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POLYMER-BASED MUCOADHESIVE DRUG DELIVERY SYSTEMS: RECENT ADVANCES AND FUTURE PROSPECTS

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ABSTRACT

Mucoadhesive drug delivery systems are designed to tackle the limitations of conventional oral formulations, specifically limited bioavailability and rapid drug degradation in the gastrointestinal tract. These systems extend the time a drug stays in contact with the absorption site by allowing it to adhere to mucosal surfaces such as the oral, nasal, vaginal, or gastrointestinal mucosa. The longer residence helps in improving the absorption of drug and more effective local and systemic therapy. The mechanism of mucoadhesion is based on theories, like diffusion, wetting, and adsorption, which describes the interaction of polymers with glycoproteins of mucin in the mucus layer. Mucoadhesive polymers like Polyacrylic acid, carbopol, sodium carboxymethylcellulose, chitosan, and hydroxypropyl methylcellulose are mostly used, these polymers control the release of drug and are present in dosage forms like tablets, patches, gels, and nanoparticles. The major sites for drug delivery are mouth, nose, eyes, vagina and stomach. The advanced and future studies focus on the development of smart, stimuli responsive polymers and targeted delivery of drugs to improve therapeutic outcomes and patient compliance.

Keywords: Mucoadhesion; Mucoadhesive Polymers; Drug Delivery Systems; Controlled Release; Targeted Drug Delivery; Smart Polymers; Nanoparticles; Bioavailability Enhancement

1. INTRODUCTION

Drug delivery systems (DDS) are specially designed to deliver the active substance or drugs safely and effectively to a specific target site in body to improve the efficacy of drug and minimize side effects. Conventional methods face challenges like poor bioavailability, rapid clearance, and toxicity **[1-11]**. Modern drug delivery systems overcome these challenges by controlling the rate of drug release, provide targeted delivery of drug and protect some drugs from enzymatic degradation by advanced techniques like Mucoadhesive drug delivery system that increases the residence time of drug at mucosal surface **[4-20]**. The development of smart and stimuli sensitive focus on personalized and precise therapies. A mucoadhesive drug delivery system is a challenging structure that is intended to adhere to soft surfaces such as the mouth, nose, eyes, vagina, and gastrointestinal tract because of its characteristic of strongly attaching to the mucous membrane **[3]**. These mucoadhesive systems adhere firmly to the mucous membrane, extending the duration of the medication's contact with the surface. This, in turn, increases drug absorption, improves efficacy, and permits a controlled release of the medication. Polymers with the ability to expand, enter the mucus membrane's mucin, and form hydrogen bonds play a key role in adhering these systems to the mucus membrane **[2-22]**. A number of drugs are not able to dissolve properly, disintegrate quickly, and leave the body before reaching the active site, they are unable to show their full effects. This leads to reduction in bioavailability, requiring a high dosage that may have side effects. By delivering the drugs to the exact site where it is needed most, targeted delivery helps to reduce drug waste and increase the outcome of treatment **[4]**. Here, mucoadhesive drug delivery systems are important because they adhere to mucosal surfaces like the buccal, nasal, or gastrointestinal tissues, increasing the retention time of drug. This type of drug delivery system not only improves the absorption but it allows controlled and sustained release also **[5]**.

The primary objective of mucoadhesive drug delivery systems is to increase the bioavailability of medications that have poor absorption or that are broken down in the gastrointestinal tract by providing a prolonged release of the medication at a particular site. This lowers the frequency of doses and side effects, skips the first-pass metabolism, and allows for regulated release. These include both synthetic and natural polymers that provide the best possible residence at the mucosal sites which allows in easily attachment. Future developments in mucoadhesive drug delivery systems will focus on nanotechnology and smart polymers to

increase the bioavailability of the drug and its therapeutic action **[6]**. Stimuli-responsive and targeted formulations are developing to release the drug in response to changes in pH, temperature, and some enzymes of the mucosal surface. Nanotechnologies are widely used to create micro- and nano-capsules to increase the site-specific action of drugs **[17-24]**. Working to design some advanced Multifunctional polymers that improve penetration of drug and also protect from enzymes that degrade proteins, peptides, and other biological agents. Biodegradable and biocompatible polymers are used to maintain the stability and safety of formulations **[7]**.

2. Mucoadhesion and Principles

Mucoadhesion is the process by which polymers, either synthetic or natural, attach to the mucous membrane by interfacial molecular attractive forces, extending the duration of the drug's occupancy at the application site **[2-9]**.

There are two steps in the mucoadhesion mechanism:

- The Contact stage
- The Consolidation stage

2.1.1 Contact stage: **-** The mucoadhesive polymer and mucus membrane interact during this stage of mucoadhesion, which is followed by the formulation spreading and swelling to make contact with the mucosa. Thus, the polymer chain can align with the mucin network, creating an important condition for future interaction **[2-26]**.

2.1.2 Consolidation stage: At this stage, moisture activates the mucoadhesive system, allowing molecules to penetrate one another and form secondary bonds such as hydrogen bonds, van der Waals forces, and electrostatic interactions between the polymer and mucin chains **[8-27]**.

2.2 Theories of Mucoadhesion

2.2.1 Electronic theory-

According to this theory, transfer of electrons is responsible for attachment between the polymer and glycoproteins of mucous and this transfer is due to different electrical properties of mucoadhesive polymer and glycoproteins of mucin, which creates an electrical double layer at the contact. This double layer helps the polymer to bind with the mucous by generation of electrostatic forces **[13]**.

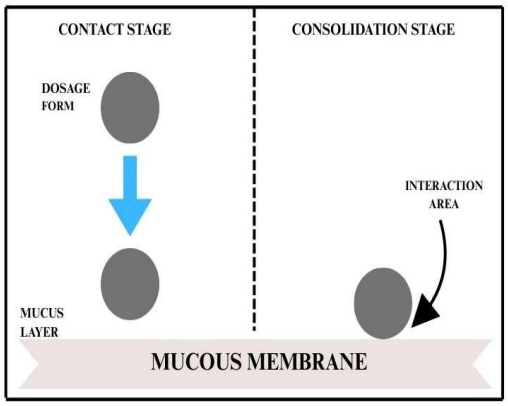


Figure 1: Stages of Mucoadhesion

2.2.2 Wetting theory -

According to this theory, adhesion or attachment happens when the mucoadhesive

polymer is evenly distributed across the mucosal surface, increasing contact. Contact angle can be used to determine the mucosal layer's ability; a lower contact angle indicates better adherence and spread ability. This idea works best with liquids or systems with low viscosity **[1]**.

2.2.3 Diffusion theory-

According to this theory, adhesion is caused by the interpenetration of the polymer chain and the mucin glycoprotein chain. This process works on factors like mobility, compatibility of polymer and mucin chain, and contact time. Stronger microscopic adhesive connections resulting from increased chain interpenetration provide strong and long-lasting adherence. Concentration gradients and the molecular makeup of the mucoadhesive and mucus layers determine how much diffusion occurs **[28]**.

2.2.4 Adsorption theory-

According to this theory, after initial contact, primary and secondary bonds are responsible for adhesion such as hydrogen bonds, van der Waals forces, and electrostatic attractions between the polymer and mucosal surface. This process is important for long-term drug release and therapeutic efficacy for different mucosal routes because secondary bonds are stable and reversible **[6]**.

2.2.5 Fracture theory

This theory explains the mucoadhesion in a way that after bonding together how much force required to separate the mucoadhesive material from the mucosal surface. It analyses the breaking strength of the bond between two surfaces instead of how well the polymers mix or diffuse. The separation becomes more difficult when the bond is well-formed and a stronger or more elastic material is used. This theory is used by scientists to dose forms that are solid or semisolid.

The strength produced during detachment is calculated by dividing the total surface area [Ao] involved in adhesion by the maximum force of detachment [Fm] **[29-7]**.

$$Sm=Fm/Ao$$

3. Anatomy and Physiology of Mucosal Tissues

Mucosal tissues are soft, moist layers that cover the mouth, nose, eyes, vagina, rectum, and gastrointestinal tract **[3]**. These tissues are made up of layers: connective tissues below, a supporting basement membrane, and outer epithelium. Mucus is a slippery, protective substance released by goblet cells and submucosal glands, which covers these layers. The main goal of mucus is to keep the tissues moist and safe. The thickness of each mucosal site varies. For example, the vaginal tissues are thicker for prolonged contact, but the buccal mucosa present on the inner side of the mouth is thin and responsible for the rapid absorption **[9]**. Mucoadhesive drug delivery systems are made to adhere to mucosal surfaces in a gentle way. Then

adhesion allows a longer duration of the drug's attachment for better and slower absorption in the body.

3.1 Mucus composition and functions:

Mucus is a slippery, gel-like substance that covers the tissues of mucosal surfaces in the gastrointestinal, reproductive, ophthalmic, and respiratory systems. It is composed of water (about 95%), large glycoproteins like mucins (2–3%), and small quantities of proteins, lipids, salts, and cell debris [9]. The sticky and elastic nature of mucus is due to mucin, which creates a mesh-like structure that acts as a barrier. This mucus blocks entry of pathogens and foreign particles during passage of gases. Mucus keeps tissues moist and protects them from damage. The distribution of drugs is affected by the composition and functions of mucus, which change in response to diseases like cystic fibrosis and asthma **[30-31]**.

4. Polymers Used in Mucoadhesive Drug Delivery

Polymers are large molecules made up of many small repeating structural units called monomers. Due to the ability of polymers to interact with mucosal tissues and finally enhance the retention of drugs, polymers are used in mucoadhesive drug delivery systems. Both natural and synthetic polymers such as chitosan, sodium alginate, pectin, hyaluronic acid, cellulose derivatives (HPMC and CMC), polyacrylic acid and its cross-linked forms like carbopol, and more recent polymers like thiolated polymers which increase adhesion and bioavailability of drugs are used in mucoadhesive delivery **[10, 11]**. Proper attachment of these polymers to the mucosal surface increases the drug residence time, protects sensitive drugs, and finally gives controlled and prolonged release. For stronger and long-lasting mucoadhesion in formulations such as tablets, gels, films, and patches, recent researches prefer polymers like thiolate chitosan and poloxamer-based formulations.

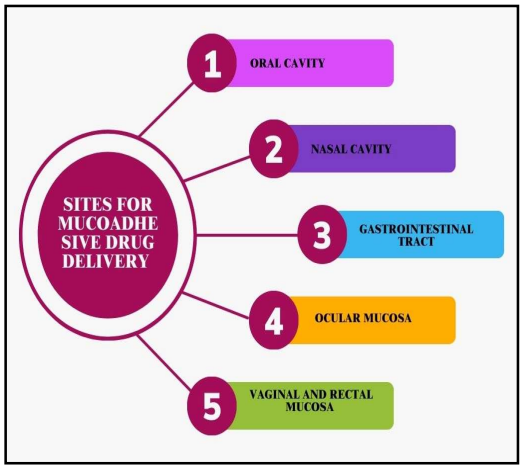


Figure 2: Sites for Mucoadhesive drug delivery

4.1 Ideal characteristics of Mucoadhesive polymers

- Nontoxic and Biocompatible
- Strong Adhesion
- Rapid onset of Adhesion
- Good swelling capacity
- Flexible
- Hydrophilic and wetting ability

Controlled drug release

Table 1: Types of Polymers		
Types	**Polymers**	**Sites of mucoadhesion**
Natural	**Chitosan, Sodium alginate, Guar gum, Xanthan gum, Pectin, Tragacanth, Gum arabic, Starch, Gelatin, Agar, Honey, Carrageenan, Locust bean gum, Tamarind seed polysaccharide, Purified mucin, Alginic acid, Lecithin**	**Buccal, gastric, nasal, ocular, vaginal**
Semi-synthetic	**Cellulose derivatives: Hydroxypropyl methylcellulose (HPMC), Sodium carboxymethyl cellulose Methylcellulose, Ethylcellulose, Microcrystalline cellulose**	**Buccal, nasal, vaginal, ocular, GI tract**
Synthetic	**Polyacrylic acid (Carbopol), Polycarbophil, Polyvinyl alcohol (PVA), Polyethylene glycol (PEG), Polymethacrylates (Eudragit RS100), Polyvinyl acetate, Polystyrene,Dimethylaminoethyl methacrylate, Pluronic F68**	**Nasal, ocular, oral, vaginal, gastric, rectal**

Table 2: Ideal Characteristics and Description of Polymers		
S. No	**Ideal Characteristics of Mucoadhesive Polymers**	**Description**
1	**Non-toxic and Biocompatible**	**Safe, non-irritant, and compatible with mucosal tissue without adverse reactions**
2	**Strong Adhesion**	**Capable of forming strong physical bonds (hydrogen bonds, electrostatic, Van der Waals) with mucin and cells**
3	**Rapid Onset of Adhesion**	**Should quickly adhere to mucosal surface to increase retention time**
4	**Good Swelling Capacity**	**Moderate swelling after hydration to enhance interpenetration with mucus without loss of adhesion**
5	**Flexible**	**Allows polymer chain entanglement and better adhesion with mucus networks**
6	**Hydrophilic and wetting ability**	**Must be wet and spread well on mucosal surfaces to maximize adhesion**
7	**Controlled drug release**	**Supports controlled release of drug without affecting bioavailability**

4.2 Comparison of polymers based on the mucoadhesive strength, biocompatibility and degradation:

- **Natural polymers-** Polymers like chitosan and alginate provide very good mucoadhesive strength due to their cationic nature and a number of functional groups, which allows the formation of hydrogen bonds and electrostatic interaction with mucin. These polymers are highly biocompatible, as they are obtained naturally and generally do not cause toxicity, which makes them more favourable for mucosal tissues. The main advantage of these polymers is that they get easily degraded by enzymes [38].
- **Semi Synthetic polymers-** Polymers like sodium carboxymethyl cellulose (sodium CMC) and hydroxypropyl methyl cellulose (HPMC) provide moderate to good mucoadhesive strength due to optimisation, which allows effective hydrogen bonding and swelling properties. These polymers are specially designed to improve the biocompatibility of natural polymers with mechanical properties and reproducibility. These polymers are degraded by enzymes, and the rate can be controlled by modifying molecular weights and functional groups, which offering wide use in controlled release systems **[39]**.

- **Synthetic polymers-**Due to the high mucoadhesive strength, polymers like carbopol and polyacrylates are used because these polymers have compacted carboxylic groups and the ability to make ionic and hydrogen bonds with mucus. These polymers are used in formulations, as they are safe, but they are less biodegradable than natural polymers, elimination slower **[40]**.

5. Formulation Approaches

5.1 Tablet Formulations - The Mucoadhesive tablets are solid dosage forms made from polymers such as sodium CMC, carbopol, and HPMC through methods like direct compression or wet granulation. These tablets stick to mucosal surfaces, especially in the mouth (buccal cavity), allowing medicine to be released slowly over 8-12 hours. When saliva comes into contact with the tablet, it swells and forms a gel-like layer, which allows it to adhere to the tissue better. This gel acts as a barrier, slowly releasing the drug through processes such as diffusion and polymer breakdown, making the medicine more effective than normal tablets **[37]**.

5.2 Film/Patch Systems- Mucoadhesive films or patches are thin, flexible sheets prepared by dissolving polymers like HPMC, PVA, or chitosan in a liquid and by drying liquid to make a film. These films stick on wet surfaces which includes the inner layer of cheeks, where they absorb moisture and stick gently. Due to ability to adhere at surface, the film releases the drug slowly by a network of polymers, which improves absorption and lower the dose frequency as compared to conventional dosage forms **[38]**.

5.3 Gel Formulations- Mucoadhesive gel formulations use water-loving polymers such as carbopol, sodium CMC, and xanthan gum to create thick, gel-like substances that stick well to moist body surfaces. The flow property of these gels is excellent which makes the easy delivery of drugs to specific sites and maintaining their presence for a long period of time. These gels are applied directly to areas such as mouth, vagina, or eyes to stick longer and works more effectively. The drug released from gel up to 6-8 hours in a controlled manner. These gel formulations work perfectly for disorders that require longer contact time **[39]**.

5.4 In-situ Gel Systems- These formulations change their phase when comes in contact with body temperature and pH because firstly they are present in liquid forms and then convert into sol-gel system. Heat-sensitive polymers, like poloxamer 407, which reacts when temperature changes, and carbopol 934, which reacts when pH changes, are widely used. These polymers change phases at body temperature, allows for controlled release of

drug. These systems are simple to deliver in liquid form, which then settles in place to enhance retention time. Due to their ability to deliver drugs at tricky sites like nose, eyes, and vagina, where conventional gels are difficult to apply **[41]**.

5.5 Floating Systems- Floating systems are the formulations that float over the gastric fluids by using low-density polymers of gas-generating agents like sodium bicarbonate and citric acid. These systems increase the gastric residence time to 8-12 hours for enhanced absorption of the drug. When the polymers come in contact with gastric fluid, gas generating agents release CO_2 gas, which makes formulation float, and the mucoadhesive polymers also enhance the residence time. These systems are useful for drugs that have lesser absorption in the upper gastrointestinal tract or for treating the gastric disorders such as peptic ulcers and gastroesophageal reflux disease **[28]**.

5.6 Microparticulate System- The advanced microparticles like microspheres and microcapsules having particle size ranges between 1-1000 μm are formulated by using polymers that biodegrade easily, like chitosan, alginate, and ethyl cellulose, by different methods like spray drying and coacervation. These systems release drugs in a controlled manner via diffusion and polymer degradation mechanisms. Different formulations can be prepared, like dry powders for inhalation and suspensions in gels for topical applications, and tablets are also prepared for oral delivery, and in all of these formulations, mucoadhesive properties are maintained. These microparticles provide targeted delivery and also improve the stability **[42]**.

5.7 Nanoparticulate System- Mucoadhesive nanoparticles range in size between 10 and 1000 nm, and these are formulated by using polymers that can biodegrade easily to increase the penetration across the barriers of mucosa and finally provide a targeted delivery of drugs. These are specially designed because they improve the cellular uptake, improve bioavailability, and protect the sensitive drugs like proteins, peptides, and nucleic acids. The surface of nanoparticles can be modified by mucoadhesive polymers like chitosan and thiolated derivatives, which finally improve the permeation and retention of the mucosal surface. Due to their small size, they can easily penetrate into deep tissues, and the modified surface provides targeted delivery. These are commonly used for the delivery of vaccines and genes and the treatment of diseases that require intracellular delivery of drugs.

5.8 Liposomal Systems- Mucoadhesive liposomes are prepared by using phospholipids that are modified with the polymers like chitosan, carbopol, and hyaluronic acid. These systems improve the efficiency of encapsulation, control the

release of drugs, and improve the ability to penetrate the mucosal tissues. Liposomes protect the encapsulated drugs from enzymatic degradation, and the mucoadhesive polymers increase the residence time at the site of absorption, which finally increases the bioavailability of poorly permeable drugs. Due to its vesicular structure, it allows both hydrophilic and hydrophobic drugs. Surface modification with mucoadhesive polymers increases interaction with the mucosal surface and provides sustained release of the drug, which improves the therapeutic efficacy of routes like oral, nasal, and ocular

5.9 Spray-based Systems- Spray-based systems use volatile solvents that get easily evaporated and leave a film as residue that contains the active ingredient or drug. These systems provide uniform distribution, easy application, and patient compliance, especially for oral and nasal routes. This system ensures precise dosing and covering of target surfaces in a uniform way. When the solvent evaporates, the film formed continuously dissolves and provides a controlled release of the drug over an extended duration. These formulations are mainly used for pediatrics, emergency treatment, and rapid onset of action. The spray delivery method is noninvasive and improves patient compliance as compared to conventional dosage forms.

5.10 Cyclodextrin-based Systems- When complexes like α-, β-, or γ-cyclodextrins are combined with mucoadhesive polymers, the solubility of drugs and mucoadhesive properties are increased. These systems are mainly used for ocular delivery of drugs to overcome solubility of drugs and corneal penetration. The role of cyclodextrin is to improve the solubility of the drug via complex formation, and mucoadhesive polymers increase the pre-corneal retention and increase therapeutic efficacy. These systems increase bioavailability and reduce the dosing frequency. This system overcomes challenges like poor solubility, less retention time, and improper permeation across the barriers.

6. Applications of Mucoadhesive Drug Delivery Systems

Mucoadhesive drug delivery systems improve the efficiency and effectiveness of drugs by allowing them to attach at mucosal surfaces in body like mouth, nose, eyes, gastrointestinal tract and reproductive organs. This attachment increases the residence time of drugs formulations at the absorption site which allows for sustained and controlled release of drugs. This concept is based on ability of specific polymers that forms bonds with mucin layer which covers the mucosal tissues. By overcoming rapid mucosal clearance and enzymatic degradation, mucoadhesive systems increase

the bioavailability of drug and reduces the dosing frequency.

6.1 Buccal and sublingual delivery- Mucoadhesive drug delivery systems play an important role in buccal and sublingual delivery because they help in the direct uptake of drugs through the oral mucosa and bypass the hepatic first-pass metabolism. This leads to increased bioavailability and rapid onset of action. Mucoadhesive films, patches, and tablets attach to the mucosal lining and prevent washout from saliva and tongue movements, which allows for maintaining the drug level. These are mainly used for painkillers, cardiovascular drugs and peptides that shows poor absorption and gets easily degraded by GI fluids. Advanced methods include nano-carriers and multilayered systems for controlled and sustained release. Overall, buccal and sublingual mucoadhesive systems improve patient compliance and therapeutic efficacy, especially in emergency conditions **[46]**.

6.2 Nasal delivery- The main function of nasal mucoadhesive systems is to increase the delivery of drugs by increasing the residence time of drugs in the nasal cavity, by increasing contact between drug and membrane and finally increases the absorption. This system includes formulations like gels, sprays, and nanoparticle carriers made with polymers like chitosan and HPMC. These systems provide advantages like rapid systemic absorption of drugs and a noninvasive route to deliver peptides, proteins, vaccines, and CNS-active drugs by bypassing the blood-brain barrier. These are widely used for migraine and allergic rhinitis. Current innovations focus on nanotechnology to increase penetration and retention while reducing the irritation of mucosa and dose frequency **[47]**.

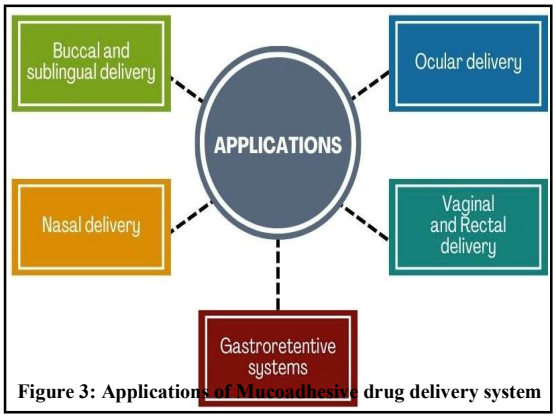
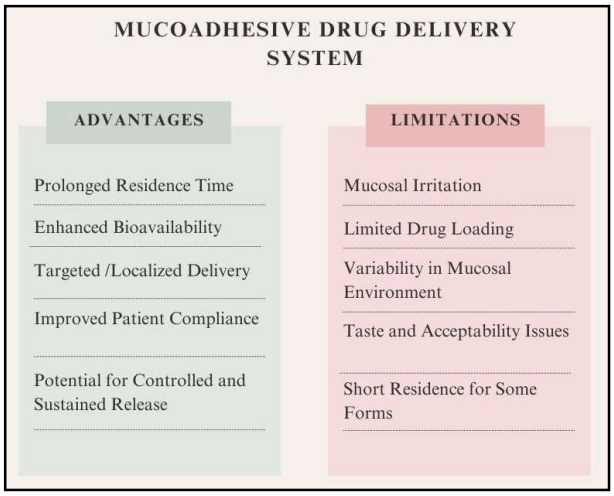


Figure 3: Applications of Mucoadhesive drug delivery system

6.3 Ocular delivery- In recent years, the mucoadhesive drug delivery system has been improved for eye treatment by helping to overcome the challenges like fast drainage of drugs and the need for frequent eye drops. Mucoadhesive gels, inserts, and nanoparticles are designed to stick in the eye for a longer time, which allows for controlled release of the drug at a constant rate. Many polymers are used in advanced technologies to release the drug to change in environmental factors like pH and temperature **[48]**.

Figure 4: Advantages and limitations [10]



6.4 Vaginal and Rectal delivery- By increasing the drug-mucosa contact time, local therapies like infections, contraception, and hormonal regulation can be improved. Gels, tablets, and suppositories attach to tissues of mucosa and provide prolonged release of drugs. This system leads to increased bioavailability and decreased dosage frequency. Vaginal and rectal mucoadhesive systems decrease the systemic side effects by acting at the target site. Recent research focuses on advanced hydrogels, nanotechnology, and polysaccharide systems to increase the adhesion and penetration for localized action **[2]**.

6.5 Gastroretentive systems- Gastroretentive mucoadhesive systems are designed to increase the retention time of drugs in the stomach for better delivery of drugs. These systems attach to the gastric mucosa to prevent the degradation of drugs in the intestines and for drugs having lesser absorption. These systems treat conditions like peptic ulcers and oral delivery of poorly soluble and sensitive drugs. Various systems like hydrogels and nanoparticles are designed to absorb drugs in gastric pH and its motility **[8]**.

7. Advantages and limitations

8. Recent Advances and Future Perspectives

- **Smart polymers and stimuli-responsive systems-** Smart and stimuli-responsive systems are specially designed to deliver the drug according to demand and to control the release of the drug. Advanced polymers are used for these systems that can easily respond to changes in pH, temperature, and enzymes, and some even respond to ultrasound waves, which changes their solubility and activates the release of drugs at a specific time and site **[17]**. For example, in mucoadhesive systems, polymers have the ability to swell or break, which ensures that the drug releases at the targeted site according to needs. These systems designed to improve the therapeutic action and minimize dose frequency. The main focus of recent research is to combine these polymers with nano-carriers and microneedles for patient compliance and personalized medicine.

- **Mucoadhesive nanoparticles-** Recent advances in mucoadhesive nanoparticles provide improvements in mucosal drug delivery. These nanoparticles are specially designed to initially attach to the mucus layer and then penetrate into mucosal tissues to provide deep distribution of drugs. These systems are highly beneficial for oral, nasal, and vaginal routes, which allows for increased absorption of drugs and protects drugs from enzymatic degradation. The adhesion and penetration of nanoparticles can be controlled by modifying the surface with polymers like chitosan and PEG. These nanoparticles help in the encapsulation of drugs that can degrade by enzymes and are poorly soluble. The main focus of recent research is to explore dual nanoparticles that provide efficient, site-specific treatment with improved patient compliance **[42]**.
- **Personalized drug delivery approaches-** Personalized techniques helps scientists to design medicines according to requirements of patient which maybe shape and size of tablets of films for right dose of drug for each person. With the help of 3D printing, the release of drug can be adjusted which either be quickly or slowly release, means that the patient gets proper quantity of dose at right time. This system helps for children and old age patients who needs special dosing or having difficulties in swallowing regular pills. Studies show that 3D printed mucoadhesive tablets or films attach to mucosal surfaces more perfectly and provide better absorption of drugs. By the help of Artificial Intelligence, these systems use real time data for on time adjustment which provide better treatment and lesser side effects **[1]**.
- **Regulatory challenges and market trends-** The development of advanced mucoadhesive drug delivery system face regulatory and market problems. There is highly need for harmonized guidelines on efficacy, safety, and quality for latest emerging formulations. Special focus on the multicomponent systems like smart polymers and nanoparticles. Some economic challenges like high manufacturing cost, source of raw material and upscale of laboratory innovations for commercial use. Market trends now focus on increased demand for patient friendly, non-invasive techniques, mucoadhesive patches, films, and orally disintegrating **[16]**.

9. CONCLUSION

Mucoadhesive drug delivery systems play a major role in modern pharmaceutics due to their ability to provide solutions to limitations of conventional oral drug delivery system. The main function of these systems is to improve the absorption and bioavailability of drugs by increasing the retention time of drug to mucosal surfaces

like in mouth, nose, eyes, vagina, and gastrointestinal tract.With the help of polymers like chitosan, carbopol, and hydroxypropyl methylcellulose, mucoadhesive formulations are designed to control the release of drug and provide targeted delivery which helps in increasing the therapeutic effect and reducing the side effects. Both systemic and local treatments are supported by this technology across various routes. However, ongoing research focus on challenges like mucosal irritation, stability of formulation and regulatory hurdles. Future development focus on creating smart, stimuli responsive polymers for personalised delivery to optimise the patient outcomes and safety. This advanced research is fulfilled only when researches, industry, and regulatory bodies collaborate and translate these systems into clinical practice which ultimately improve the effect of drug and patient compliance.

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