and the polymer material where the polymer is bonded to the nanoparticles via strong low-molecular-weight covalent bonds. Thin films find significant application in the manufacture of sensors based on surface plasmon resonance technology [66].

D. Microbial Applications: Thin films composed of silver nanoparticles and polyvinyl alcohol exhibit antibacterial activity. They are reusable and easy to monitor [67]. Polymers, such as polyvinyl alcohol, demonstrate antibacterial activity. We can enhance their antibacterial properties by combining them with metals such as copper and silver as well as with inorganic nanoparticles. The metal ions are released into the microbial cell, and these ions aid in the study of antimicrobial activities. Released metal ions can damage the microbial environment of cells [68-69]. Titanium dioxide polymer with inorganic nanofillers provides excellent photochemical activity.

E. Conductivity: Metal nanopolymer composites can improve conductivity. Therefore, they can be used in electronic circuits. Nanofibers can be produced via electrospinning technology. Conductive polymers are then prepared, and nanocomposites are prepared in this way To enhance electrical conductivity, these polymers are used due to their light weight, low cost, high flexibility, and efficient reaction with solutions. They are considered bioelectrochemical materials used in biomedical fields [70-71]. A materials conductivity depends primarily on the abundance of free electrons the polymer conducts electricity using the free electrons available in its atoms. A polymer structure containing alternating single and double bonds is called a conjugated double bond system. A polymer with such a system can conduct electricity through oxidation or reduction processes. Electrical conductivity can also be improved by doping with various molecules [72]. Semiconductor polymers are used as optical switches in electric lighting applications in light-emitting diodes (LEDs) and in energy-saving lamps [73].

9 Conclusions

Polymers are not merely alternative materials; they are fundamental and driving forces in all areas of life (from packaging to electronics and medicine) due to their exceptional malleability and superior properties (lightweight, corrosion resistance, and insulation). The field of polymers is undergoing a paradigm shift from the traditional macroscopic to the nanoscale, moving from reliance on conventional polymers to the use of nanohybrid materials. The incorporation of nanoparticles (metal-based or oxide-based) endows polymers with advanced properties (optical, electrical, and catalytic) previously unavailable, paving the way for promising applications in renewable energy sectors (such as photovoltaic cells) and biomedicine (such as biosensors and antimicrobial materials). The close relationship between structure and properties underscores a fundamental scientific principle in polymer chemistry: the final characteristics of any polymer are organically linked to its molecular structure (linear, branched, or cross-linked), its degree of molecular plurality, and the van der Waals forces between polymer chains.This explains the vast diversity in the behavior of polymers (plastics, rubbers, and thermosets). Table 2 highlights the challenge between performance and sustainability, contrasting the excellent functional performance of many synthetic polymers (e.g., durability, insulation, cost) with their negative environmental impacts (difficulty in decomposition, release of harmful substances). This underscores the strategic importance of research into biodegradable biopolymers as a pathway toward a more sustainable circular economy

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