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Review Article

Natural and synthetic polymers: A comprehensive review of their applications in drug delivery and pharmaceutical research

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Abstract

Polymers are crucial to rapid and modified release dosage formulation. Some drug delivery systems use polymers to provide dosage forms that release the therapeutic ingredient at a steady dose over lengthy periods of time, reducing cyclic dosing. Many dose formulations use it as an excipient to capture the medicine in the bulk amount. Tablets and capsules are immediate-release, whereas extended-release and gastro-retentive release are modified-release. Polymers are modified to generate conjugates, such as polymer-drug and polymer-protein, which are employed as biological carriers. Pharmacy medication delivery relies on polymers to manage drug release through implants and other medical devices. Due to their biocompatibility with other medicinal agents and biodegradability, biodegradable polymers are frequently used in biological applications. It resists medications from the biological environment and prolongs their release to stabilise them. In vivo and in vitro biocompatibility testing are conducted for natural and synthetic biodegradable polymers utilised in biomedical applications and dosage forms. Polymers are made of many tiny molecules. Cotton, wool, rubber, Teflon (TM), and all polymers are used in most industries. A cosmic infrared absorption spectrum matches cellulose's, proving its existence. The surface film is a cellulose pellicle. Most elastic materials, including spring metals, are elastic due to bond distortions. Rubber is long, coiled polymer chains interconnected at several locations when relaxed. Polymeric drug delivery systems aim for controlled or sustained distribution. Polysaccharides can also target oral medications to the colon. The future holds many fascinating possibilities for polymeric materials. Many applications for polymers are being developed.

Keywords: Polymer, Drug delivery system, Natural, Cellulose, Polymer-protein

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1. Introduction

The growing importance of the biopolymers sector has fuelled the quick development of this unique class of polymeric materials in recent decades. Biodegradable polymers have attracted a lot of attention because of their unique and flexible electrical conductivity as well as their biodegradable properties, which make them desirable in a variety of applications.[1] Implantable biomaterials were expected to have a market value of about $75.1 billion in 2013. According to forecast projections, the global market is expected to reach $109.5 billion in 2019, up from $79.1 billion in 2014, with a 6.7% compound annual growth rate (CAGR) between 2014 and 2019. Natural enzymatically degradable polymers have been used in biomedicine for thousands of years, but synthetic biodegradable polymers have been used since the late 1960s. The investigation of biodegradable biomaterials as substitutes for permanent prosthetic devices to aid in tissue regeneration and repair has received more attention recently. Along with the benefits provided over biostable materials in terms of long-term biocompatibility, this change is being driven by growing concerns about the technical and ethical issues of modification operations. Because of their versatility, polymeric biomaterials are rapidly gaining traction and replacing more conventional materials like metals, alloys, and ceramics.[2] A polymer is a big molecule composed of repeated structural units, often known as a macromolecule. Covalent chemical bonds frequently link these components together. While both natural and synthetic polymers exist, natural polymers are favoured in medicinal applications because

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of their non-toxicity, greater availability, and lower cost. In addition to these advantages, the majority of natural polymers are, with very few exceptions, chemically modifiable, biocompatible, and even biodegradable.[3] Polymerisation, with or without the aid of heat, water, or other solvents, is the process by which two or more chemicals unite to produce a molecule with a high molecular weight.

A polymer is the final product of this process, whereas a monomer is the basic substance used to make polymers. The physicochemical characteristics of polymers vary widely depending on factors such as homo/co-polymerisation, conformation, configuration, molecular weight (MW), and the percentage of crystallinity. Pharmaceutical polymers, which are constantly evolving, have attracted a lot of interest in the field of pharmaceutical dosage forms. Polymeric excipients, which can be made from synthetic, semi-synthetic, or natural materials, are important components that help formulators find new solutions and develop innovative dosage forms for specific areas or controlled-release drug delivery.[4]

2. Polymers

A polymer, also known as a macromolecule, is a big molecule made up of repeating structural units. Covalent chemical bonds are usually used to create the connection between these subunits. Although there are synthetic and natural polymers, natural polymers are preferred in medicinal applications due to their affordability, accessibility, and lack of toxicity. With very few exceptions, these natural polymers exhibit biocompatibility, the ability to undergo chemical changes, and the possibility for biodegradability.[5]

Combining two or more substances to produce a molecule with a high molecular weight either with or without heat, water, or other solvents is referred to as polymerisation. A monomer is the basic material required to create polymers; the final product is known as a polymer. Homo/co-polymerization, conformation, configuration, molecular weight (MW), and percentage of crystallinity control numerous physicochemical characteristics of polymers. Consequently, pharmaceutical polymers, which are constantly evolving, have gained significant attention as essential excipients in pharmacological dosage forms. Polymeric excipients, which can be made from man-made, partly man-made, or natural materials, allow researchers to solve various formulation problems and develop new ways to deliver drugs, like those designed for targeted or controlled release. Polymer classification according to origin. **(Figure 1)**

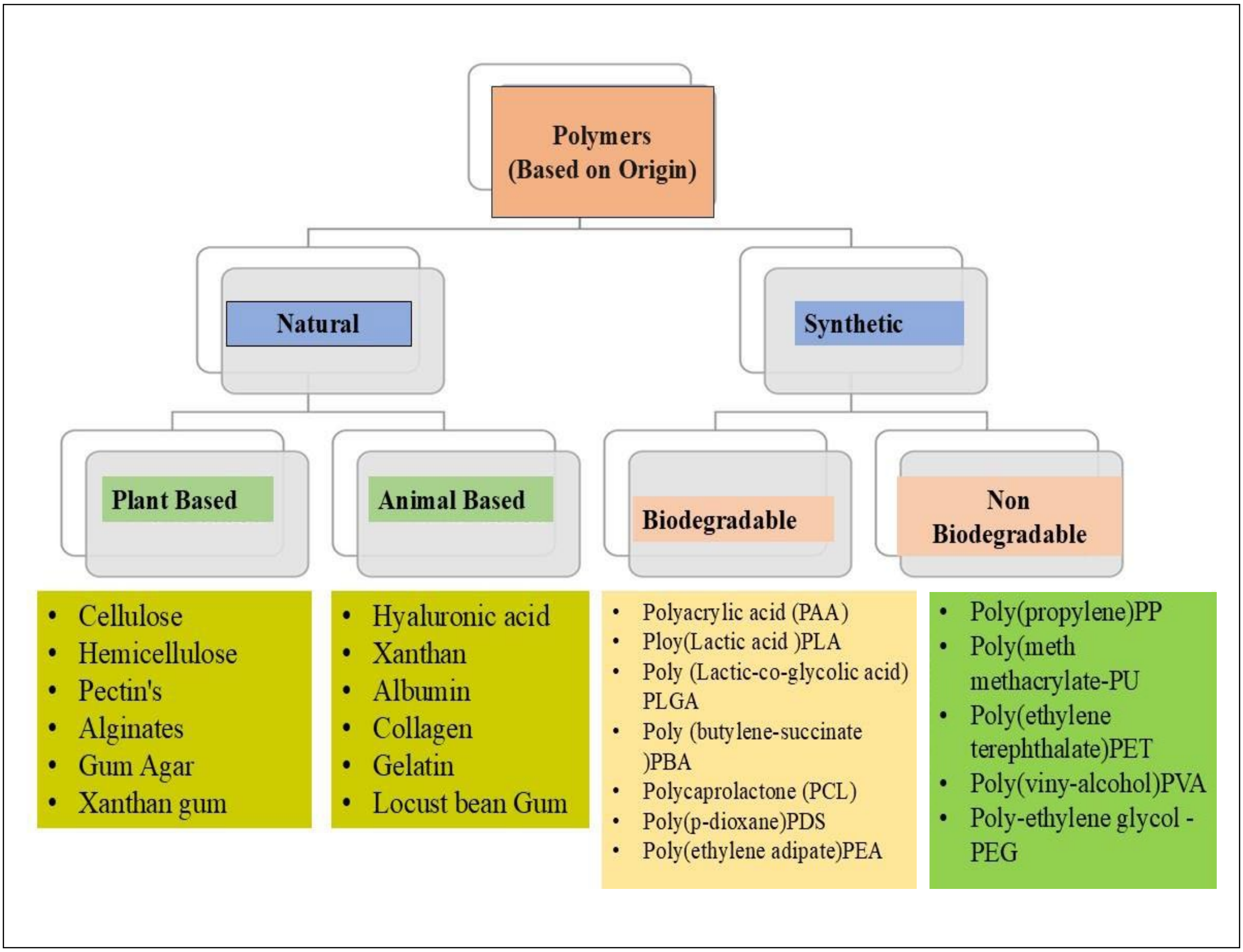


Figure 1: Classification of polymers[6]

2.1. Natural polymers

Plant-based natural polymers are more interesting since they have several benefits over synthetic ones. Accessible, affordable, nontoxic, chemically inert, and biodegradable are all characteristics of these organic materials. Beads, matrix systems, implants, and micro- and nanoparticles all use plant-derived polymers. We also use them to create viscous liquids.[5] The use of natural polymers has begun to increase recently. The benefits of using natural polysaccharides in medicines include their ability to break down by enzymes, their similarity to cells, their interactions with the surrounding tissue, and also their ability to decompose naturally, being safe for health, cost-effective, easy to find, renewable, and environmentally friendly.[7] Natural polysaccharides are increasingly being used as excipients in medications that target chronic and site-specific illnesses. Research is still being done on new ways to use natural polymers for personalised care and drug administration. The growing need for research and development centred on the extraction, purification, modification, characterisation, and processing of novel natural polysaccharides to realise subsequent commercialisation is reflected in the growing interest in using natural polymers to transport pharmaceuticals. Natural polymers have long been employed as constituents in herbal remedies.[7]

2.1.1. Plant based polymers

Polysaccharides, which are biopolymers, are composed of monosaccharide units joined by glycosidic linkages. In living things, polysaccharides are both structural elements and a source of energy for cell processes. Polysaccharides frequently interact effectively with living cells, are enzyme-degradable, and have high hemocompatibility. They are therefore suitable for use in medicine since they are biocompatible.[8] Polysaccharides exhibit a wide range of qualities because they vary greatly in their monosaccharide unit concentration, link types and patterns, chain lengths, and forms. Their solubility, gelling capacity, flow properties, and surface features are all impacted by these factors. Based on their functions, we can categories polysaccharides into two types: storage polysaccharides and structural polysaccharides. While starch and inulin are examples of the latter mentioned polysaccharides, pectin, cellulose, and hemicellulose are examples of structural polysaccharides. Gums belong to a different category of polysaccharides. They can also be divided into groups based on the resources they use, such as plant, animal, microbial, and seaweed polysaccharides.[9]

2.1.2. Chitosan

In 1859, Rouget's investigation of the deacetylated forms of the parent chitin natural polymer marked the beginning of chitosan's history. Chitosan has been the subject of much research over the last 20 years, with an emphasis on its possible uses in a range of bio-related domains. The exoskeletons of insects, crustaceans, and fungi are the source of chitosan, which has been shown to be biocompatible and biodegradable. These semi-synthetic amino polysaccharides have multifaceted properties, distinctive structures, and extremely sophisticated functioning. They are used in a wide range of industrial and medical fields.[10] It has been shown that chitosan and its related forms, like N-trimethyl chitosan and mono-N-carboxymethyl chitosan, are safe and effective at helping substances get absorbed, particularly through the nose and mouth.

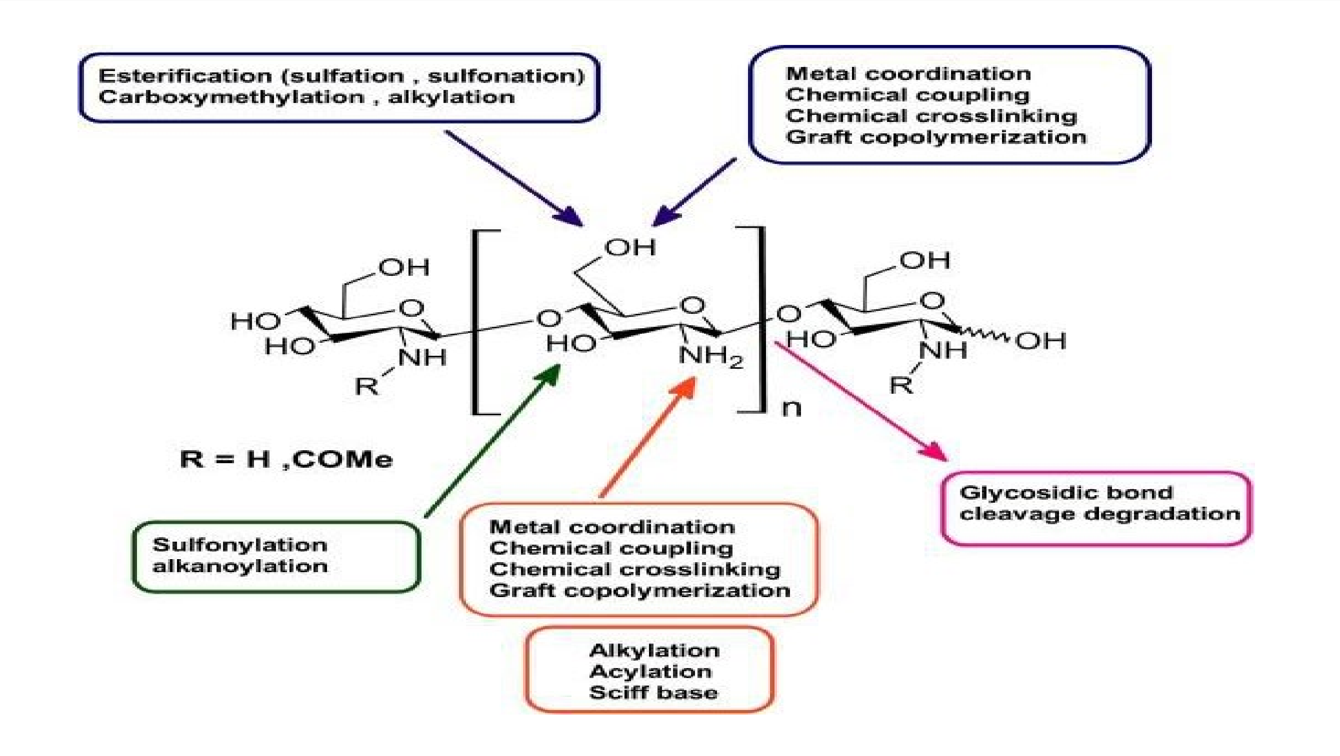


Figure 2: Chitosan[11] (Source: https://www.mdpi.com/2073-4360/15/13/2867)

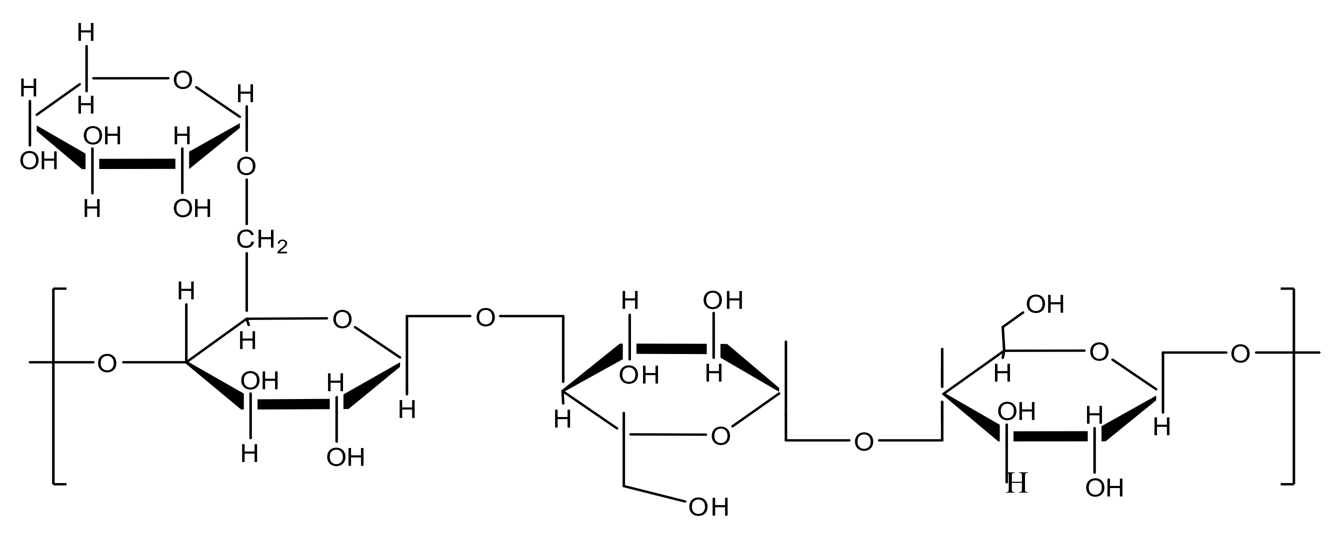


Figure 3: Chemical structure of TGP

This is especially helpful for water-loving large molecules like peptides, proteins, and heparins. For hydrophilic macromolecules like peptides, proteins, and heparins, this property is especially advantageous. Chitosan helps macromolecular drugs move between cells by opening tight junctions, which makes it easier for the drugs to be absorbed.[10] Furthermore, chitosan microparticles and nanoparticles are useful instruments for regulated medication release. Vaccines that use specific particle systems can enhance the absorption of antigens in mucosal lymphoid tissues, leading to strong immune responses in both the body and mucosal areas. In a wide range of disciplines and sectors, including waste management, the food industry, healthcare, biotechnology, and the pharmaceutical sector, chitosan has found widespread use. Its helpful features, like being safe for the body, breaking down naturally, and working well with living tissues, make it popular as an ingredient in medicine. The pharmaceutical industry uses chitosan for a variety of purposes, including mucoadhesive formulations, oral absorption improvement, and protein and gene transfer.[12] The first stage in the synthesis of chitosan is the removal of proteins and minerals such as calcium carbonate and calcium phosphate using alkali and acid, respectively. **(Table 1)** The shells are first ground before treatment to improve accessibility. Chitin is dried after manufacture to act as a stable bridge for the deacetylation of chitin into chitosan. Chitin is exposed to a concentrated sodium hydroxide solution at high temperatures during the actual deacetylation process.[13]

2.1.3. Tamarind gum polysaccharide

The seeds of the Tamarindus Indica Linn plant, part of the Fabaceae family, are used to make tamarind gum polysaccharide (TGP), which is a plant-based polymer. There are 1735 kDa of it. There are 1735 kDa of it. the eleventh Tamarind gum polysaccharide (TGP) is a well-known branching polymer that is both water-soluble and non-ionic. Aside from being hydrophilic and mucoadhesive, it also possesses the ability to produce gels.[14] Tamarind gum polysaccharide, a biopolymer with potential applications in food, medicine, and cosmetics, is a fascinating discovery. Among its many useful properties are its biodegradability, lack of irritation, compatibility with living organisms, and lack of carcinogenicity in.[15] The extraction of tamarind gum is now underway to develop drug delivery systems that may suit many administration routes, including oral, buccal, intestinal, ophthalmic, and nasal systems.[16] Displayed below is the chemical structure of TGP. **(Figure 2), (Figure 3)**

Tamarind gum polysaccharide (TGP) seeds contain as much as 65% medication-delivering gum. The specific polysaccharide isolated from TGP is known as Tamarind Seed Polysaccharide.[17] An assortment of advantageous characteristics, including cytotoxic, hypoglycemic, antibacterial, anti-inflammatory, gastrointestinal, antioxidant, and cholesterol-lowering effects, have been discovered in extracts from Tamarindus indica (T. indica). Natural food products such as jams, sweets, ice creams, and jellies can benefit from the addition of tamarind seed polysaccharide due to its adaptability and ability to increase viscosity and gelling. the eleventh.[18]

2.1.4. Fucoidan

In 1913, researchers discovered this family of sulfated polysaccharides in several marine crustaceans and brown algae. Fucus vesiculosus, the most prevalent type, contains the most basic form of this group, which consists solely of L-fucose and sulphate units. The structure and composition of fucoidan are partially determined by the kind of algae and the method of extraction. For example, fucoidan produced by Fucus vesiculosus is abundant in fucose and sulphates, in contrast to fucoidan produced by Sargassum Stemphylium, which contains various residues such as glucose, glucuronic acid, xylose, mannose, and galactose. The year 19 Fucoidan, similar to heparin, blocks blood clots and reduces inflammation. Additionally, it possesses anti-adhesive and anti-viral properties. in According to sources, a fucoidan substance called "Haikun Shenxi capsules" was licensed by China in 2003 and has been used clinically to treat chronic renal failure in.[19] According to clinical trials, fucoidan has a synergistic effect on cancer. The plasma concentrations of anticancer medicines were unaffected by the co-administration of fucoidan. However, the combination has the potential to significantly reduce side effects and improve therapeutic effects when compared to conventional anti-cancer therapy.[20]

2.1.5. Animal derived polymers

It is also possible to extract natural gums from animal sources. Examples of chitin and chitosan may be necessary. A polymer called chitin takes the place of cellulose in lower plant and animal species. Tamarind seed, the polysaccharide in question Fungi and red, green, and brown algae contain polysaccharide, which is an essential part of insect exoskeletons and outer shells.[21]

2.1.6. Hyaluronic acid

Hyaluronic acid (HA) is a long chain made up of repeating pairs of two sugar molecules: N-acetyl-D-glucosamine and D-glucuronic acid. It goes by the name hyaluronan. A type of glycosaminoglycan known as HA is found in the jelly-like fluid in the eyes and in the spaces between cells in cartilage.[22] John Palmer and Karl Meyer were the first to isolate hyaluronic acid (HA) in 1934. Unlike other glycosaminoglycans, which are synthesised inside the cell's Golgi apparatus and subsequently exocytosis outside, HA is created by three transmembrane enzymes. Three different enzymes known as HA synthetase are located on the inner side of the plasma membrane. Their names are HAS1, HAS2, and HAS3. A wide variety of chemical alterations can be performed on hyaluronic acid, which is defined by its one amide functional group, many alcohol and carboxylic acid groups, and flexibility.[23] The drug delivery techniques that make extensive use of hyaluronic acid and its derivatives include film, microsphere, nano emulsion, nanoparticle, cationic polymer, and polyelectrolyte microcapsules. Hyaluronic acid derivatives that are amphiphilic can self-assemble in water into core-shell nanoparticles. Because of this ability, nanoparticles can be used for both diagnosis and treatment by putting anticancer drugs and contrast agents into their inner water-repelling core.[24] The capacity of hyaluronic acid (HA) and its derivatives to enhance the transport of different drugs has led to their use in both in vitro and in vivo models. Antiglaucoma medications betaxolol and pilocarpine, the enzyme thrombin, the cytokine interferon, and the vasodilator serotonin (5-hydroxytryptamine) are just a few examples. Encapsulating proteins with pure or modified HA has shown promise for regulated release and possible uses in a range of medical treatments.[25]

2.1.7. Collagen

Collagen is a naturally occurring protein that is found in skin, tendons, and bones; it is one of the most essential structural proteins in the body. The term "collagen" has its roots in the Greek term's "kola" (vernacular for gum) and "gen" (meaning create). Collagen has been the subject of substantial research as a polymer for use in a wide range of biomedical products, including pharmaceutical and cosmetic items, due to its reputation as one of the most beneficial biomaterials. Its low immunogenicity and great biocompatibility enhance its attractiveness in these uses.[26] In During wound healing, cells like fibroblasts produce collagens, which then undergo a series of complex morphological changes. The tensile strength of healthy skin varies due to alterations in collagen type, amount, and organisation that take place during the wound healing process. During the healing process, collagen undergoes dynamic changes that greatly impact the structural and functional characteristics of the regenerated tissue.[27] There are currently at least 29 recognised collagen varieties. Because of its biodegradability, low antigenicity, and biocompatibility, collagen is a material that has several potential uses. Due to its adaptability and positive properties, collagen finds extensive application in biomedicine and other areas where it must be compatible with the body's biological processes.[28]

2.1.8. Albumin

Albumin is the main protein in blood plasma, making up around half to two-thirds of all proteins. The tiny globular protein known as albumin has a molecular weight of 67 kDa, an average half-life of 19 days, and is highly soluble in water. It is stable for 10 hours at 60 °C and works well in a pH range of 4 to 9. Bovine serum albumin (BSA), rat serum albumin (RSA), and egg white (OVA) are three other sources of albumin that can be isolated from various animals. But HSA and BSA are the two most popular ways to give medication.[29] Among this protein's primary functions is the transportation of hydrophobic compounds, such as hormones and fatty acids, and the maintenance of blood osmotic pressure. These characteristics make it an excellent choice for drug delivery due to its ability to transport various hydrophobic chemicals across the bloodstream in A non-glycosylated globular protein, mature human serum albumin (HSA) consists of 585 amino acids. Its molecular weight is 66.5 kDa, and its maximal circulatory half-life is 19 days in humans.[30] Serum albumin-based nano vehicles are one type of efficient drug delivery carrier. For targeted drug delivery to tumours, these vehicles use serum albumin as a dependable carrier material to encapsulate or conjugate therapeutic chemicals. Abraxane, a paclitaxel formulation, is a good example of this method since it uses hydrophobic interactions between paclitaxel molecules and human serum albumin to generate a compound. This formulation was given the green light by the US Food and Drug Administration (FDA) in 2005 for the treatment of metastatic breast cancer in clinical settings.[31] An important property of albumin is its inherent ability to encapsulate hydrophobic anticancer drugs, which allows for more precise targeting of tumours and better pharmacokinetic profiles due to longer half-lives. The nanoparticles are bound and capped by options, a subset of serum proteins.[32] **(Figure 4)**

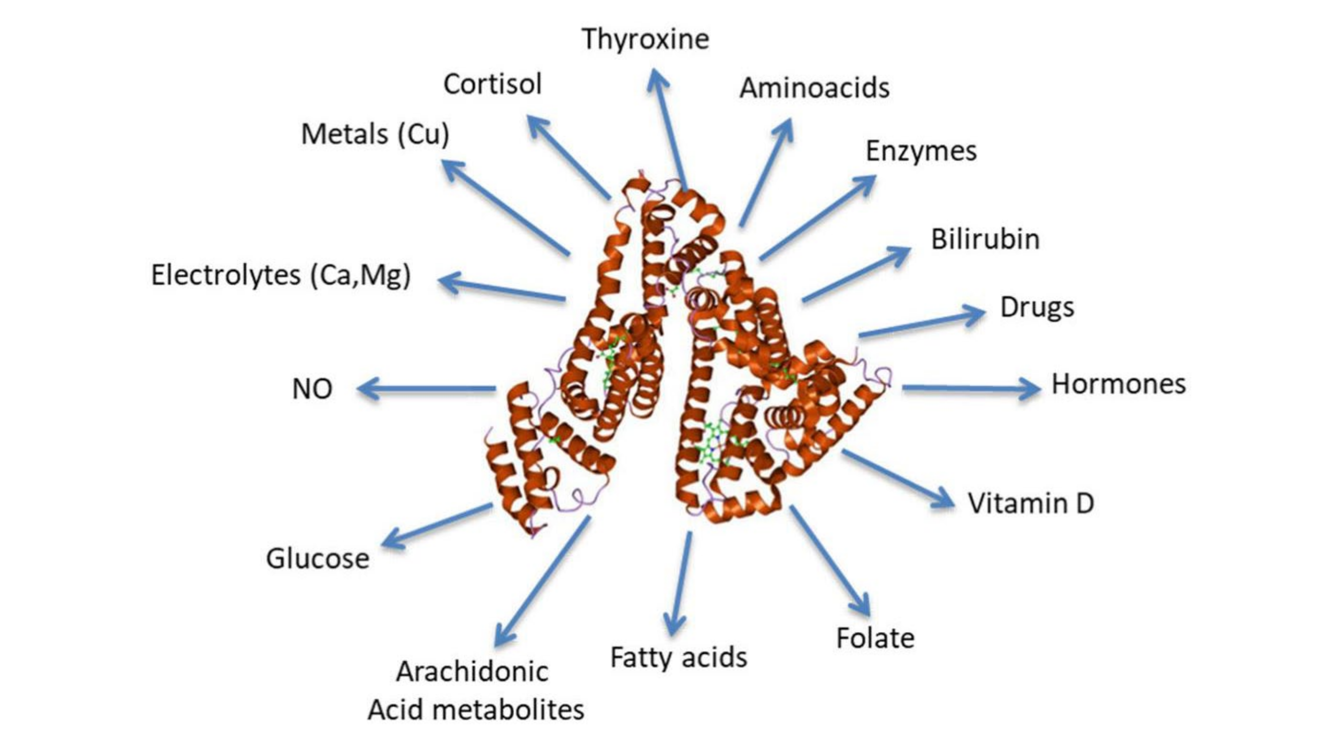


Figure 4: Albumins[33] (Source: https://www.mdpi.com/2077-0383/12/18/6017)

2.2. Synthetic polymers

The functional groups of synthetic polymers can be precisely engineered, allowing for the modification of their structure and properties. These advantages offer characteristics that can be adjusted to match certain uses, such as reliability, repeatability, and adaptability.[34] Approximately 1936 saw the introduction of poly (methyl methacrylate, or PMMA) for use in plastic contact lenses, and 1941 witnessed the publication of the first details about the use of nylon as a suture. Researchers conducted studies alongside this development to determine the biocompatibility of the new materials.[35]

2.2.1. Bidegradable Polymers

Due to their malleable nature, they find application in a variety of fields, much like other synthetic polymers like poly (lactic-co-glycolic acid) (PLGA) and polyurethanes (PURs). Among the many potentials uses for these biodegradable polymers are the areas of tissue engineering, drug delivery, dentistry, orthopaedics, and wound care. Polymers that have good qualities, like polylactic acid (PLA), poly-l-lactic acid (PLLA), polyglycolic acid (PLGA), polyether ether ketone (PEEK), and polymethyl methacrylate (PMMA), are commonly used in the medicine and healthcare fields.[36]

2.2.2. PLGA

A copolymer made up of poly glycolic acid (PGA) and poly lactic acid (PLA) is PLGA. Its design and functionality make it stand out as the most designated biomaterial currently used for medication delivery. In classic stereochemical terminology, we typically refer to the asymmetric alpha-carbon in polylactic acid as either the D or the L form. On the other hand, you can alternatively write it as R or S. The PLGA may be easily shaped and adjusted in size to suit different needs, making it suitable for encasing biomolecules of different sizes. The fact that it is very soluble distinguishes it from pure polylactic and polyglycolic acids. Common chemicals that can dissolve PLGA include acetone, tetrahydrofuran, and ethyl acetate, among others. One notable property of polylactic-co-glycolic acid (PLGA) nanoparticles is their ability to contain memantine (MEM). These nanoparticles are used in the only approved drug for moderate-to-severe Alzheimer's in the US and Europe.[37]

2.2.3. Polydipsic acid

You won't find a more "versatile" material than polyurethane (PU).[38] Using PU to carry medications is relatively recent, as the first PU microcarrier was invented twenty years ago by Hong and Park. in the 45th Biomedical polyurethanes (BioPUs) are made possible by adding hydrolysable segments to their backbones.[39] These segments can be polyether, polyester, or polyamide. These PUs can also be synthesised using biocompatible cycloaliphatic or aliphatic diisocyanates (ICs) derived from amino acids. These chemicals provide less of a threat than more conventional ICs such as toluene 2,4-diisocyanate (TDI) and 4,4′-methylenebis (phenyl isocyanate) (MDI). Furthermore, these PUs have been shown to enhance cell adhesion and proliferation while exhibiting zero adverse effects.[40]

2.2.4. HPMC

Hydroxypropyl methyl cellulose is a pale to slightly off-white powder with a free-flowing texture and serves as a synthetic alternative to the naturally occurring polymer cellulose.[41]

It is granular, tasteless, and smellless.Oral controlled drug delivery methods rely on hydrophilic carrier materials, the most important of which is hydroxypropyl methylcellulose (HPMC). One of its important characteristics is high swell ability, which greatly affects the rate of drug release upon administration. Its large drug load capacity, ease of production, chemical stability, and regulatory acceptability make it a popular choice.[42] Due to its excellent swell ability and thermal gelation properties, HPMC has so far been the principal carrier material for drug release systems. Research into developing vegetarian capsules built from HPMC films has recently gained momentum, and the idea is certainly intriguing. The nutritional supplement industry is the primary consumer market for these capsules, which offer a "green" alternative to gelatin. As a polymeric matrix, gelling agent, and viscosity enhancer, HPMC is used in injections, films, filaments, and inserts.[43]

2.3. Nonbiodegradable polymers

The interest in producing biodegradable polymers by chemical treatment, microorganisms and enzymes has increased to make it easier to dispose after the end of its use without harming the environment. Biodegradable polymers reported a set of issues on their way to becoming effective materials. In this article, biodegradable polymers, treatment, composites, blending and modeling are studied. Environmental fate and assessment of biodegradable polymers are discussed in detail. The forensic engineering of biodegradable polymers and understanding of the relationships between their structure, properties, and behavior before, during, and after practical applications are investigated.[44]

2.3.1. Colloidal silica

Undoubtedly one of the best glidants is colloidal silica. It is frequently used to increase the flowability of medicinal blends. The mix contains an ideal amount of colloidal silica to maximize the flow-enhancing impact.[45] Mesoporous silica nanoparticles have distinctive qualities that make them the best nano-carriers for storing, safeguarding, and delivering medications to the target location.[46] It is possible to deliver targeted agents to the injured tissue, increase their specificity, and lessen undesirable side effects by including them at the mesoporous silica surface. Mesoporous silica nanoparticles with many functions can also be created such that they work in concert to treat damaged tissues. The majority of research using mesoporous silica for drug delivery has been focused on cancer treatment.[47]

2.3.2. PVP (polyvinylpyrrolidone)

An example of a polymer is polyvinylpyrrolidone, or PVP, a water-soluble polymer. The internal amide bond in the lactam polymer polyvinylpyrrolidone (PVP) makes it very flexible and safe for the body, which is why it is a great choice for treating various skin, bone, and eye issues. Scientists are interested in PVP's unusual properties and potential uses as a polymer. Because of its unique properties, PVP is a popular choice for dissolvable microneedles used for the transdermal delivery of macromolecules such as DNA, proteins, vitamins, and others.[48] Binding, coating, suspending, and pore-forming are just a few of the many uses for this versatile excipient in the pharmaceutical and allied industries. Both traditional formulations and new controlled or targeted delivery systems can benefit from it. As a solubilizes, it has potential. The Polyvinylpyrrolidone (PVP) hydrogels have proven biocompatibility and durability, making them ideal for a wide range of uses.[49]

2.3.3. PVA (Polyvinyl alcohol)

Polyvinyl alcohol (PVA), the first synthetic polymer, is a common hydrogel material. We make polyvinyl acetate by polymerising vinyl acetate and then hydrolysing the acetate groups, either partially or completely. The result of this procedure is polyvinyl alcohol, a linear synthetic polymer that is soluble in water. The degree of hydrolysis and polymerisation determines how well PVA dissolves in water; highly hydrolysed PVA does not dissolve in any water at all. As an adhesive, polyvinyl alcohol (PVA) works well with both paper and packaging. The high concentration of hydroxyl groups in this material, however, gives it a high rate of moisture absorption. Adding pineapple leaf fibres to the recipe will help reduce this problem.[50]

3. Applications of Polymers

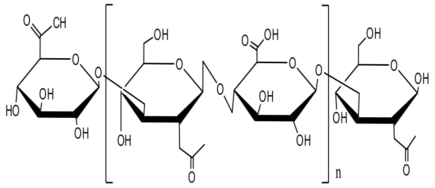
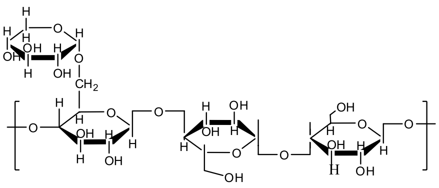
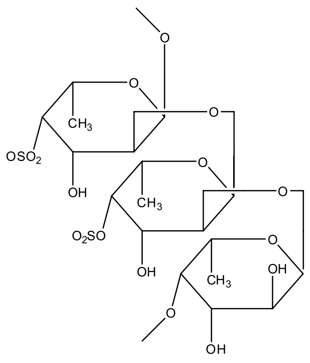
3.1. Biodegradable and biocompatible polymer

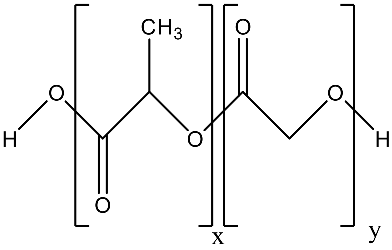
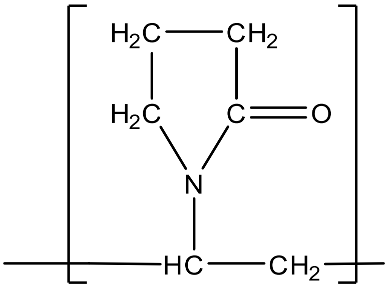
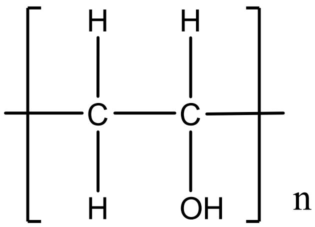
The polymer sciences have paid a lot of attention to biodegradable polymers because of their remarkable properties, such as their biocompatibility, uniform and tunable breakdown rates, and outstanding biodegradability. The An aliphatic polyester with a stellar reputation for being both biodegradable and biocompatible, polyglycolic acid, or polyglycolide (PGA), finds frequent usage in medical applications. **(Figure 5)** The polymerisation of glycolic acid through ring-opening results in the production of PGA. Polylactic acid, or the thermoplastic aliphatic polyester version, is used to make a wide range of medical implants, such as mesh, screws, pins, rods, and orthopaedic devices (PLA). Because of its biocompatibility, bio absorption, and biodegradability, polycaprolactone (PCL) is another multipurpose polyester commonly used in tissue engineering, dental braces, medical implants, and targeted medication delivery.[51] Polymer that undergoes thermal reactions The poly (N-isopropylacrylamide, or PNIPAAm) polymer has several applications, including biosensors, drug delivery, and tissue engineering. The poly (caprolactone/lactide) copolymer, also called the PCL-PLA copolymer, is another biocompatible and biodegradable polymer that has multiple uses in tissue engineering. Coating polyesters (PLA, PCL, and PLGA) with cationic polymers considerably improves nucleic acid transport. Hyaluronic acid (HA) has several uses in nanomedicines, including mucosal therapies, vaccine administration, and more generally. It is a supplement for fluid in arthritic joints and has various applications such as surgical augmentation, wound healing, and tissue regeneration.[52]

3.2. Targeted drug delivery system

The polymer sciences have paid a lot of attention to biodegradable polymers because of their remarkable properties, such as their biocompatibility, uniform and tunable breakdown rates, and outstanding biodegradability.[53] The An aliphatic polyester with a stellar reputation for being both biodegradable and biocompatible, polyglycolic acid, or polyglycolide (PGA), finds frequent usage in medical applications.[54] Polymerization of glycolic acid through ring-opening results in the production of PGA. Polylactic acid, or the thermoplastic aliphatic polyester version, is used to make a wide range of medical implants, such as mesh, screws, pins, rods, and orthopaedic devices (PLA). Because of its biocompatibility, bio absorption, and biodegradability, polycaprolactone (PCL) is another multipurpose polyester utilised in tissue engineering, dental braces, medical implants, and targeted medication delivery. Polymer that undergoes thermal reactions The poly (N-isopropylacrylamide, or PNIPAAm) polymer has several applications, including biosensors, drug delivery, and tissue engineering.[55] The poly(caprolacton/lactide) copolymer, also called PCL-PLA copolymer, is another biocompatible and biodegradable polymer that has multiple uses in tissue engineering. Coating polyesters (PLA, PCL, and PLGA) with cationic polymers considerably improves nucleic acid transport. Hyaluronic acid (HA) has several uses in nanomedicines, including mucosal therapies, vaccine administration, and more generally.It is a supplement for fluid in arthritic joints and has various applications such as surgical augmentation, wound healing, and tissue regeneration.[56]

Table 1: Significant polymer used in pharmaceutical industry

Name of polymer	Chemical structure of polymer[57]	Advantages	Applications	References
HA		Innovative formulations with increased mucoadhesive properties, particularly for ocular applications, are created by combining hyaluronic acid (HA) and tamarind seed polysaccharide (TSP) in an aqueous solution.	These substances have a wide range of uses, including filling up wrinkles, boosting the immune system, fighting infections, viruses, and cancer. They also promote the production of cartilage matrix, reduce inflammation, and even stimulate tissue regeneration, all of which contribute to better skin quality.	56,58
TGP		Because it is thermally stable, TSP remains unaffected when heated in water. Studies on polyion complexes that include fucoidan and chitosan for delivering drugs and genes have shown encouraging outcomes.	TSP, a thickening ingredient, is said to enhance the volume and storage qualities of bread.	59,60
Fucoidan		Thermostability ensures that TSP is unaffected by water heating. Research on fucoidan and chitosan polyion complexes for gene and medication delivery has demonstrated promising results.	Wound and burn healing is aided by heparin-like activity, which increases transforming growth factor (TGF-b1) and facilitates the migration and activation of fibroblasts in wounded tissue.	61,62

Name of polymer	Chemical structure of polymer	Advantages	Applications	References
PLGA		The potential to include both organic and inorganic substances—such as proteins, vaccines, small-molecule medications, and magnetic and metallic nanoparticles—into polylactic acid (PLGA).	PLGA-encapsulated manganese oxide (MnO) nanocrystals are employed for cellular magnetic resonance imaging (MR imaging), while PLGA-NPs incorporating nano-ZnO and organic-Ag hybrid materials are utilized for cancer treatment. Additionally, these formulations exhibit bacteriostatic effects against a range of bacteria, including both Gram-positive and Gram-negative types, as well as the yeast Candida albicans.	[63,64]
PVP		PVP's widespread solubility in water and a variety of organic solvents, including butanol, dichloromethane, and chloroform, is one among its notable characteristics. PVP's ability to form films is utilised in the film-coating of tablets, transdermal systems, and pharmaceutical sprays.	Wound care, pharmaceutical drug delivery,	[65,66,67]
PVA		The plasticizing effect of water molecules reduces its characteristics when it is wet. However, both alone and in combination with natural and synthetic polymers like chitosan and polycaprolactone (PCL), it has demonstrated encouraging results in the development of drug delivery systems.	PVA composites, including PVA gels, find application in various biomedical domains, including contact lens production, cardiac artificial repair, pharmaceutical delivery systems, and wound care. PVA is utilised as a biomaterial in medical devices due to its many advantageous qualities, including biocompatibility, nontoxicity, non-carcinogenicity, swelling properties, and bioadhesive qualities.	[68,69]

3.3. Long-acting Drug Delivery System (LADDS)

Long-Acting Drug Delivery Systems (LADDS) offer a wide variety of drug release durations, from three years to twenty-four hours, depending on the medication's properties and the specific delivery technique chosen. Patients may find LADDS to be a more pleasant, safer, and effective alternative to more intrusive medication delivery procedures like small incisions or numerous injections.[58] There has been a lot of buzz around long-acting (LA) drug delivery systems lately due to their potential applications in numerous medical domains, such as pain management, ophthalmic disease, contraception, anticancer treatment, antipsychotic medication, and many more chronic diseases. This is due to the fact that these technological advancements may lead to better treatment outcomes and more patient compliance.[59] Nowadays, most polymeric solid implants are crafted from non-biodegradable materials such as silicones, poly(urethanes), poly(acrylates), and poly (ethylene vinyl acetate). Octreotide and semaglutide's historic oral approval revolutionised peptide delivery and prompted scientists to develop long-acting formulations for other important peptide drugs.[60] Researchers initially investigated Poly(e-caprolactone) PCL for its potential use as a carrier for long-acting medications, such as the long-acting contraceptive Capronor. This method involved the subdermal implantation of biodegradable PCL capsules to regulate Levonorgestrel for long-term use.[61] The implanted formulations with a lengthy half-life are also useful for birth control and vaccination.

3.4. Gene delivery

A variety of non-viral vectors, including as lipids, polymers, and peptides, have been created throughout the past three decades. Nanoparticles, formed when these polymers interact with nucleic acids, provide numerous advantages, such as being inexpensive, easy to produce, versatile, and exhibiting minimal toxicity.[62] These characteristics enhance gene delivery in the end New, versatile delivery vehicles fabricated from synthetic polymer synthesis have become feasible thanks to advancements in gene therapy. When it comes to studying gene delivery strategies for cationic biopolymers, such as chitosan derivatives and liposomes, many researchers have investigated the potential benefits of polymeric carriers for genes. Polymeric systems can encapsulate negative DNA charges and condense big genes into small molecular structures when it comes to gene conveyance employing cationic polymers.[63] Polyplex is the molecular building block of nucleic acid in complexes based on cationic polymers. Furthermore, there are lipid-based gene carriers called "lipoplexes" that are cationic and non-viral is a Cationic polymer, or CPs, are made from a wide variety of polymers. Common examples of traditional polymeric vectors used for gene delivery are poly (2-N-(dimethyl aminoethyl) methacrylate), poly(L-lysine) (PLL), and polyethyleneimines (PEI) is a Making and modifying polymeric vectors to achieve specific physiochemical properties is a breeze. More and more research is showing that using synthetic polymers to transmit genes for cartilage regeneration is a practical approach. The use of grafted oligo-amine residues onto natural polysaccharides has led to the discovery of several biodegradable cationic polymers.[64]

3.5. Hydrogels

The recent progress in tissue engineering has heightened the attractiveness of hydrogels, particularly as matrices for repairing and regenerating various tissues and organs. Whether made from natural or synthetic polymers, hydrogels remain highly attractive as cell encapsulation materials is a Hydrogels, produced from various materials, such as cellulose derivatives, poly (vinyl alcohol), poly (N-vinyl 2-pyrrolidone), and poly (ethylene glycol), are characterised by their ability to swell significantly when exposed to water.[65] However, hydrogels made from copolymers and poly (hydroxyethyl methacrylate) (PHEMA) show moderate to weak swelling. Copolymerising basic hydrophilic monomers with additional monomers of varying degrees of hydrophilicity typically yields the desired swelling properties. Hydrogels are one of the most promising biomaterials for ophthalmic applications in preclinical research, especially when it comes to the continuous release of bioactive proteins into intraocular tissues. Researchers have exploited synthetic polymer hydrogels to deliver bioactive substances into the eye under controlled settings.[66] Among the extensively utilised synthetic polymers for producing ocular drug delivery systems are poly (ethylene glycol) (PEG), poly (2-hydroxyethyl methacrylate) (PHEMA), poly (vinyl alcohol) (PVA), polyacrylamide (PAM), poly (D, L-lactide-co-glycoside) (PLGA), and poly(caprolactone) (PCL). Because of their excellent refractive index and relatively good mechanical stability, hydrogels are particularly useful as contact lenses. Hydrogel integration into analytical sensing systems has recently made amazing progress. Among the intriguing sensing applications are those for pressure, temperature, ionic strength, organic analytes, biomolecular sensing, and humidity sensing. Hydrogel-based sensors have been employed in optical, chemical, and surface plasmon resonance (SPR), colorimetry, fluorescence, and strain sensing systems, to name a few. Hydrogels serve as a technique to boost the water-absorbing capabilities of soil in dry locations by spreading absorbed water throughout the soil. Therefore, we typically refer to hydrogels as superabsorbent polymers (SAP). The use of SAP in biomedical applications, artificial snow, coal dewatering, sealing, hygienic biosensor products, wound dressing, tissue engineering, regenerative medicine, barrier materials for controlling biological adhesions, and diagnostics for the separation of biomolecules or cells are among its noteworthy uses.[67]

3.6. Stimuli responsive polymers

Polymeric nanocarriers have attracted a lot of attention as a potential tool for cancer imaging and tailored medication delivery. When smart nano polymers are part of a system, they may react to changes in temperature, pH, light intensity, and wavelength in addition to electrical, magnetic, and auditory fields.[68] Nuclear imaging, photoacoustic imaging (PAI), positron emission tomography (PET), optical imaging, magnetic resonance imaging (MRI), and single-photon emission computed tomography (SPECT) are among the various imaging modalities that have been studied in this area. Evidence suggests that stimuli-responsive polymer systems can improve therapeutic efficacy while reducing side effects by establishing controlled drug release. Clinical use of polymeric nanoparticles like poly (D, L-lactic acid), poly (D, L-glycolic acid), and polyethylene glycol has already received approval. The temperature response is among the most studied and understood stimuli-responsive behaviours in polymers. Lower critical solution temperature (LCST) is a useful measure for several polymers it is the lowest temperature at which temperature-induced demixing occurs. Some polymers have LCST behaviours; they include PDEAEAM, PDMAEMA, PDEAEMA, and PMEMA, among others.[69] When it comes to light- and temperature-responsive polymers, photochromic compounds are a prominent example of a light-responsive chemical used to modify responsiveness. The melting points, boiling points, and phase separation points of temperature-responsive polymers with photochromic parts, like Spiro pyran, azobenzene, diarylethene, and spiroxazine, can be changed back and forth by using light.[70] We have created a multi-responsive switchable copolymer using pH- and light-responsive Spiro benzopyran and temperature-responsive NIPAAm (N-isopropylacrylamide). In water, this copolymer reacts to variations in light, pH, and temperature. Carbon dioxide (CO_2) is a flexible and plentiful gas that may initiate the synthesis of many polymer materials.[71] Feng, Theato, and colleagues have provided a thorough review of recent developments in this area. Manouras and Vamvakaki explore field-responsive materials in a different setting; their work includes photo responsive, electro responsive, magneto responsive, and ultrasound-sensitive polymers. Next, we'll go over some of the possible uses for these materials' spatiotemporally regulated switching capabilities.[72]

3.7. Nanoparticles

Polymers from either naturally occurring or partially synthesised sources typically form solid colloidal particles, also known as polymeric nanoparticles.[73] You may classify these nanoparticles as biodegradable or non-biodegradable based on their size, which ranges from 1 to 100 nm. Oral medication administration is one area where nanotechnology has shown to be highly useful in improving drug delivery.[74] It makes it easier for drugs to (i) make it across the intestinal barrier and (ii) be targeted to certain parts of the digestive system. The third capability made possible by nanotechnology is the transport of big macromolecules both inside and outside of cells. The therapeutic index, specificity, efficacy, and tolerability of associated pharmaceuticals may be improved with the application of nanomedicines. By itself or in combination with other substances such as dextran, gelatin, alginate, or agar, chitosan is by far the most popular natural ingredient for the oral distribution of nanoparticles. The Synthetic polymers like poly(lactide), poly(glycolide), poly(lactide-co-glycolide), poly(cyanoacrylates), polyethyleneimine, and polycaprolactone facilitate the oral administration of pharmaceuticals. Particularly noteworthy are the hydrolysable and biodegradable properties of PLA, PLGA, and PCL, which allow them to break down into monomeric units in the body.[75] In this instance, PCL is more suited for long-term distribution due to its slower degradation rate compared to PLGA. The function of esterases in biological fluids is to degrade poly(cyanoacrylates).[76,77] Polymer nanocomposites (PNCs) are materials with nano-sized fillers that have attracted a lot of attention from academia and industry in the last few decades.

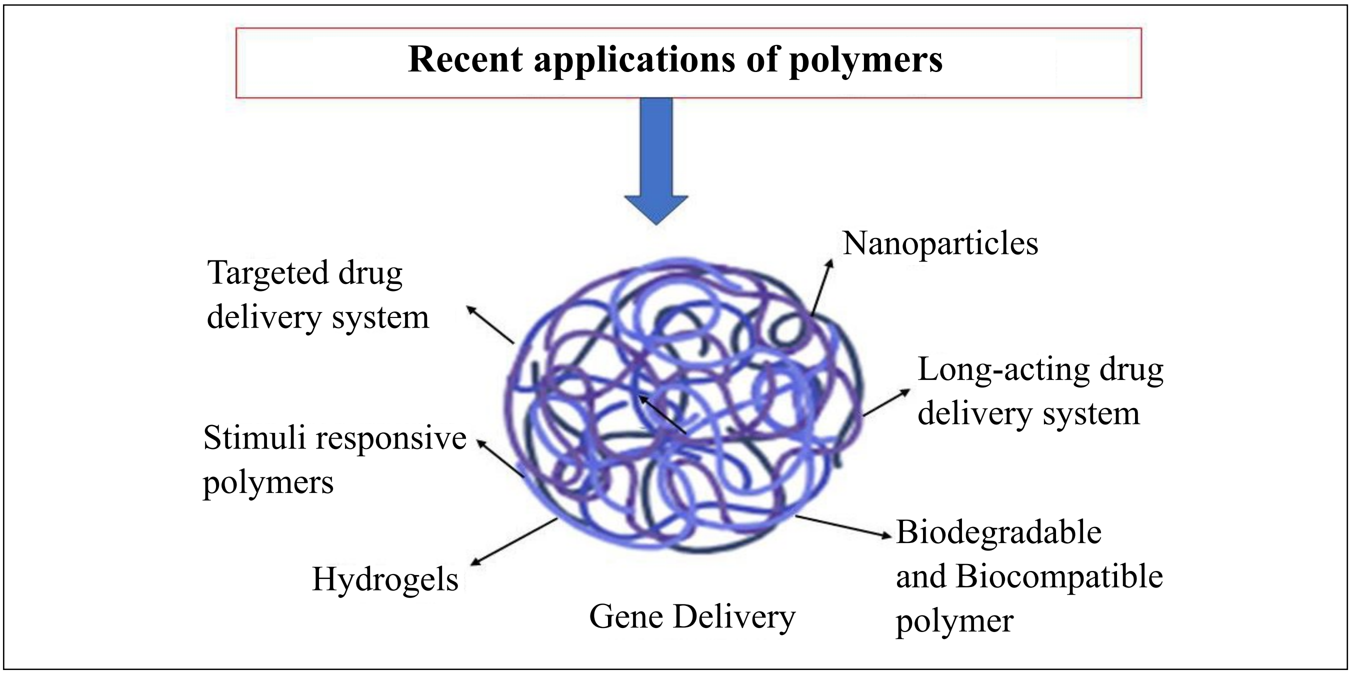


Figure 5: Application of polymers[8]

4. Conclusion

The intriguing world of polymers begs for more research and development, which, in turn, might lead to exciting new discoveries. In areas like gene delivery, skin absorption, nanoparticles, long-lasting drug delivery systems, and the eye and digestive systems, there have been some really good and promising results. Polymers have a lot of uses in medicine, and they're very inexpensive compared to heavy metals and other materials. When compared to heavy metals and traditional treatments, polymers were shown to have fewer negative effects in certain trials.

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None.

6. Conflict of Interest

The authors declare that there is no conflict of interests regarding the publication of this article.

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