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Review Article

Multifunctional Polymeric Nanocarriers To Overcome Gastrointestinal Barriers in Insulin Delivery

P. Nanthagopal*, D. Nagavalli, G. Abirami, R. Prethingadevi

Department of Pharmaceutical Chemistry, Adhiparasakthi College of Pharmacy, Melmaruvathur-603 319, Affiliated to the Tamil Nadu Dr. M.G.R. Medical University, Chennai-600 032, Tamil Nadu, India

The delivery of insulin via oral means presents a promising alternative to traditional injections, enhancing patient adherence and overall quality of life. Nevertheless, its use is constrained by gastrointestinal obstacles such as enzymatic breakdown, fluctuating pH levels, mucus barriers, and limited intestinal permeability. These elements contribute to a significantly low bioavailability of insulin. Polymeric nanocarriers have surfaced as a viable solution to address these issues. They safeguard insulin from the harsh conditions of the stomach and improve its stability. Additionally, these carriers facilitate a controlled and sustained release of insulin. Systems that are surface-functionalized, such as chitosan and PLGA, enhance absorption through mucoadhesion and pH-responsive characteristics. They also encourage active transport across the intestinal epithelium. Research indicates high drug entrapment efficiency and advantageous particle attributes. Enhanced pharmacokinetics and notable reductions in glucose levels have been recorded in experimental models. Despite these advantages, challenges such as large-scale manufacturing and long-term safety concerns persist. In summary, polymeric nanocarriers hold significant promise for the effective delivery of oral insulin.

Keywords: Oral insulin delivery; Polymeric nanoparticles; Multifunctional nanocarriers; Gastrointestinal barriers; Chitosan-based nanoparticles; Controlled drug release; Intestinal absorption; Diabetes mellitus.

INTRODUCTION

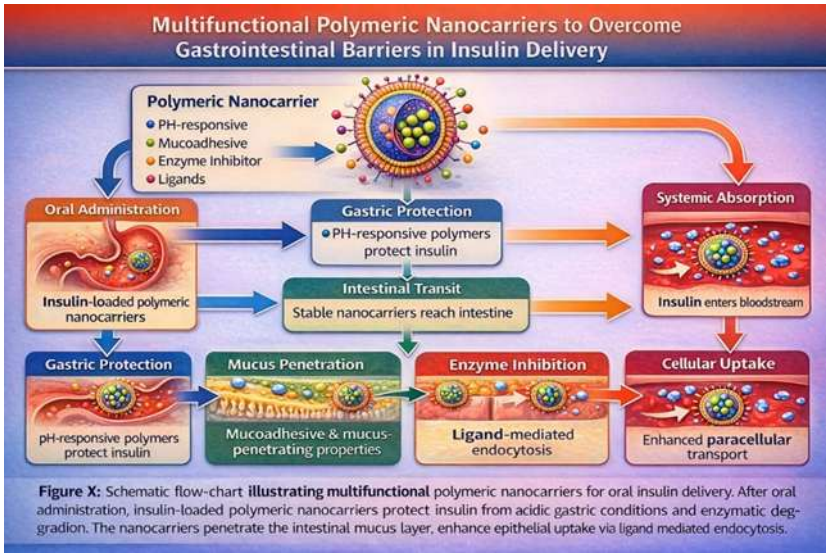


Figure:2- Versatile polymeric nanocarriers designed to surmount the gastrointestinal barrier in insulin delivery

1. Diabetes Mellitus and the Constraints of Injectable Insulin:

Diabetes mellitus is a persistent metabolic condition that frequently necessitates prolonged insulin treatment to sustain normal blood glucose levels. Currently, insulin is predominantly delivered through subcutaneous injections, which can be painful, inconvenient, and not aligned with physiological processes. The need for frequent injections may lead to decreased patient adherence and results in only approximately 25% of the insulin reaching the liver, the primary site of insulin action. In contrast, the natural mechanism of insulin secretion transports insulin directly to the liver via the portal vein, thereby underscoring the limitations associated with injectable insulin therapy.

2. The Necessity of Oral Insulin Delivery:

The delivery of insulin via oral means is highly sought after due to its painless nature, convenience, and the enhancement of patient adherence to treatment. Additionally, oral administration can more accurately replicate the physiological first-pass hepatic pathway. Nevertheless, the oral delivery of insulin presents significant challenges owing to various gastrointestinal obstacles, such as digestive enzymes, substantial pH fluctuations, mucus layers, and inadequate permeability of the intestinal epithelium. Insulin, being a hydrophilic peptide with a high molecular weight (approximately 5800 Da) and low lipophilicity, faces considerable difficulty in achieving passive diffusion across the intestinal membrane. Consequently, the bioavailability of oral insulin is exceedingly low (<0.5–2%), which restricts its clinical use.

3. Role of Nanotechnology in Drug Delivery

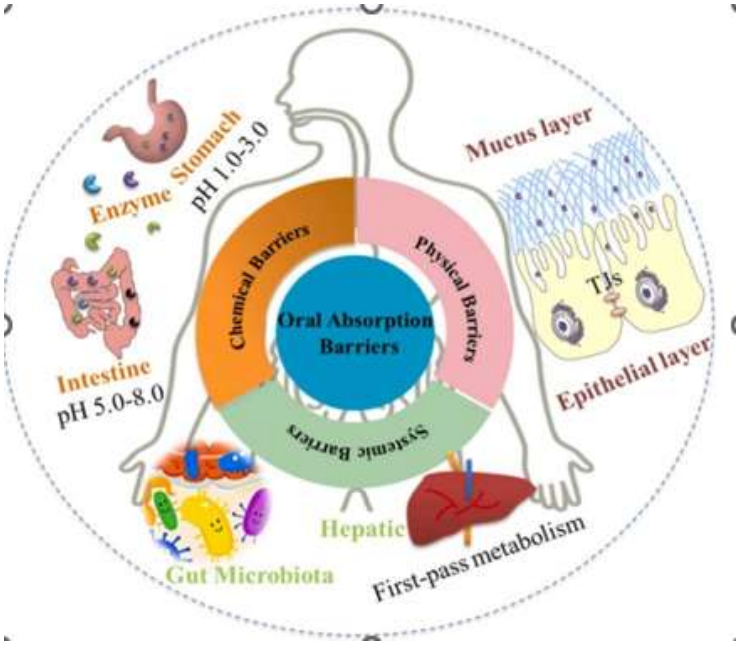


Figure:3- Various Methods for Administering Drugs via Nanotechnology.

To address issues with oral insulin delivery, sophisticated intelligent nanocarrier delivery systems (NDS) have been created that shield insulin from harsh pH levels and enzyme destruction. These systems enhance the half-life, pharmacokinetics, and stability of insulin. The biocompatibility, biodegradability, and controlled drug release of polymeric nanocarriers, particularly polymeric nanoparticles (PNPs), make them extremely effective. They facilitate continuous release at the absorption site and guarantee the safe passage of insulin through the digestive system. Positive charge and hydrophobicity are examples of surface characteristics that improve intestinal cell contact and absorption. While PLGA carriers enable regulated breakdown, chitosan-based carriers offer mucoadhesion and enzyme protection. All things considered, these multipurpose nanocarriers present a viable method for efficient oral insulin delivery.

4. Physiological Barriers to Oral Insulin Delivery:

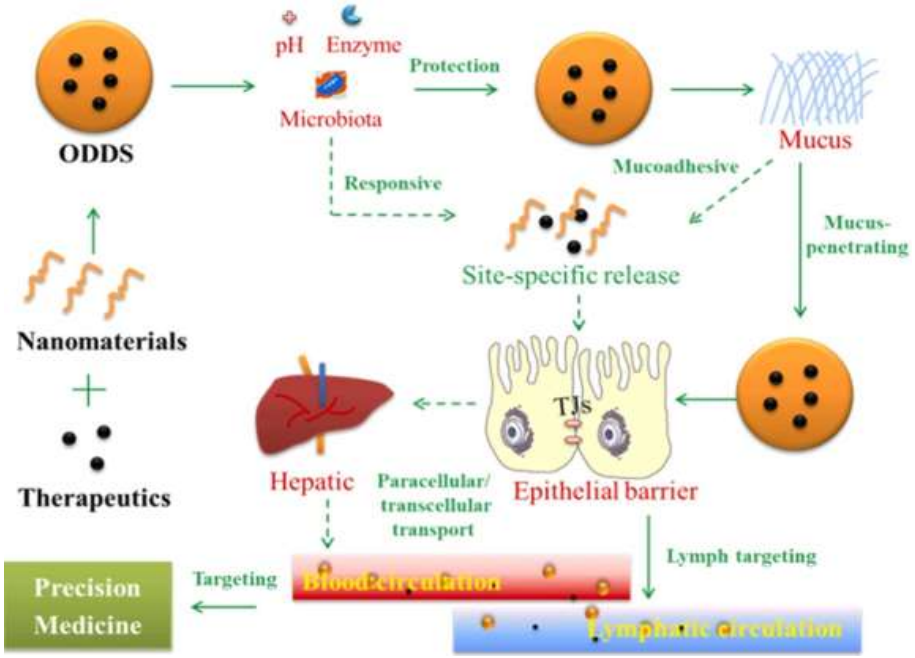


Figure:4- Physiological Obstacles to Oral Insulin Administration.

A. Gastric pH and enzymatic degradation:

Insulin is quickly broken down by the stomach's acidic environment (pH 1-3) and digestive enzymes like pepsin, trypsin, and chymotrypsin, which results in extremely low oral bioavailability. To get around this, insulin is encapsulated in polymeric nanocarriers that shield it from the harsh conditions of the stomach. Eudragit®, alginate, and chitosan are examples of pH-responsive polymers that release insulin in the intestinal environment while remaining stable in acidic pH. Additionally, these methods allow for prolonged and regulated medication release at the absorption site. Proteolytic breakdown can also be decreased by co-loading with enzyme inhibitors like bacitracin and aprotinin. Stability and protection are further improved by surface alterations and multilayer coatings. All things considered, these tactics greatly enhance insulin stability and facilitate efficient oral administration.

B. Mucus Barrier:

The intestinal mucus layer limits the passage of insulin and nanocarriers to the epithelial surface by acting as a physical and biochemical barrier that traps foreign particles. Strong interactions with mucus glycoproteins frequently result in quick clearance, which lowers the absorption of drugs. Polymeric nanocarriers are made to either pierce or stick to the mucus layer in order to solve this. Because PEGylation lessens mucoadhesion, nanoparticles can pass through mucus more easily. On the other hand, lectin-modified carriers, chitosan, and thiolated polymers improve mucoadhesion and extend residence time. For improved performance, some sophisticated systems combine mucus-penetrating shells with mucoadhesive cores. These tactics increase the retention and closeness of nanoparticles to epithelial cells. Overall, insulin absorption efficiency is greatly increased by breaking through the mucus barrier.

C. Intestinal Epithelial Tight Junctions:

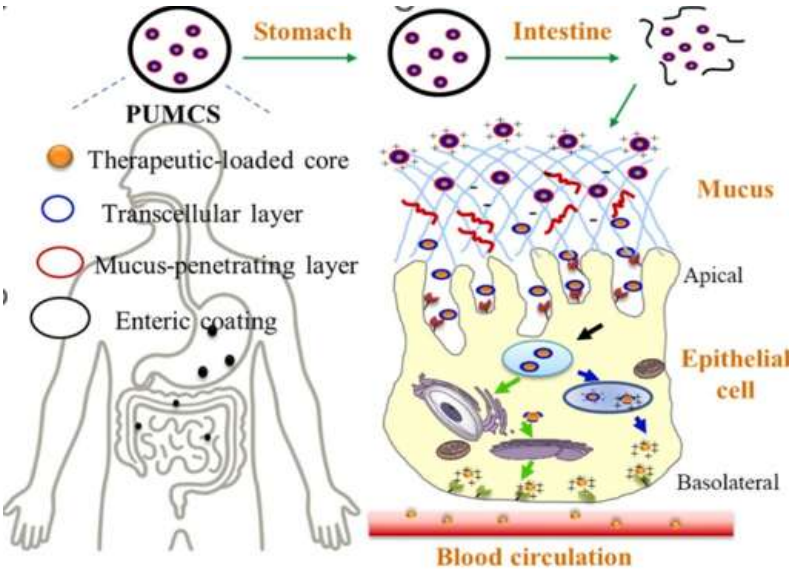


Figure:5- The absorption process is obstructed by the close junctions between intestinal epithelial cells-Insulin.

Absorption is hampered by the tight connections between intestinal epithelial cells, which limit the paracellular transit of big molecules like insulin. Insulin penetration through the gut epithelium is severely restricted by this barrier. Polymers like chitosan and poly (acrylic acid) are used by polymeric nanocarriers to temporarily and reversibly open tight junctions to get around this. By interacting with proteins such as occludin and claudins, these polymers improve paracellular transport. Furthermore, receptor-mediated transcytosis via endocytosis pathways is made possible by ligand-functionalized nanocarriers (such as vitamin B12, transferrin, and folate). This makes it possible for insulin to move actively through epithelial cells. These methods increase intestinal permeability without producing long-term harm. All things considered, polymeric nanocarriers improve the efficiency of oral insulin delivery.

D. First-Pass Metabolism:

Insulin that enters the portal circulation after absorption is extensively first-pass metabolised in the liver, which lowers its bioavailability and therapeutic impact. This poses a significant obstacle to the efficient administration of oral insulin. This is mitigated by polymeric nanocarriers, which divert insulin transport away from the liver and into the intestinal lymphatic system. In Peyer's patches, hydrophobic systems and lipid–polymer hybrid nanoparticles facilitate lymphatic uptake through M cells. By means of polymer degradation mechanisms, these carriers also offer regulated and prolonged insulin release. This keeps plasma insulin levels steady and lowers metabolic loss. Insulin stays active for a longer period of time as a result. All things considered, this strategy enhances pharmacokinetics and promotes sustained glycaemic management.

5. Rationale for Using Polymeric Nanocarriers:

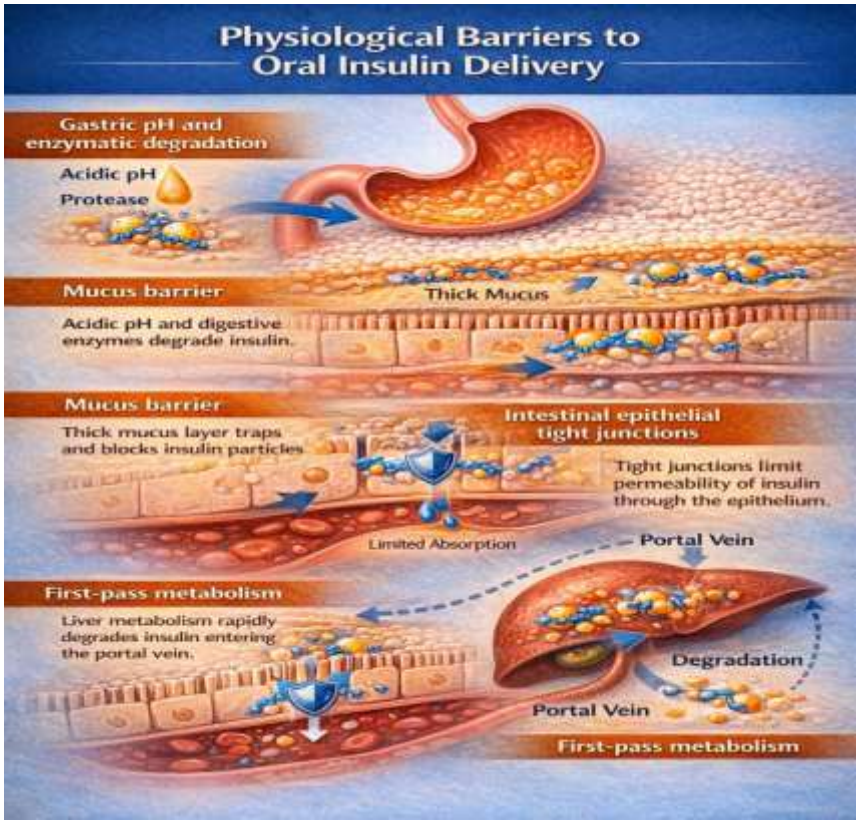


Figure: 6- Physiological barriers to oral Insulin Delivery.

A. Why Polymers Are Preferred:

The structural flexibility and adaptability of polymeric nanocarriers make them extremely promising for oral insulin administration. They provide reactivity to gastrointestinal circumstances such as pH, enzymes, and redox changes by providing precise control over design. As insulin travels through various biological barriers, this is crucial for its protection. Polymers can be readily altered to incorporate several functions into a single system, in contrast to lipid or inorganic systems. These include improved epithelial transport, mucus penetration, and enzyme protection. High insulin encapsulation efficiency is another benefit of polymeric systems. For extended activity, they make controlled and sustained drug release possible. After oral administration, they generally aid in maintaining stable glycaemic control.

B. Biodegradability and Biocompatibility:

Biodegradability and biocompatibility are essential requirements for any oral drug delivery system, and polymeric nanocarriers meet these criteria exceptionally well. Widely used polymers such as poly(lactic-co-glycolic acid) (PLGA), chitosan, alginate, and polycaprolactone decompose into non-toxic metabolites that are naturally expelled from the body. This characteristic minimizes long-term toxicity and mitigates the risk of accumulation in gastrointestinal tissues. Furthermore, biocompatible polymers demonstrate minimal immunogenicity and low irritation potential, which is vital for the repeated oral administration of insulin in diabetic patients. Their degradation rate can be customized to achieve controlled insulin release while preserving structural integrity during transit through the gastrointestinal tract. As a result, biodegradable polymeric nanocarriers ensure both safety and therapeutic efficacy, promoting their advancement toward clinical applications.

C. Size and Surface Advantages:

The nanoscale dimensions and customizable surface properties of polymeric nanocarriers offer considerable benefits in surmounting gastrointestinal obstacles. Nanoparticles, generally measuring between 50 and 300 nm, can efficiently traverse the

intestinal mucus layer and reach epithelial surfaces without being swiftly cleared. Optimizing size improves cellular uptake and facilitates transport through specialized intestinal cells, such as M cells found in Peyer's patches. Furthermore, surface modifications significantly boost performance; for instance, PEGylation minimizes nonspecific interactions with mucus, while chitosan or thiolated polymers improve mucoadhesion and extend the residence time within the intestine. Moreover, surfaces that are functionalized with ligands can specifically target intestinal receptors, allowing for receptor-mediated endocytosis and enhanced transcytosis of insulin. Collectively, these strategies in size and surface engineering improve the stability, permeability, and bioavailability of insulin after oral administration.

6. Types of Polymeric Nanocarriers for Insulin:

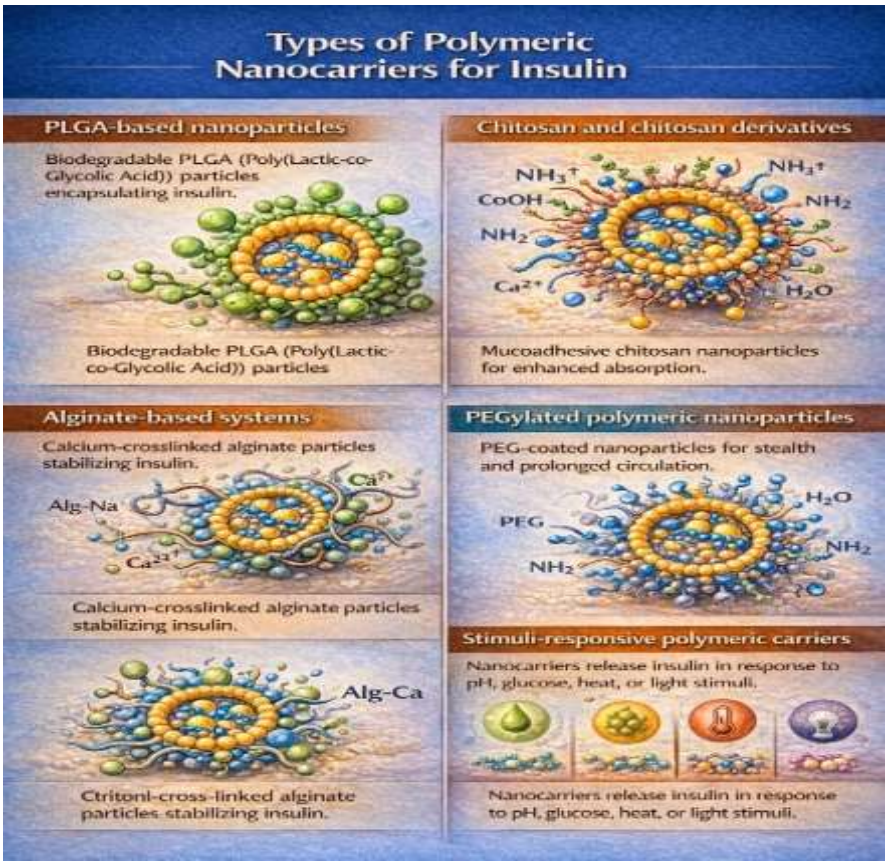


Figure:7- categories of polymeric methods for nanocarrier barriers.

1. PLGA-Based Nanoparticles:

Poly (lactic-co-glycolic acid) (PLGA)–based nanoparticles are among the most thoroughly researched polymeric systems for the delivery of oral insulin, owing to their remarkable biodegradability, biocompatibility, and regulatory approval. PLGA nanoparticles safeguard insulin from the acidic pH and enzymatic degradation that occurs in the gastrointestinal tract by encapsulating it within a polymeric matrix. The rate of degradation can be accurately regulated by modifying the ratio of lactic to glycolic acid, which facilitates a sustained release of insulin in the intestinal environment. Furthermore, PLGA nanoparticles can be modified on their surface with mucoadhesive or targeting ligands to improve their residence time in the intestine and enhance epithelial uptake. These characteristics render PLGA-based systems exceptionally suitable for multifunctional platforms for oral insulin delivery.

2. Chitosan and Chitosan Derivatives:

Chitosan and its derivatives have attracted considerable interest for the delivery of oral insulin due to their distinctive mucoadhesive properties and their capacity to temporarily open intestinal tight junctions. As a cationic polymer, chitosan engages

with negatively charged mucus and epithelial cell membranes, thereby enhancing the absorption of insulin through the paracellular pathway. Chemically modified chitosan derivatives, including N-trimethyl chitosan and thiolated chitosan, demonstrate enhanced solubility at physiological pH levels and more potent permeation-enhancing effects. These multifunctional attributes enable chitosan-based nanocarriers to effectively navigate mucus barriers, epithelial tight junctions, and enzymatic degradation simultaneously, rendering them exceptionally promising for the delivery of oral insulin.

3. Alginate-Based Systems:

Alginate-based polymeric nanocarriers are extensively studied for insulin delivery owing to their gentle gelation characteristics, compatibility with biological systems, and responsiveness to pH changes. Alginate creates stable hydrogels under acidic gastric conditions, effectively safeguarding insulin from degradation, while it swells or dissolves in the higher pH environment of the intestine to facilitate drug release. When paired with other polymers like chitosan, alginate-based systems demonstrate improved mechanical strength, mucoadhesion, and regulated insulin release profiles. These features allow alginate-based nanocarriers to function as multifunctional systems that can successfully navigate gastric and intestinal barriers in the oral delivery of insulin.

4. PEGylated Polymeric Nanoparticles:

PEGylated polymeric nanoparticles are engineered to enhance the penetration of mucus and the systemic stability of insulin delivered orally. The modification with polyethylene glycol (PEG) minimizes nonspecific interactions with mucus glycoproteins, allowing nanoparticles to diffuse more effectively through the mucus layer. Additionally, PEGylation improves the stability of nanoparticles and extends their circulation time by decreasing protein adsorption and immune recognition. When paired with biodegradable polymeric cores such as PLGA or chitosan, PEGylated nanocarriers achieve a balance between mucus penetration and controlled release of insulin, thereby enhancing intestinal absorption and bioavailability.

5. Stimuli-Responsive Polymeric Carriers:

Stimuli-responsive polymeric nanocarriers constitute a sophisticated category of multifunctional systems designed to react to specific gastrointestinal stimuli such as pH levels, enzymes, or redox conditions. pH-responsive polymers provide protection for insulin in the acidic environment of the stomach and facilitate targeted release in the intestine, whereas enzyme-responsive systems trigger insulin release in response to intestinal enzymes. Redox-responsive carriers take advantage of the intracellular environment to promote insulin release after cellular uptake. These intelligent polymeric systems combine various functional responses within a single carrier, allowing for precise spatiotemporal control over insulin release and greatly enhancing the efficiency of oral insulin delivery.

6. Multifunctional Design Strategies:

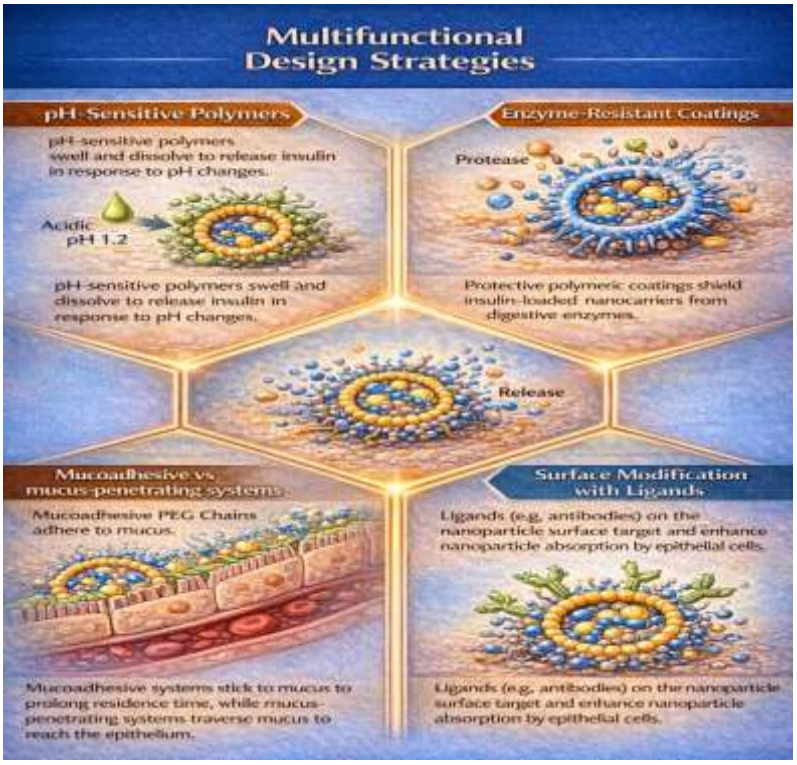


Figure:8- Multifunctional Design Strategies.

7. Multifunctional Design Strategies for Polymeric Nanocarriers in Oral Insulin Delivery:

A. pH-Sensitive Polymers:

pH-sensitive polymeric nanocarriers safeguard insulin against acidic gastric environments and facilitate targeted release within the intestine. They maintain stability at low pH levels but either swell or dissolve at intestinal pH. Frequently used polymers consist of Eudragit®, alginate, chitosan derivatives, and poly(acrylic acid). These systems inhibit acid degradation and guarantee site-specific drug release. In summary, they improve the stability and bioavailability of insulin.

B. Enzyme-Resistant Coatings:

Proteolytic enzymes present in the gastrointestinal tract substantially break down insulin, thereby restricting its oral delivery. Enzyme-resistant polymeric coatings safeguard insulin by creating a physical barrier against enzymes such as pepsin, trypsin, and chymotrypsin. Certain systems additionally incorporate protease inhibitors to improve protection. These coatings assist in preserving the structural integrity of insulin during its transit. Consequently, active insulin successfully arrives at the absorption site.

C. Mucoadhesive vs. Mucus-Penetrating Systems:

The intestinal mucus layer serves a dual role in oral insulin delivery, both obstructing and facilitating the process. Mucoadhesive nanocarriers composed of chitosan or thiolated polymers attach to the mucus, thereby prolonging their residence time and elevating the local concentration of insulin. Conversely, PEGylated systems diminish interaction with mucus and promote deeper penetration through the mucus layer. Both strategies enhance the transport of insulin to the epithelium. Recent innovations integrate both mucus penetration and adhesion within a single system, thereby improving insulin absorption and overall therapeutic efficacy.

D. Surface Modification with Ligands:

The intestinal mucus layer serves a dual purpose as a barrier and a support mechanism in the delivery of oral insulin. Mucoadhesive nanocarriers, such as chitosan and thiolated polymers, attach to the mucus,

thereby prolonging residence time and elevating insulin concentration. PEGylated systems minimize interaction with mucus and facilitate deeper penetration. Both methodologies enhance the transport of insulin to the epithelial surface. Cutting-edge systems integrate strategies for both penetration and adhesion, resulting in improved insulin absorption and therapeutic effectiveness.

8. Mechanisms of Intestinal Transport

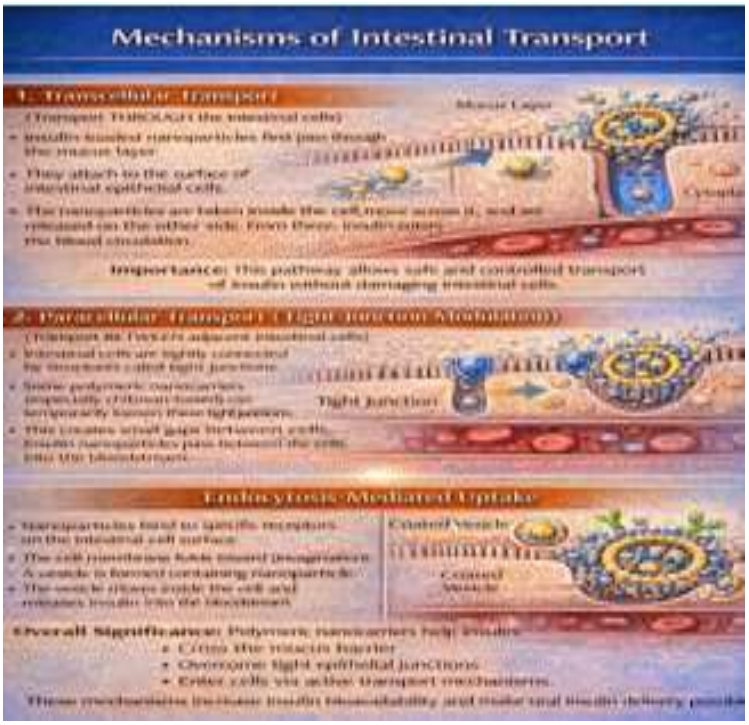


Figure:9-Transcellular transport acts as an important pathway that enables polymeric nanocarriers to enhance the absorption of insulin through the intestinal epithelium.

9. Mechanisms of Intestinal Transport of Insulin via Polymeric Nanocarriers:

i. Transcellular Transport:

Transcellular transport serves as a significant route through which polymeric nanocarriers promote the absorption of insulin across the intestinal epithelium. In this process, nanocarriers are taken up by enterocytes or specialized M cells through active transport mechanisms, followed by intracellular movement and exocytosis on the basolateral side. Multifunctional polymeric nanocarriers improve transcellular transport by fine-tuning particle size, surface charge, and hydrophobicity, all of which affect the efficiency of cellular uptake. Additionally, surface functionalization with targeting ligands enhances receptor-mediated transcytosis, allowing insulin to circumvent the restrictive paracellular space. This transport pathway is particularly beneficial as it enables the movement of intact insulin molecules while preserving the integrity of the epithelial barrier.

ii. Paracellular Transport via Tight Junction Modulation:

Paracellular transport refers to the movement of insulin through the intercellular spaces that exist between epithelial cells, which are tightly controlled by tight junction complexes. In normal physiological conditions, tight junctions significantly limit the passage of macromolecules, including insulin. Certain polymeric nanocarriers, especially those derived from chitosan and its derivatives, have the ability to transiently and reversibly modulate tight junctions by interacting with junctional proteins such as claudins and occludins. This temporary alteration increases paracellular permeability, thereby allowing insulin to diffuse across the epithelial barrier. It is crucial to note that multifunctional polymeric systems are specifically designed to ensure that the modulation of

tight junctions is reversible, thus preserving epithelial integrity and reducing the risk of long-term disruption of the barrier.

iii. Endocytosis-Mediated Uptake:

Endocytosis-mediated uptake represents a vital mechanism that underpins the intestinal transport of insulin-loaded polymeric nanocarriers. This process encompasses clathrin-mediated, caveolae-mediated, and macropinocytosis pathways, which vary based on the characteristics and surface modifications of the nanoparticles. Polymeric nanocarriers that are engineered with specific ligands or surface charges can preferentially activate receptor-mediated endocytosis, thereby enhancing the efficiency of cellular internalization. Once these nanocarriers are internalized, they serve to protect insulin from degradation within the cell and facilitate its controlled release, which enables effective transport across the intestinal epithelium. Mechanisms based on endocytosis are fundamental to multifunctional design strategies that aim to improve the bioavailability of insulin while ensuring the safety of the epithelial barrier.

iv. Integrated Transport Perspective:

Multifunctional polymeric nanocarriers frequently utilize various intestinal transport mechanisms at the same time to optimize insulin absorption. By integrating transcellular transport, regulated paracellular permeation, and endocytosis-mediated uptake into one cohesive system, these nanocarriers successfully navigate the intricate physiological barriers present in the gastrointestinal tract. This comprehensive transport strategy greatly improves oral insulin bioavailability and facilitates the advancement of non-invasive insulin therapies.

v. Insulin Loading and Release Mechanisms

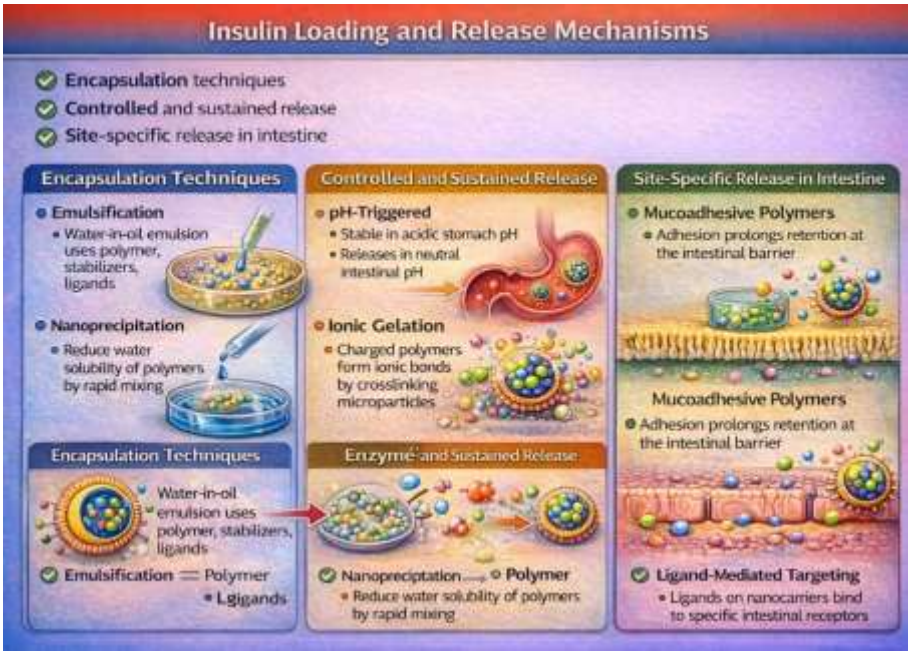


Figure:10- Mechanisms of Insulin Loading and Release in Polymeric Nanocarriers.

10. Insulin Loading and Release Mechanisms in Polymeric Nanocarriers:

A. Encapsulation Techniques:

The effective encapsulation of insulin within polymeric nanocarriers is a vital factor in the success of oral delivery, as it significantly affects drug stability, loading efficiency, and release characteristics. Various encapsulation techniques are employed, including emulsion–solvent evaporation, nanoprecipitation, ionic gelation, and polyelectrolyte complexation, which are contingent upon the type of polymer utilized. For example, PLGA-based nanocarriers frequently utilize double-emulsion techniques to encapsulate hydrophilic insulin, whereas chitosan and alginate systems rely on ionic interactions to create stable insulin-loaded

nanoparticles. These encapsulation methods safeguard insulin from the acidic environment and enzymatic degradation within the gastrointestinal tract, while preserving its structural integrity and biological functionality.

B. Controlled and Sustained Release:

The controlled and sustained release of insulin is crucial for achieving prolonged glycemic control and minimizing variations in blood glucose levels. Polymeric nanocarriers facilitate sustained insulin release through mechanisms such as polymer degradation, diffusion control, or a combination of both. By adjusting the polymer's composition, molecular weight, and crosslinking density, the release kinetics of insulin can be accurately customized. Multifunctional polymeric systems often integrate additional layers or coatings to further manage release rates, thereby preventing premature insulin leakage in the stomach and ensuring a gradual release in the intestine. Such controlled delivery profiles enhance therapeutic effectiveness while decreasing the frequency of dosing.

C. Site-Specific Release in the Intestine:

The targeted release of insulin within the intestine represents a fundamental goal in the design of multifunctional polymeric nanocarriers. pH-sensitive polymers are frequently utilized to inhibit insulin release in the acidic environment of the stomach while facilitating drug release at the elevated pH levels found in the small intestine. Additionally, enzyme-responsive and stimuli-sensitive polymers further improve site specificity by releasing insulin in response to intestinal enzymes or local physiological signals. These targeted release mechanisms guarantee that insulin is delivered to the optimal site for absorption, thus maximizing bioavailability and reducing degradation or loss during gastrointestinal transit.

D. Integrated Perspective:

By merging effective encapsulation methods with controlled and site-specific release mechanisms, multifunctional polymeric nanocarriers successfully tackle the significant challenges related to oral insulin delivery. These integrated approaches allow for protection, precise release, and improved absorption of insulin, marking a vital progression towards clinically feasible oral insulin formulations.

E. Conclusion of Discussion:

Overall, the study confirms that multifunctional polymeric nanoparticles represent a viable and innovative strategy for non-invasive insulin delivery in diabetes mellitus. Their ability to overcome complex gastrointestinal barriers positions them as a strong candidate for future translational and clinical research.

Section	Key Findings	Implications for Oral Insulin Delivery
Physicochemical Characterization	Particle size: 100–300 nm; PDI < 0.3; positive zeta potential; encapsulation efficiency >70%	Carrier size and charge enhance mucosal interaction, stability, and efficient drug loading
Protection Against GI Degradation	Mucosal against enzymatic degradation (pepsin, proteases); preserved insulin bioactivity	Ensures insulin remains active through harsh gastric and intestinal environments
Controlled Drug Release	pH-responsive behavior; minimal release at pH 1.2; sustained release at pH 6.8–7.4	Enables targeted intestinal release, improving absorption and therapeutic efficiency
Mucoadhesion & Permeation Enhancement	Strong mucoadhesion; transient opening of tight junctions; improved permeability in Caco-2 models	Increases residence time and facilitates paracellular transport of insulin
Cellular Uptake Mechanism	Uptake via clathrin- and caveolae-mediated endocytosis; ligand modification improves uptake	Enhances intracellular transport and absorption across intestinal epithelium
In Vivo Performance	Significant hypoglycemic effect; improved bioavailability; sustained glucose control	Demonstrates effectiveness as a non-invasive alternative to injections

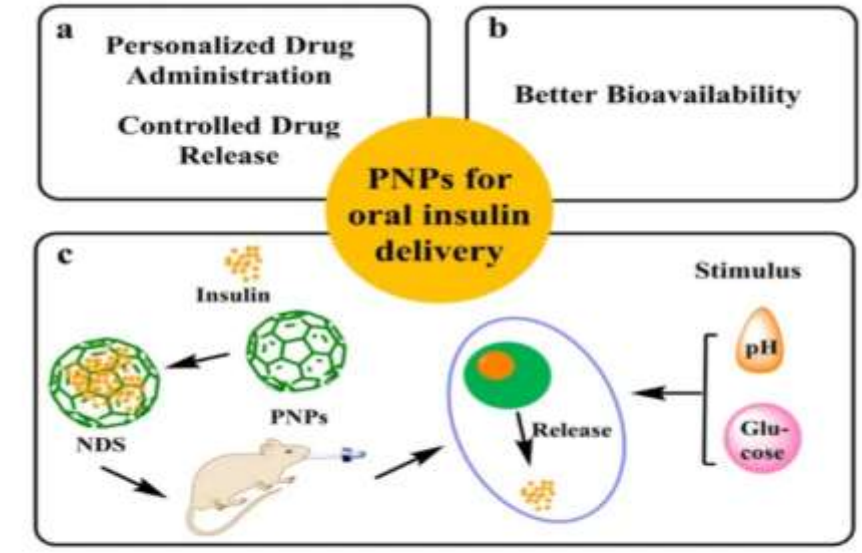
Safety & Biocompatibility	Non-toxic; no intestinal tissue damage observed	Confirms suitability for oral administration
Overall Discussion	Multifunctional design addresses multiple GI barriers simultaneously	Promising strategy for improving oral insulin delivery and patient compliance
Limitations	Scale-up challenges; stability concerns; variability in human absorption	Requires further optimization and clinical validation

F. Outcome:

The present study demonstrates the successful development and evaluation of multifunctional polymeric nanocarriers designed to enhance the oral delivery of insulin. These nanocarriers, particularly chitosan-based nanoparticles, were engineered to address key gastrointestinal (GI) barriers including enzymatic degradation, acidic pH, mucus entrapment, and limited epithelial permeability.

G. Experiment (Review):

PNPs facilitate the secure, effective, and intelligent delivery of oral insulin by safeguarding the insulin, enhancing its absorption, and releasing it in reaction to biological indicators such as pH or glucose concentrations.



Characterization of PNPs and the mechanism of insulin release. **a**, **b** Schematic diagrams showing the unique features of PNPs. **c** Insets show details of insulin release strategies from PNPs nanocarriers (relying mainly on glucose and pH responses)

Figure:11- This diagram demonstrates the application of polymeric nanoparticles (PNPs) in the delivery of oral insulin and highlights their advantages.

Feature:

"PNPs for oral insulin delivery" — nanoparticles made from polymers are engineered to transport insulin through the gastrointestinal tract and release it in a regulated manner.

A. Customized medication delivery and regulated release

• Polymeric nanoparticles (PNPs) can be designed to release insulin at predetermined rates or intervals.

• This enables personalized dosing according to the requirements of the patient.

They safeguard insulin (a delicate protein) from deterioration in the stomach.

B. Improved bioavailability

• Typically, oral insulin has low absorption rates due to its degradation in the gastrointestinal tract.

• PNPs enhance bioavailability by:

Protecting insulin from enzymes and acidic pH levels Facilitating absorption via the intestinal lining.

C. Mechanism of Insulin Delivery

This panel illustrates the operational process of the system step by

1. Encapsulation:

Insulin is encapsulated within polymeric nanoparticles (PNPs).

2. Administration:

The nanoparticles are administered orally (as demonstrated with the animal model).

3. Stimulus-Responsive Release:

PNPs are engineered to react to physiological stimuli such as:

a) pH variations (for instance, from stomach to intestine)
b) b) Glucose concentrations.

4. These stimuli trigger the release of insulin from the nanoparticles.

5. Controlled Release:

Insulin is released gradually at the designated site, enhancing its effectiveness while minimizing side effects.

CONCLUSION:

Polymeric nanoparticles (PNPs) present a promising method for delivering insulin orally by addressing the significant challenges posed by the gastrointestinal tract. They safeguard insulin from degradation, improve its absorption (bioavailability), and facilitate controlled, stimulus-responsive release influenced by factors such as pH and glucose concentrations. Collectively, this strategy promotes more effective, patient-friendly, and personalized management of diabetes, potentially decreasing the dependence on injectable insulin.

Features:

Enhanced stability: Insulin is safeguarded against degradation within the gastrointestinal environment. Improved bioavailability: A greater amount of insulin is effectively absorbed into the bloodstream. Controlled and targeted release: Insulin is released in reaction to physiological stimuli such as pH and glucose concentrations. Better glycaemic control: Results in more efficient management of blood glucose levels. Improved patient compliance: Minimizes or lessens the necessity for frequent injections.

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