The Pharmaceutical Polymer's; A Current Status In Drug Delivery: A Comprehensive Review

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Abstract:
Polymers are a large class of materials consisting of many small molecules. Polymers are the backbone of a pharmaceutical drug delivery system as they control the release of the drug from the device. The main role of polymer is to protect drug from physiological environment and prolong release of drug to improve its stability. The drug is release from polymer by diffusion, degradation and swelling. Nowadays, due to many problems associated with drug release and side effects of synthetic polymers, manufacturers are inclined towards using natural polymers. Natural polymers being poly saccharides are biocompatible and without any side effects. The main highlights of this review article to discuss the basics of polymers, polymerization chain with their ideal characterization including their classification. The lastly discussed points to utilization of polymer role in diverse drug delivery and their various pharmaceutical application including future directions and challenges as well widely in polymer's application.

Keywords: Polymer's, Drug delivery, Classification, Natural polymer, Biodegradable.

INTRODUCTION

Pharmaceutical polymers play a crucial role in the development and formulation of various drug delivery systems, offering numerous advantages such as improved drug solubility, controlled release, and enhanced bioavailability. Pharmaceutical polymers must be non-toxic, biocompatible, and have the desired physical and chemical properties for the intended application.

A polymer is a substance or material consisting of very large molecules called macromolecules, composed of many repeating subunits. Due to their broad spectrum of properties, both synthetic and natural polymers play essential and ubiquitous roles in everyday life. Polymers range from familiar synthetic plastics such as polystyrene to natural biopolymers such as DNA and proteins that are fundamental to biological structure and function [1]. Polymers, both natural and synthetic, are created via polymerization of many small molecules, known as monomers.

Pharmaceutical polymers are a diverse group of materials that are used in a wide range of pharmaceutical applications. They can be used to control drug release, improve drug stability, and deliver drugs to specific sites in the body.

Polymers are now used in a wide range of pharmaceutical applications, including:

- ***Drug delivery systems:*** Polymers are used to create a variety of drug delivery systems, including tablets, capsules, injectables, implants, transdermal drug delivery systems, and topical formulations.
- ***Excipients:*** Polymers are also used as excipients in a variety of pharmaceutical formulations. Excipients are inactive ingredients that are added to formulations to improve their processing, stability, or delivery characteristics.
- ***Medical devices:*** Polymers are used to manufacture a wide range of medical devices, such as stents, catheters, and artificial organs [1-2].

The use of polymers in pharmaceuticals has revolutionized the way that drugs are delivered and used. Polymers have enabled the development of new and more effective treatments for a wide range of diseases.

Historical perspective on the use of polymers in pharmaceuticals. The use of polymers in pharmaceuticals dates back to the early 20th century. One of the first examples is the use of cellulose acetate as a coating for tablets to improve their appearance and stability. In the 1930s, poly (ethylene glycol) (PEG) was first used as a lubricant and binder in tablet formulations.

In the 1950s and 1960s, there was a significant increase in the development of new synthetic polymers for pharmaceutical applications. This was driven by the need for new drug delivery systems for emerging therapies, such as antibiotics and vaccines [3].

In the 1970s and 1980s, there was a growing interest in the use of polymers for controlled drug delivery. Controlled drug delivery systems can release the drug over a period of time, rather than all at once. This can improve the efficacy and safety of some drugs, and it can also reduce the frequency of dosing.

The historical development of polymer's shown in the given Table. 01 as below discussion:

Table. 01: The historical development of polymer's in pharmaceuticals

Decade	Historical significance development of the use of polymers in pharmaceuticals
1920s	Cellulose acetate is used as a coating for tablets.
1930s	PEG is first used as a lubricant and binder in tablet formulations.
1950s	Poly (lactic acid) (PLA) is first synthesized.
1960s	Poly (glycolic acid) (PGA) is first synthesized.
1970s	Poly (lactic-co-glycolic acid) (PLGA) is first synthesized. PLGA is a biodegradable polymer that is now widely used in controlled drug delivery systems.
1980s	The first controlled release drug delivery systems based on polymers are developed.
1990s	Polymers are used to develop new and innovative drug delivery systems, such as transdermal patches and micelles.
2000s and beyond	Research continues into the development of new and improved polymer-based drug delivery systems [1-4].

The future of the use of polymers in pharmaceuticals is very promising. Polymers are being investigated for use in a number of emerging technologies, such as 3D printing of drugs and medical devices, and targeted drug delivery using nanoparticles.

This review article aims to provide a comprehensive overview of pharmaceutical polymers, including their types, applications, challenges, and emerging trends in the field.

IDEAL PROPERTIES OF POLYMER'S: The ideal properties of polymers for pharmaceutical applications are:

- **Non-toxic and biocompatible:** The polymer must be non-toxic and not cause an immune response in the body.
- **Biodegradable:** The polymer should be biodegradable, meaning that it can be broken down by the body over time. This is important for polymers that are used in implants and other drug delivery systems that need to be present in the body for a period of time.
- **Good mechanical properties:** The polymer should have good mechanical properties, such as strength, toughness, and elasticity. This is important for polymers that are used in medical devices and implants.
- **Good barrier properties:** The polymer should have good barrier properties to protect the drug from moisture, oxygen, and other environmental factors. This is important for polymers that are used in packaging and drug delivery systems.
- **Easy to process:** The polymer should be easy to process into the desired dosage form or medical device [3-5].

In addition to these general properties, there are also specific properties that may be desired for specific pharmaceutical applications. A polymer that is used in a controlled drug delivery system may need to have a specific degradation rate in order to release the drug at the desired rate.

POLYMERIZATION: Polymerization is a chemical process in which small molecules, called monomers, are chemically bonded together to form a long-chain or three-dimensional network structure known as a polymer. This process is crucial in the production of various synthetic polymers, plastics, and many natural materials. Polymerization can occur through various mechanisms and under different conditions. Polymerization shown in the given (**Fig. 01**) as below:

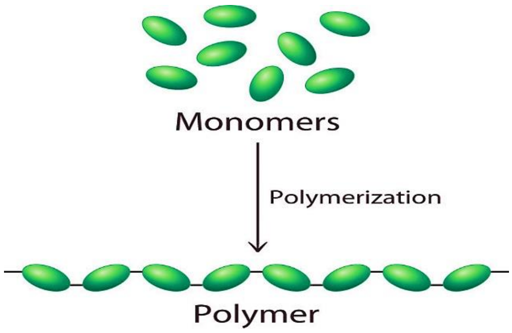

Figure: 01. The schematic representation of polymerization step in the formation of polymer

The key aspects of polymerization in polymer formation as below following discussed with their types:

Types of Polymerization:

01) Chain Polymerization: In this process, monomers are added one by one to the growing polymer chain. Chain polymerization can be further divided into three main types:

- ***Radical Polymerization:*** Initiated by free radicals, commonly used for the production of materials like polyethylene and polyvinyl chloride (PVC).
- ***Anionic Polymerization:*** Initiated by anionic initiators and is used to produce materials like synthetic rubbers.
- ***Cationic Polymerization:*** Initiated by cationic initiators and is employed in the production of polymers like polyisobutylene [3-6].

02) Step Polymerization: In this process, monomers with functional groups react together to form covalent bonds, releasing small molecules (usually water or methanol) as byproducts. Examples include the formation of polyesters and polyamides.

Table. 02: The list of polymerization types in table form

Type of polymerization	Description	Example
Addition polymerization	Monomers add together without the loss of any atoms.	Polyethylene, polypropylene, polystyrene, polyvinyl chloride
Condensation polymerization	Monomers react together with the loss of small molecules, such as water or alcohol.	Nylon, polyester, polyurethane
Ring-opening polymerization	A cyclic monomer is opened up and the monomer units are added together to form a polymer chain.	Polystyrene, polyisoprene
Crosslinking	Polymer chains are joined together to form a three-dimensional network.	Vulcanized rubber, epoxy resins [5-7]

03) Ring-Opening Polymerization: Involves opening a cyclic structure to form a linear polymer chain. It's commonly used in the production of materials like polyethylene terephthalate (PET) and polypropylene oxide (PPO).

04) Living Polymerization: A controlled form of polymerization where chain growth can be initiated, stopped, and reinitiated multiple times, resulting in precise control over polymer chain length and structure.

Applications of Polymerization:

- Polymerization is used to manufacture a wide range of materials, including plastics, synthetic rubbers, adhesives, coatings, fibers, and composites.
- It is crucial in various industries such as automotive, packaging, construction, electronics, and healthcare.
- Polymerization is also employed in the production of specialty polymers for advanced applications, such as aerospace, biotechnology, and nanotechnology [3-7].

Polymerization is a fundamental process in the field of materials science and chemistry, and ongoing research is focused on developing new polymers, improving polymerization techniques, and addressing environmental and sustainability issues associated with polymer production and disposal.

CLASSIFICATION OF PHARMACEUTICAL POLYMER'S

Pharmaceutical polymers play a crucial role in drug formulation and delivery systems. They can be classified based on various criteria, including their source, biodegradability, and function. Pharmaceutical polymers can be classified (**Fig. 02**) into different groups depending on their origin, biodegradability, reaction mode of polymerization, and interaction with water.

Classification based on origin:

- ***Natural polymers:*** These polymers are derived from natural sources, such as plants, animals, and microorganisms. Examples of natural polymers used in pharmaceuticals include cellulose, starch, alginate, and collagen.
- ***Synthetic polymers:*** These polymers are produced by chemical synthesis. Examples of synthetic polymers used in pharmaceuticals include poly (ethylene glycol), poly (lactic acid), and poly (methyl methacrylate).
- ***Semisynthetic polymers:*** These polymers are produced by chemically modifying natural polymers. Examples of semisynthetic polymers used in pharmaceuticals include cellulose acetate and hydroxypropyl methylcellulose.

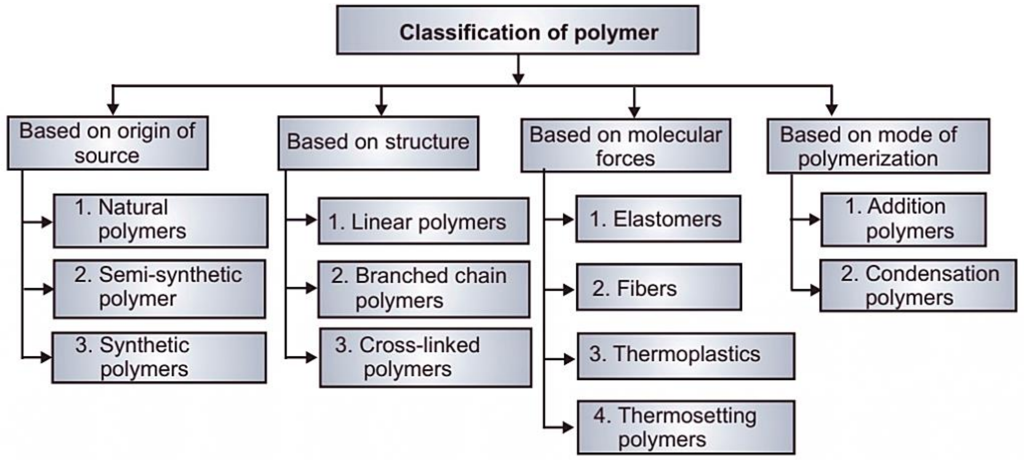

Figure: 02. The classification of polymer in pharmaceutical fields

Classification based on biodegradability:

- ***Biodegradable polymers:*** These polymers can be broken down by enzymes or other biological processes in the body. Examples of biodegradable polymers used in pharmaceuticals include poly (lactic acid), poly (glycolic acid), and poly(caprolactone).

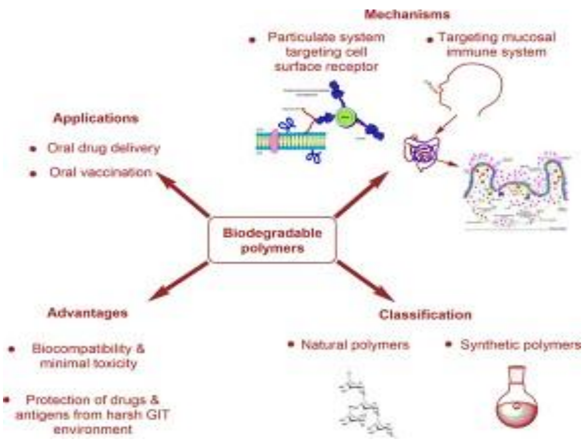

Figure: 03. The representation of biodegradable polymer with their various applications

- ***Non-biodegradable polymers:*** These polymers are not easily broken down by the body. They may be eliminated from the body unchanged or remain in the body for long periods of time. Examples of non-biodegradable polymers used in pharmaceuticals include poly (vinyl chloride) and silicone.

Classification based on reaction mode of polymerization:

- ***Addition polymers:*** These polymers are formed by the addition of monomer molecules to each other. Examples of addition polymers used in pharmaceuticals include polyethylene, polypropylene, and polystyrene.
- ***Condensation polymers:*** These polymers are formed by the condensation of two or more monomer molecules with the loss of a small molecule, such as water or alcohol. Examples of condensation polymers used in pharmaceuticals include polyesters, polyamides, and polyurethanes [7].

Classification based on interaction with water:

- ***Hydrophilic polymers:*** These polymers attract water and can dissolve in water. Examples of hydrophilic polymers used in pharmaceuticals include poly (ethylene glycol), poly (vinyl pyrrolidone), and hyaluronic acid.
- ***Hydrophobic polymers:*** These polymers repel water and do not dissolve in water. Examples of hydrophobic polymers used in pharmaceuticals include poly (lactic acid), poly(methyl methacrylate), and poly(vinyl chloride).

Charge-based Classification:

- ***Cationic Polymers:*** These polymers have a positive charge and are often used in drug delivery systems to interact with negatively charged biological molecules or cell membranes. Examples include polyethyleneimine (PEI) and chitosan [4-8].
- ***Anionic Polymers:*** These polymers have a negative charge and can be used in drug formulations for controlled release or stability enhancement. Examples include sodium alginate and NaCMC.

These are some of the common classifications of pharmaceutical polymers, and they can be further categorized based on specific properties and applications in drug development and delivery systems. The choice of polymer depends on the desired drug delivery mechanism, biocompatibility, and other factors relevant to the pharmaceutical formulation.

NATURAL PHARMACEUTICAL POLYMER'S: Natural pharmaceutical polymers are polymers that are derived from natural sources, such as plants, animals, and microorganisms. They have a number of advantages over synthetic polymers for pharmaceutical applications, including:

- ***Biocompatibility:*** Natural polymers are generally more biocompatible than synthetic polymers, meaning that they are less likely to cause an immune response in the body.
- ***Biodegradability:*** Many natural polymers are biodegradable, meaning that they can be broken down by the body over time. This is important for polymers that are used in implants and other drug delivery systems that need to be present in the body for a period of time.
- ***Low cost:*** Natural polymers are often less expensive than synthetic polymers. This is important for developing affordable pharmaceutical products.

The various examples of natural pharmaceutical polymers and their applications:

1. **Cellulose and Cellulose Derivatives:** Cellulose and its derivatives (e.g., hydroxypropyl cellulose, carboxymethyl cellulose) are used as excipients in tablet formulations, controlled-release drug delivery systems, and as binders in granulation processes.
2. **Starch and Starch Derivatives:** Starch is used as a binder, disintegrant, and filler in tablet formulations. Modified starches are also used in controlled-release dosage forms.
3. **Chitosan:** Chitosan, derived from chitin found in crustacean shells, is used in drug delivery systems due to its mucoadhesive properties. It can be used in wound dressings, drug-loaded nanoparticles, and scaffolds for tissue engineering.
4. **Alginate:** Alginate, extracted from brown algae, is used in wound dressings, dental impressions, and drug delivery systems. It forms gels in the presence of calcium ions, making it suitable for controlled release.
5. **Gelatin:** Gelatin, derived from animal collagen, is used in the production of capsules, coatings for tablets, and as a stabilizer in emulsions and suspensions.
6. **Hyaluronic Acid:** Hyaluronic acid, found in connective tissues, is used in ophthalmic solutions, intra-articular injections for joint lubrication, and as a dermal filler in cosmetic applications.
7. **Collagen:** Collagen, a major component of skin and connective tissues, is used in wound dressings, tissue engineering scaffolds, and as a carrier for drug delivery.
8. **Dextran:** Dextran, a polysaccharide produced by bacteria, is used as a plasma volume expander and in ophthalmic solutions to reduce intraocular pressure.
9. **Heparin:** Heparin, a naturally occurring anticoagulant, is used in various pharmaceutical and medical applications, including blood thinning medications and as a coating for medical devices like catheters.
10. **Gum Arabic:** Gum arabic, extracted from Acacia trees, is used as a stabilizer and emulsifier in oral suspensions, syrups, and in the production of solid dosage forms [6-9].

These natural polymers offer several advantages in pharmaceutical applications, such as reduced risk of allergic reactions, biodegradability, and environmental sustainability. Their properties can vary depending on their source and processing methods, so careful consideration is required when selecting and formulating with these polymers in pharmaceutical products.

Table. 03: The list of natural polymer's in pharmaceutical applications

Natural Pharmaceutical Polymer	Example
Alginate	Wound dressings, drug delivery systems, tissue engineering scaffolds
Cellulose	Binders, disintegrants, tablet coatings
Chitosan	Drug delivery systems, wound dressings, hemostats
Gelatin	Binders, capsules, drug delivery systems
Guar gum	Suspending agents, thickeners, drug delivery systems
Hyaluronic acid	Drug delivery systems, ophthalmic preparations, tissue engineering scaffolds
Pectin	Binders, disintegrants, drug delivery systems
Starch	Binders, disintegrants, tablet coatings [5-9]

Natural pharmaceutical polymers are used in a variety of pharmaceutical formulations, including tablets, capsules, suspensions, and injectables. They offer a number of advantages over synthetic polymers, including:

- ***Biocompatibility:*** Natural polymers are generally well-tolerated by the body and can be degraded and eliminated naturally.
- ***Biodegradability:*** Natural polymers can be broken down by microorganisms, which reduces their environmental impact.
- ***Versatility:*** Natural polymers can be modified to meet the specific needs of different pharmaceutical applications.

Alginate is a natural polymer that is derived from seaweed. It is often used in wound dressings and drug delivery systems because it is biocompatible and biodegradable. Alginate can also be formed into gels, which can be used to deliver drugs to the body in a controlled manner.

Chitosan is another natural polymer that is derived from the shells of crustaceans. It is often used in drug delivery systems and wound dressings because it is biocompatible, biodegradable, and has antimicrobial properties. Chitosan can also be used to form nanoparticles, which can be used to deliver drugs to specific cells or tissues in the body [10].

Natural pharmaceutical polymers are an important part of the pharmaceutical industry. They offer a number of advantages over synthetic polymers, and they are being used to develop new and innovative pharmaceutical products.

Table. 04: The differentiation in natural and synthetic polymers with their characterization

Characteristic	Natural Pharmaceutical Polymers	Synthetic Pharmaceutical Polymers
Source	Derived from natural sources, such as plants, animals, and microorganisms	Derived from synthetic sources, such as petroleum
Biocompatibility	Generally well-tolerated by the body	May not be as well-tolerated by the body as natural polymers
Biodegradability	Can be broken down by microorganisms	May not be biodegradable
Versatility	Can be modified to meet the specific needs of different pharmaceutical applications	Can also be modified to meet the specific needs of different pharmaceutical applications
Examples	Alginate, cellulose, chitosan, gelatin, guar gum, hyaluronic acid, pectin, starch	Poly(lactic-co-glycolic acid), polyethylene glycol, polyvinylpyrrolidone [8-11]

Research continues into the development of new and improved natural pharmaceutical polymers for use in drug delivery and medical devices.

NOVEL AND INVESIGATIONAL POLYMER'S: Novel and investigational pharmaceutical polymers refer to relatively new or experimental polymer materials that are being explored for various pharmaceutical and biomedical applications. These polymers often offer unique properties and capabilities that make them promising candidates for drug delivery systems, medical devices, and other pharmaceutical purposes.

Novel and investigational pharmaceutical polymers are polymers that are being developed for new or improved pharmaceutical applications. The various novel and investigational pharmaceutical polymers include as following::

a) **Polymeric nanoparticles:** Polymeric nanoparticles are small particles that are made from polymers. They can be used to deliver drugs to specific tissues or cells in the body. For example, polymeric nanoparticles can be used to deliver chemotherapy drugs directly to a tumor.
b) **Polymeric micelles:** Polymeric micelles are another type of polymeric nanoparticle. They are self-assembling structures that are formed from amphiphilic polymers. Polymeric micelles can be used to deliver drugs in a controlled manner.
c) **Polymeric hydrogels:** Polymeric hydrogels are cross-linked polymer networks that can absorb a large amount of water. They can be used to deliver drugs in a controlled manner, or they can be used to create implants that release drugs over a period of time.
d) **Stimuli-responsive polymers:** Stimuli-responsive polymers are polymers that change their properties in response to external stimuli, such as temperature, pH, or light. They can be used to create drug delivery systems that release the drug in response to a specific stimulus. For example, a temperature-responsive polymer can be used to create a drug delivery system that releases the drug when it reaches the body temperature.
e) **Dendrimers:** Dendrimers are highly branched polymers with a well-defined structure. They are explored for drug delivery due to their ability to encapsulate drugs and targeting ligands, making them suitable for precision medicine [9-12].

Table. 05: The novel or synthetic polymer, chemical structure and with their applications in pharmaceuticals

Polymer	Chemical Structure	Example Applications
Poly(lactic-co-glycolic acid) (PLGA)	A biodegradable polyester	Drug delivery systems, tissue engineering scaffolds, sutures
Poly(ε-caprolactone) (PCL)	Another biodegradable polyester	Medical implants, sutures, tissue engineering scaffolds
Poly(hydroxybutyrate) (PHB)	A biodegradable polyester produced by bacteria	Food packaging, medical devices, tissue engineering scaffolds
Poly(3,4-ethylenedioxythiophene) (PEDOT)	A conductive polymer	Batteries, solar cells, sensors
Poly(N-isopropylacrylamide) (PNIPAM)	A stimuli-responsive polymer	Drug delivery systems, medical implants, environmental sensors [8-11]

These novel and investigational pharmaceutical polymers hold great potential for advancing drug delivery, medical device design, and the overall field of pharmaceutical sciences. Their development and application continue to evolve as researchers explore their unique properties and capabilities.

PHARMACEUTICAL POLYMERS IN THE DIVERSE DRUG DELIVERY

Pharmaceutical polymers play a critical role in diverse drug delivery systems, offering a wide range of advantages in terms of drug solubility, stability, controlled release, and targeted delivery (**Fig. 04**). The diverse drug delivery systems where pharmaceutical polymers are prominently used:

Oral Drug Delivery:

- ***Polymeric Nanoparticles and Microparticles:*** These can protect drugs from degradation in the gastrointestinal tract and enable controlled release.
- ***Polymeric Coatings:*** Coatings can modify drug release profiles or provide taste masking for oral dosage forms.

Injectable Drug Delivery:

- ***Polymeric Microspheres:*** Injectable microspheres enable sustained release of drugs over extended periods. Polymers like PLGA are commonly used.
- ***Hydrogels:*** Injectable hydrogels are used for local drug delivery, tissue engineering, and sustained release of biologics [10-12].

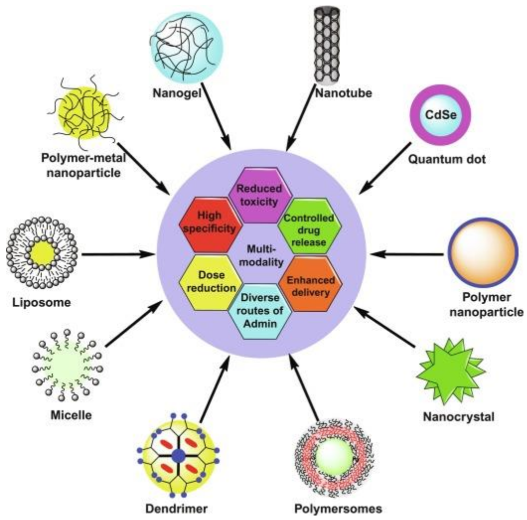

Figure: 04. The representation of polymer in various drug delivery system

Transdermal and Topical Drug Delivery:

- ***Polymer Matrix Patches:*** These patches use polymers to control the release of drugs through the skin over time.
- ***Polymeric Nanocarriers:*** Nanoparticles and liposomes can encapsulate drugs for enhanced skin penetration and targeted delivery.

Ocular Drug Delivery:

- ***Polymeric Nanoparticles:*** Nanoparticles can enhance the solubility of poorly water-soluble drugs and improve drug retention in the eye.
- ***Contact Lenses:*** Polymers are used in contact lens materials to release drugs directly onto the ocular surface.

Intravenous Drug Delivery:
- ***Polymeric Micelles:*** These can improve the solubility of hydrophobic drugs and enhance their circulation time in the bloodstream.
- ***Polymeric Drug Conjugates:*** Polymers can be conjugated to drugs to increase their stability and reduce side effects.

Pulmonary Drug Delivery:
- ***Polymeric Nanoparticles:*** Nanoparticles can be engineered for inhalation delivery, allowing targeted treatment of lung diseases.
- ***Polymeric Nanofibers:*** Nanofiber-based systems can improve drug dispersion and adhesion in the respiratory tract.

Intranasal Drug Delivery:
- ***Polymeric Nanoparticles:*** Nasal delivery systems use polymers to encapsulate drugs and enhance their absorption through the nasal mucosa [11-14].

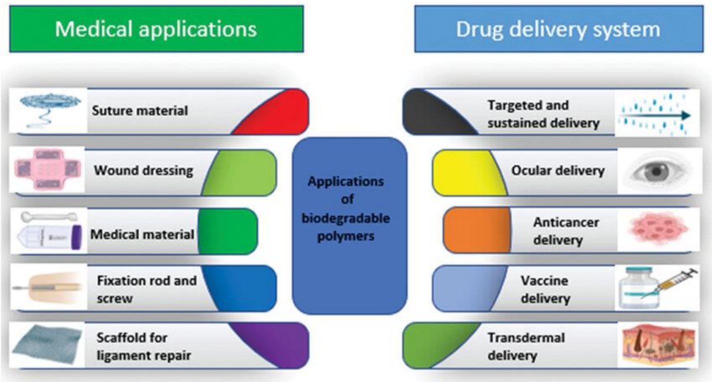

Figure: 05. The medical and drug delivery applications of polymers as biodegradable in drug delivery system

Gastrointestinal Drug Delivery:
- ***Enteric Coatings:*** Polymers like Eudragit are used for enteric coatings to protect drugs from stomach acid and deliver them to the intestines.
- ***Polymeric Microsponges:*** These can encapsulate drugs and release them slowly in the GI tract.

Implantable Drug Delivery Systems:
- ***Biodegradable Polymers:*** Implants made from biodegradable polymers gradually release drugs over time, eliminating the need for repeated dosing.

Targeted Drug Delivery:
- ***Polymeric Nanocarriers:*** Nanoparticles can be functionalized with ligands to target specific cells or tissues, reducing systemic side effects.

Intratumoral Drug Delivery:
- ***Polymeric Microspheres:*** Microspheres can be injected directly into tumors to provide sustained drug release at the site of action [13-15].

Table. 06: The some novel synthetic polymers in various drug delivery system

Pharmaceutical Polymer	Drug Delivery System	Key Features and Benefits
Poly(lactic-co-glycolic acid) (PLGA)	Microparticles, nanoparticles, implants	Biodegradable, controlled release
Poly(ε-caprolactone) (PCL)	Microparticles, nanoparticles, implants	Biodegradable, biocompatible, controlled release
Chitosan	Microparticles, nanoparticles, films	Biodegradable, biocompatible, mucoadhesive
Cellulose acetate phthalate (CAP)	Enteric coatings	Protects drugs from gastric acid
Eudragit	Sustained release coatings	Controls the release of drugs in the gastrointestinal tract
Poloxamers	Micelles, hydrogels	Biodegradable, biocompatible, controlled release
Hyaluronic acid	Hydrogels, nanoparticles	Biodegradable, biocompatible, controlled release [14-16]

Pharmaceutical polymers offer versatility in formulating drug delivery systems to meet specific therapeutic needs. They can be tailored to control drug release rates, protect drugs from degradation, and enhance drug targeting, ultimately improving the safety and efficacy of drug therapies across a wide range of applications.

PHARMACEUTICAL APPLICATIONS OF POLYMER'S

Pharmaceutical polymers have a wide range of applications in the field of pharmaceuticals. They are used for various purposes, including drug delivery, formulation, and as excipients. The various important pharmaceutical applications of polymers:

Drug Delivery Systems:

- ***Oral Drug Delivery:*** Polymers are used to formulate oral drug delivery systems, such as tablets, capsules, and oral films, to control drug release, enhance bioavailability, and improve patient compliance.
- ***Transdermal Drug Delivery:*** Transdermal patches and gels utilize polymers to deliver drugs through the skin, ensuring a controlled and sustained release over time.
- ***Injectable Drug Delivery:*** Injectable polymer-based formulations, including microparticles and nanoparticles, are used for sustained release and targeted drug delivery.
- ***Ocular Drug Delivery:*** Polymers are employed in eye drops, contact lenses, and ophthalmic inserts to improve drug retention and release in the eye [15-17].

Topical and Dermatological Products:

- Polymers are used in creams, ointments, and gels to provide desirable rheological properties and enhance skin penetration of active pharmaceutical ingredients (APIs).
- Hydrogels and nanogels made from polymers are used for wound healing and as carriers for dermatological drugs.

Parenteral Drug Delivery:

- Polymers are utilized in parenteral drug formulations, such as injectable solutions, to improve the solubility and stability of APIs.
- Biodegradable and biocompatible polymers are employed in sustained-release formulations for long-acting injectable drugs.

Controlled Drug Release Systems:

- Polymers play a critical role in the development of controlled-release drug delivery systems, ensuring a steady and prolonged release of drugs over time.
- Implantable devices, such as drug-eluting stents and intrauterine devices (IUDs), often use biodegradable polymers to release drugs at a controlled rate.
- Biopharmaceuticals: Polymers are used as excipients in the formulation of biopharmaceuticals, including proteins and peptides, to stabilize these sensitive molecules and improve their bioavailability.
- Polymer-based nanoparticles can be employed to protect and deliver biopharmaceuticals to specific target sites [17-19].

Table. 07: The list of pharmaceutical applications of polymers with examples:

Applications	Example
Drug delivery	Extended-release tablets, transdermal patches, nanospheres and microspheres, implant devices
Excipients	Binders, disintegrants, lubricants
Coating	Enteric coatings, moisture barriers, light barriers
Biomaterials	Sutures, scaffolds, tissue engineering products [15-17]

Oral Disintegration and Taste Masking:

- Polymers like superdisintegrant are used in orally disintegrating tablets (ODTs) to enhance disintegration and patient compliance.
- Polymers can also be used for taste masking of bitter drugs, making them more palatable for patients.

Gastrointestinal Drug Delivery: Polymers are used in gastroretentive drug delivery systems to prolong drug residence time in the stomach, ensuring improved drug absorption and efficacy [17-19].

Vaccine Formulation: Polymers are employed in vaccine delivery systems to stabilize antigens, enhance immunogenicity, and provide controlled release for prolonged protection.

Gene Delivery: Polymers are used as carriers in gene therapy to protect and deliver genetic material to target cells, facilitating gene expression [14-20].

The choice of polymer depends on the specific requirements of the drug formulation or delivery system, including solubility, biocompatibility, and release kinetics, among other factors. Polymers continue to be a critical component in advancing drug development and improving patient outcomes.

FUTURE DIRECTIONS AND CHALLENGES OF POLYMER'S

Pharmaceutical polymers have a wide range of applications in the field of pharmaceuticals. They are used for various purposes, including drug delivery, formulation, and as excipients. Polymers have the potential to revolutionize the field of pharmaceuticals in the future. The important key future directions and challenges of polymers in pharmaceuticals include:

Future directions:

- ***Development of new and innovative polymer-based drug delivery systems:*** Polymers can be used to develop new and innovative drug delivery systems that can improve the efficacy, safety, and convenience of drug administration. For example, polymers can be used to develop targeted drug delivery systems that deliver drugs specifically to diseased cells or tissues, or controlled release systems that release the drug over a period of time [21].
- ***Development of new polymer-based biomaterials:*** Polymers can be used to develop new biomaterials that can be used to repair or replace damaged tissues and organs. For example, polymers can be used to make scaffolds for tissue engineering, or sutures and other devices for medical implants.
- ***Development of new sustainable and biodegradable polymers:*** Many of the polymers that are currently used in pharmaceuticals are derived from petroleum-based feedstocks. There is a growing need to develop sustainable and biodegradable polymers that can be used in pharmaceutical applications. This would help to reduce the environmental impact of the pharmaceutical industry [22-24].

Table. 08: The list of some important pharmaceutical applications of polymers with examples and challenges

Application	Example	Challenges
Drug delivery	Extended-release tablets, transdermal patches, nanospheres and microspheres, implant devices	Developing targeted drug delivery systems and controlled release systems, understanding and controlling the complex properties of polymers, developing scalable and cost-effective manufacturing processes, demonstrating safety and efficacy in clinical trials
Excipients	Binders, disintegrants, lubricants	Developing new excipients with improved properties, ensuring the compatibility of excipients with drugs and other excipients
Coating	Enteric coatings, moisture barriers, light barriers	Developing coatings with improved durability and resistance to environmental factors, ensuring the compatibility of coatings with drugs and other excipients
Biomaterials	Sutures, scaffolds, tissue engineering products	Developing biomaterials with improved biocompatibility and biodegradability, designing biomaterials that can mimic the structure and function of natural tissues [25-28]

Challenges:

- ***Understanding and controlling the complex properties of polymers:*** Polymers are complex materials with a wide range of properties. It is important to understand and control these properties in order to develop new and effective polymer-based pharmaceutical products.
- ***Developing scalable and cost-effective manufacturing processes for polymer-based pharmaceutical products:*** Polymer-based pharmaceutical products can be expensive to produce. It is important to develop scalable and cost-effective manufacturing processes in order to make these products more affordable.
- ***Demonstrating the safety and efficacy of polymer-based pharmaceutical products in clinical trials:*** Before polymer-based pharmaceutical products can be marketed and used by patients, they must be shown to be safe and effective in clinical trials. This can be a challenging and time-consuming process [28-30].

Polymers have the potential to make a significant impact on the future of pharmaceuticals. Researchers are working to develop new and innovative polymer-based drug delivery systems, biomaterials, and manufacturing processes. As these technologies continue to develop, we can expect to see more and more polymer-based pharmaceutical products on the market in the years to come.

CONCLUSION

In conclusion, polymers are essential materials in the pharmaceutical industry. They are used in a wide variety of applications, and they play a vital role in improving the efficacy, safety, and convenience of drug administration. Polymers are also being used to develop new and innovative drug delivery systems and biomaterials. This review article has shed light on the multifaceted and indispensable role of polymers in the field of pharmaceuticals. Polymers have revolutionized drug delivery, formulation, and various therapeutic applications. They have enabled the development of innovative drug delivery systems that enhance the bioavailability of poorly soluble drugs, provide controlled and sustained drug release, and target specific sites within the body. Moreover, polymers have contributed to the stability and solubility

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