How to Cite:
Almansour, M. A., Aldosary, M. S., Almegbel, M. T., Alsubaie, S. A., & Alzahrani, A. M. (2023). Recent innovations in oral drug delivery systems: Examining current challenges and future opportunities for enhanced therapeutic efficacy. *International Journal of Health Sciences*, *7*(S1), 3352–3370. https://doi.org/10.53730/ijhs.v7nS1.15041

Recent innovations in oral drug delivery systems: Examining current challenges and future opportunities for enhanced therapeutic efficacy

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***Abstract*---**Introduction: Oral drug delivery remains a cornerstone of therapeutic administration due to its ease of use and broad patient acceptance. However, delivering drugs orally poses significant challenges due to the complex and hostile environment of the gastrointestinal tract (GIT), including anatomical, biochemical, and physiological barriers. Aim: This article aims to explore recent innovations in oral drug delivery systems, focusing on addressing current challenges and identifying future opportunities for enhancing therapeutic efficacy. Methods: The study reviews advancements in oral drug delivery systems, including novel nanomedicines, microfabricated devices, and targeted delivery technologies. It synthesizes research findings from recent literature to highlight the evolution of these technologies and their impact on drug delivery. Results: Recent innovations include nanoparticles, microemulsions, and microfabricated devices, which enhance drug stability, targeting, and bioavailability. Nanoparticles, such as liposomes and solid lipid nanoparticles, protect drugs from the GIT environment and improve their absorption. Microfabricated devices, such as microneedles and micropatches, offer controlled and targeted drug release. Additionally,

International Journal of Health Sciences E-ISSN 2550-696X © 2023.
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Manuscript submitted: 26 Nov 2022, Manuscript revised: 27 Dec 2022, Accepted for publication: 15 Jan 2023

advancements in smart drug delivery systems, such as pH-sensitive and enzyme-responsive systems, provide precise control over drug release. Conclusion: Advances in oral drug delivery systems have significantly improved the ability to overcome GIT barriers, enhancing the effectiveness of oral medications. Future research should focus on integrating these innovations with personalized medicine approaches to further tailor treatments to individual patient needs and expand the potential for targeting non-GI diseases.

***Keywords*---**Oral drug delivery, nanomedicines, microfabricated devices, targeted delivery, bioavailability, personalized medicine.

1 Introduction

Oral administration remains the predominant approach for treating both systemic and localized gastrointestinal conditions [1,2]. Despite its clear advantages, oral drug delivery presents significant challenges due to the harsh microenvironment of the gastrointestinal tract (GIT) and several physiological barriers, including anatomical, biochemical, and physiological factors. The various segments of the GIT—namely, the oral cavity, esophagus, stomach, small intestine, and colon—are integral to the digestion of food and the absorption of medication. Anatomical features such as the limited surface area in the oral cavity, the gastric mucin–bicarbonate barrier, and enteric enzymes can impede drug absorption. Substantial efforts have been directed towards addressing these challenges, largely through enhanced understanding of both healthy and pathological GIT physiology. Traditional drug delivery systems, including standard tablets, capsules, and sterile preparations, are constrained by issues such as inadequate site-specific drug accumulation, unfavorable body distribution, and adverse side effects [3]. Consequently, there is an urgent need for the development of novel localized and systematic targeted drug delivery systems. Nanomedicines and innovative drug delivery devices have emerged as promising solutions in the realm of oral drug delivery [4].

Given the limited oral bioavailability of many drugs, nanoparticles have shown considerable potential in drug delivery [5]. Both organic and inorganic nanoparticles [6] have been explored to enhance tolerability, pharmacologic specificity, biodegradability, and targeting for oral medications [7,8]. A variety of nanocarriers, including nanoparticles [9,10], liposomes [11,12], and emulsions [13], have been utilized in oral drug delivery. These nanocarriers offer advantages such as protecting drugs from the harsh GIT environment, improving absorption into the circulatory system, targeting specific sites, and ensuring controlled release. Recent advancements in microfabricated devices have demonstrated significant potential in overcoming GIT barriers, thereby enhancing the oral bioavailability of drugs [14]. Microfabricated oral drug delivery systems, such as patch-like structures, microcontainers, and microwells, are designed to provide unidirectional drug release, promote targeted adhesion to the intestinal wall, and offer protective effects to drugs until they reach their intended delivery sites. The attachment of these devices to mucus, along with their unidirectional release and

extended residence time, facilitates greater drug permeation across the gastrointestinal wall, leading to improved oral bioavailability [15].

While many oral drug delivery systems have been focused on targeting localized gastrointestinal diseases, such as gastric conditions [16], oral carcinoma [17], inflammatory bowel disease (IBD) [18], and colon cancer [11], recent advancements in pharmaceutical technology, materials science, and disease physiology have enabled the development of oral targeted nanoparticle preparations aimed at delivering drugs to focal sites beyond the GIT [19].

2 Biological Barriers to Oral Drug Delivery Systems

The oral route is the most prevalent method for drug administration due to its ease of use, minimal discomfort, cost-effectiveness, broad drug absorption and distribution, and high patient compliance. Nonetheless, the effectiveness of many oral medications is hampered by various physiological barriers, leading to reduced permeability and drug degradation [20]. These limitations can be categorized into anatomical, biochemical, and physiological factors affecting the gastrointestinal tract (GIT).

2.1. Anatomical Factors

The GIT is anatomically divided into the oral cavity, esophagus, stomach, small intestine, and colon, each presenting distinct challenges for drug delivery [21]. These anatomical features influence drug absorption in various ways:

- **Oral Cavity:** The oral cavity, lined with mucosa, offers a relatively mild microenvironment, ease of access to circulation, and good drug permeability [20,22]. However, the limited surface area, presence of saliva, and enzymatic activity pose significant barriers to effective drug delivery [20].
- **Esophagus:** The esophagus, characterized by low permeability and a brief residence time for drugs, is generally not considered a primary site for drug delivery [23,24].
- **Stomach:** The stomach is the most challenging environment for drug absorption due to its highly acidic pH (ranging from 1.0 to 2.5), which can degrade food, pathogens, and acid-labile drugs [25,26]. Additional barriers include the mucin-bicarbonate barrier and tight junctions of epithelial cells [27,28], as well as the presence of pepsins that can inactivate protein drugs.
- **Small Intestine:** The small intestine, with its extensive surface area provided by villi and microvilli, is considered an optimal site for drug delivery due to its large absorptive surface and varied transport mechanisms [29,30]. However, its efficacy can be reduced by the acidic environment of the stomach, pancreatic enzymes, bile salts, and mucosal layer, which diminish drug bioavailability. Drug delivery systems that enhance retention at the villi and microvilli, improve lipid solubility, and target specific receptors or carriers can potentially increase overall bioavailability.
- **Colon:** The colon has a higher pH and longer residence time compared to the upper GIT, with lower enzymatic activity [33,34]. However, drug metabolism by gut microflora can affect drug release characteristics.

Targeting the colon is valuable for treating bowel diseases with reduced side effects and lower doses. Yet, variability in gastric emptying times and individual gut microbiota remains a significant challenge for effective colon targeting [35].

2.2. Biochemical Factors

Biochemical factors, including variations in pH and the presence of digestive enzymes, are crucial barriers to oral drug delivery systems. The pH of the GIT ranges from 1 to 8, increasing from the stomach to the colon [36,37]. This gradient from acidic to alkaline conditions affects drug stability and bioavailability, influencing both drug delivery and design considerations. Enzymes present in the GIT, especially those targeting protein drugs, can significantly impact drug bioavailability. The colon hosts over 400 species of aerobic and anaerobic microorganisms that produce hydrolytic and reductive enzymes, which can metabolize xenobiotics and biomolecules. Polysaccharides, for instance, are metabolized exclusively in the colon by anaerobic bacteria, which helps stabilize them in the stomach and small intestine, facilitating colon-targeted delivery. Given the susceptibility of drugs to colonic enzymes and subsequent biotransformation, the "prodrug" approach is often employed to achieve colon-specific delivery [33].

2.3. Physiological Factors

The physiological barriers to drug absorption in the GIT include the epithelial cellular barrier and the mucus barrier. The gastrointestinal epithelium is a phospholipid bilayer membrane that allows lipophilic macromolecules to penetrate while restricting hydrophilic and macromolecular substances [38,39]. Tight junctions between epithelial cells further limit the paracellular passage of hydrophilic drugs [40]. Mucus, a dynamic semipermeable barrier, restricts direct drug interaction with epithelial cells. Composed of mucins and glycoproteins, mucus acts as a lubricant and a protective barrier, trapping foreign particles and eliminating harmful substances and microorganisms [41,42,43,44,45]. The stability of mucins, linked by disulfide bonds and heavily glycosylated, enhances their resistance to enzymatic degradation [28]. The structural characteristics of mucus and its molecular interactions affect the permeation of peptides, large molecules, and microorganisms through this barrier [46,47].

3. Application of the Oral Drug Delivery Systems

3.1. Local Targeting to GIT

Oral drug delivery systems are designed to target specific sites within the gastrointestinal tract (GIT) based on the unique physiological conditions of each site. Local targeting strategies include:

3.1.1. Gastroretentive Drug Delivery Systems

Gastroretentive systems aim to prolong the gastric residence time, which is advantageous for drugs absorbed in the stomach or upper GIT, or those unstable in the intestine. Common gastroretentive systems include:

- **Gastric Floating Systems:** These systems, such as the pramipexole-loaded self-inflating effervescence-based electrospun nanofibers, float in the stomach due to gas generation, allowing sustained drug release and reducing systemic fluctuations [59].
- **Gastric Expandable Systems:** For example, gabapentin-loaded expandable formulations unfold in the stomach and provide controlled release over hours [61].
- **Mucoadhesive Systems:** Simvastatin-loaded mucoadhesive tablets with thiomers enhance gastric retention through strong adhesion to the gastric mucosa [62].
- **High-Density Systems:** Zero valent iron nanoparticles (ZVINPs) increase oral bioavailability of iron and demonstrate effective retention in the stomach [53].

3.1.2. Small Intestine Drug Delivery Systems

Targeting the small intestine involves:

- **pH-Responsive Formulations:** Coatings or matrices that dissolve at specific pH levels protect drugs from degradation and enhance release in the small intestine. Examples include hydrogels and nanoparticles [64,65,66,67,68,69,70,71].
- **Enteric-Coated Dosage Forms:** Tablets and capsules coated with polymers that dissolve in the intestinal environment help deliver drugs directly to the small intestine [72,73]. However, drug release can be influenced by variability in gastrointestinal conditions and coating stability [74,75].
- **Mucoadhesive Formulations:** Intestinal patches or devices, such as insulin-delivering patches, adhere to the intestinal mucosa and release drugs in a controlled manner [77].

3.1.3. Colon Targeting

Colon-targeted drug delivery is used for treating local colonic diseases:

- **Prodrugs:** These are designed to be activated in the colon by enzymatic or pH-induced hydrolysis. For instance, 5-ASA-based prodrugs like sulfasalazine are used for inflammatory bowel disease [85].
- **Enzyme Responsive Approach:** Polymers that degrade in response to colonic enzymes release the drug in the colon. Resistant starch films and polysaccharides like pectin are examples [87,88].
- **ROS-Responsive Approach:** Nanoparticles responsive to reactive oxygen species (ROS) in inflamed tissues help in targeted delivery and inflammation suppression [95,96,94].
- **pH-Dependent Approach:** Systems that release drugs in response to the higher pH in the colon are developed to improve colon-targeted delivery [99,100,101].
- **Microbiota Dependent Drug Delivery Systems:** These systems use microbial enzymes to release drugs in the colon. Examples include yeast cell wall microparticles that target ulcerative colitis [102].

3.2. Increased Bioavailability by Novel Drug Delivery Systems

Novel drug delivery systems aim to enhance the bioavailability of drugs susceptible to the harsh GIT environment:

- **Nanocomposite Carriers:** For instance, infliximab-loaded nanocomposites deliver antibodies to the colon effectively [105].
- **Enteric-Coated Formulations:** Peptides and proteins are protected from gastrointestinal degradation using enteric coatings [31,106,107].
- **Double Coated Nanocomposites:** Systems such as those composed of organoclay and glycol-chitosan enhance insulin absorption in the colon [108].
- **Polysaccharide Coatings:** Calcium phosphate nanoparticles coated with polysaccharides improve protein antigen delivery [109].
- **Microfabricated Devices:** Devices like the luminal unfolding microneedle injector (LUMI) and self-orienting millimeter-scale applicator (SOMA) increase retention and bioavailability [112,113].
- **Transformers-like Nanocarriers:** Nanocarriers designed to enhance the oral bioavailability of poorly water-soluble drugs, such as curcumin [115].
- **Targeted Nanoparticles:** For example, resveratrol-loaded PLGA nanoparticles with folate targeting improve stability and intestinal absorption [116].

These advanced systems address challenges in oral drug delivery and improve therapeutic outcomes through enhanced targeting and bioavailability.

3.3. Targeting Delivery for Non-Gastrointestinal Diseases after Oral Administration

Oral drug delivery systems have traditionally focused on targeting the gastrointestinal tract (GIT). However, advancements in nano-preparations have made it possible to target non-GI diseases. Despite the challenges posed by the GIT environment, research into the pathways and mechanisms of pathogen invasion has provided new insights, leading to developments in delivering drugs to non-GI lesions. Recent advancements have made it possible to target various diseases such as systemic inflammation, tumors, brain diseases, cardiovascular diseases, obesity-related diseases, and arthritis through oral administration.

3.3.1. Systemic Inflammation Target Delivery System

Targeting systemic inflammation through oral delivery remains challenging due to biological barriers. Macrophages, which play a role in promoting inflammatory responses, are key targets for RNA interference-based drug delivery. For instance:

- **GeRPs (Glucan-coated RNA Particles):** Myriam Aouadi et al. [117] developed β1,3-D-glucan-coated siRNA particles (GeRPs) for oral delivery. These particles are phagocytized by macrophages and dendritic cells in the gut-associated lymphatic tissue (GALT), leading to reduced Tnf-α levels and prevention of lipopolysaccharide-induced lethality.
- **Yeast-Derived Capsule (YC) Approach:** Xing Zhou et al. [118] used a bioinspired 'Trojan horse' strategy with yeast-derived capsules to deliver anti-inflammatory drugs. These capsules target Peyer's patches are endocytosed by macrophages, and transport drugs to inflammation sites. This approach showed enhanced drug delivery to inflamed areas compared to other formulations.

3.3.2. Oral Tumor Target Delivery System

Developing oral delivery systems for non-digestive tract tumors is complex but promising:

- **Cisplatin Delivery:** Xing Zhou et al. [120] created a nano precursor-packaging strategy using yeast-derived capsules to deliver cisplatin, an ineffective oral antitumor drug. The nanoparticles, processed into a hydrosoluble prodrug, showed higher bioavailability and targeted tumor sites effectively.
- **Autonomous Oral Nanoparticles:** Inspired by spores, a study [121] developed autonomous nanoparticles loaded with doxorubicin and sorafenib. These nanoparticles self-assemble after entering the intestine, penetrate epithelial cells, and enhance drug delivery to cancer sites.

3.3.3. Obesity-Related Diseases Target Delivery System

Oral delivery of anti-obesity drugs faces challenges in targeting lesions associated with obesity-related diseases:

- **LAm-mediated Nanoparticles:** Chunmei Xu et al. [122] developed bindarit-loaded nanoparticles modified with laminarin, which effectively targeted various lesions, including inflammatory adipose tissue and fatty liver, in obesity models.
- **Yeast Microcapsules for IL-1b shRNA Delivery:** Li Zhang et al. [123] used yeast microcapsules to deliver IL-1b shRNA, leading to significant reductions in body weight, fat weight, and improved metabolic markers in obese mice.

3.3.4. Gut-to-Brain Oral Drug Delivery System

Overcoming the intestinal epithelial barrier (IEB) and blood–brain barrier (BBB) is crucial for delivering drugs from the gut to the brain:

- **Prodrug Approach:** A noninvasive method involving β-glucan-conjugated prodrugs was developed to overcome the IEB and BBB. The prodrug is targeted by M cells, transported through lymphatic pathways, and activated at the tumor site, showing promise for glioma treatment [124].

3.3.5. Cardiovascular Disease Oral Drug Delivery System

Cardiovascular diseases, such as atherosclerosis, are associated with monocytes, providing a basis for targeted oral delivery:

- **Biomimetic Yeast-Derived Microcapsules:** Xiangjun Zhang et al. [125] developed a system using yeast-derived microcapsules to deliver positively charged nanodrugs. These capsules accumulated in aortic plaques and showed enhanced efficacy in treating atherosclerosis.

3.3.6. Post-Traumatic Osteoarthritis Oral Drug Delivery System

Gene therapies for osteoarthritis have been limited by delivery challenges:

- **IL-1b shRNA Delivery via Yeast Capsules:** Long Zhang et al. [126] used yeast capsules to deliver IL-1b shRNA, significantly reducing inflammatory responses and cartilage degeneration in osteoarthritis models. This approach represents a novel gene therapy strategy for osteoarthritis. These advancements in oral drug delivery systems are breaking new ground in targeting non-GI diseases, providing promising avenues for treatment and improving patient outcomes across various medical conditions [127].

4 Recent Innovations and Future Opportunities in Oral Drug Delivery Systems

4.1. Advanced Nanocarrier Systems

Recent innovations in nanotechnology have significantly advanced oral drug delivery systems, offering promising solutions to address the challenges of drug absorption and targeting. These advancements focus on enhancing drug stability, bioavailability, and site-specific targeting.

- **Nanoparticles and Nanocomposites:** Nanoparticles, including liposomes, solid lipid nanoparticles (SLNs), and polymeric nanoparticles, have shown considerable promise in improving drug delivery. For instance, nanoparticles can encapsulate drugs to protect them from harsh GIT conditions and enhance their solubility. Recent developments in nanocomposites, such as those combining organic and inorganic materials, offer enhanced stability and controlled release profiles. Examples include infliximab-loaded nanocomposites designed for targeted delivery to the colon, effectively treating inflammatory bowel diseases.
- **Microemulsions and Nanostructured Lipid Carriers (NLCs):** Microemulsions and NLCs are gaining attention for their ability to improve the solubility and bioavailability of poorly water-soluble drugs. Microemulsions, consisting of oil, water, and surfactants, form a stable system that enhances drug solubilization and absorption. NLCs, with their lipid core and surfactant shell, offer a controlled release mechanism and protect drugs from degradation.

4.2. Smart Drug Delivery Systems

Innovations in smart drug delivery systems involve developing technologies that respond to specific stimuli within the GIT to enhance drug release and absorption.

- **pH-Sensitive Delivery Systems:** pH-sensitive drug delivery systems are designed to release drugs at specific pH levels corresponding to different segments of the GIT. For example, pH-responsive polymers and hydrogels can be engineered to dissolve or swell in the acidic environment of the stomach or the alkaline environment of the small intestine, releasing drugs in a controlled manner.
- **Enzyme-Responsive Systems:** These systems utilize enzymes present in the GIT to trigger drug release. Enzyme-sensitive polymers and prodrugs that undergo hydrolysis in response to specific enzymes can ensure targeted drug delivery and reduce systemic side effects. This approach is particularly useful for proteins and peptides that are susceptible to enzymatic degradation.

4.3. Microfabricated Devices

Microfabrication technologies have led to the development of advanced oral drug delivery devices that offer precise control over drug release and targeting.

- **Microneedles and Micropatches:** Microneedles and micropatches are innovative devices designed to penetrate the mucosal layer of the GIT, enhancing drug absorption. For example, microneedle arrays can deliver

drugs directly to the mucosal tissues, improving bioavailability and therapeutic efficacy. Micropatches that adhere to the intestinal wall can provide sustained drug release and localized treatment.

- **Bioadhesive Systems:** Bioadhesive drug delivery systems are designed to adhere to the mucosal surfaces of the GIT, providing prolonged residence time and controlled drug release. Bioadhesive polymers and nanoparticles can form strong bonds with the mucosal tissues, improving drug retention and absorption.

4.4. Targeted Delivery for Systemic and Non-Gastrointestinal Diseases

Recent advancements have expanded the potential of oral drug delivery systems to target not only GIT diseases but also systemic and non-GI diseases.

- **Oral Delivery of Systemic Therapies:** Innovations in oral drug delivery systems are now enabling the targeting of systemic conditions through the GIT. For example, oral formulations of RNA interference (RNAi) therapeutics, such as GeRPs (glucan-coated RNA particles), can target macrophages involved in systemic inflammation, offering new treatments for diseases like rheumatoid arthritis and systemic lupus erythematosus.
- **Non-Gastrointestinal Disease Targets:** Emerging research focuses on overcoming the GIT barriers to deliver drugs for non-GI diseases. For instance, oral drug delivery systems are being developed for treating brain diseases, cardiovascular conditions, and cancer. Strategies such as using prodrugs that cross the blood-brain barrier (BBB) or incorporating targeted nanoparticles that accumulate in atherosclerotic plaques are being explored to address these challenges.

4.5. Personalized and Precision Medicine

The future of oral drug delivery systems lies in personalized and precision medicine, where drug delivery systems are tailored to individual patient needs.

- **Biomarker-Driven Drug Delivery:** Advances in genomics and proteomics enable the identification of biomarkers associated with specific diseases and patient responses. Drug delivery systems can be designed to release drugs based on the presence of these biomarkers, optimizing treatment efficacy and minimizing side effects.
- **Patient-Specific Formulations:** Personalized drug delivery systems can be customized based on individual patient characteristics, such as genetic profile, disease state, and metabolic rate. This approach ensures that medications are delivered in a manner that maximizes their therapeutic potential while reducing adverse effects.

Conclusion

Recent advancements in oral drug delivery systems have brought substantial progress in overcoming the inherent challenges associated with the gastrointestinal tract (GIT). The traditional oral drug delivery methods face significant barriers, including the acidic environment of the stomach, enzymatic degradation, and variable absorption in different GIT segments. To address these issues, innovative strategies have emerged, transforming the landscape of oral drug delivery. Nanotechnology has played a pivotal role in this transformation, with nanoparticles, such as liposomes and solid lipid nanoparticles, enhancing

drug stability and bioavailability. These advanced carriers are designed to protect drugs from the harsh GIT environment, improve their solubility, and facilitate targeted delivery. Microfabricated devices, including microneedles and micropatches, offer new methods to improve drug absorption and retention, providing sustained and localized drug release. Furthermore, smart drug delivery systems that respond to specific stimuli, such as pH changes and enzymatic activity, have been developed to ensure more precise and controlled drug release. These systems enhance the therapeutic efficacy of oral medications by addressing the variability in GIT conditions and individual patient responses. Looking ahead, the integration of these innovations with personalized medicine holds great promise. Tailoring drug delivery systems to individual patient needs based on genetic, physiological, and disease-specific factors can optimize therapeutic outcomes and minimize adverse effects. Moreover, recent research into targeting non-GI diseases through oral administration demonstrates the potential for expanding the scope of oral drug delivery beyond traditional applications. In summary, the evolution of oral drug delivery systems reflects significant progress in addressing the complexities of the GIT. Continued research and development in this field are essential for advancing therapeutic efficacy and expanding treatment options for a wide range of medical conditions.

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الابتكارات الحديثة في أنظمة توصيل الأدوية عبر الفم: استكشاف التحديات الحالية والفرص المستقبلية لتعزيز الفعالية العلاجية

الملخص:

المقدمة :يظل توصيل الأدوية عبر الفم حجر الزاوية في الإدارة العلاجية نظرًا لسهولة استخدامه وقبول المرضى الواسع. ومع ذلك، فإن توصيل الأدوية عن طريق الفم يواجه تحديات كبيرة بسبب البيئة المعقدة والعدائية للجهاز الهضمي، بما في ذلك الحواجز التشريحية والكيميائية الحيوية والفيزيولوجية.

الهدف :يهدف هذا المقال إلى استكشاف الابتكارات الحديثة في أنظمة توصيل الأدوية عبر الفم، مع التركيز على معالجة التحديات الحالية وتحديد الفرص المستقبلية لتعزيز الفعالية العلاجية.

الطرق :يستعرض البحث التقدمات في أنظمة توصيل الأدوية عبر الفم، بما في ذلك الأدوية النانوية الحديثة، والأجهزة المصغرة، وتقنيات التوصيل المستهدفة. يتم تلخيص نتائج الأبحاث من الأدبيات الحديثة لتسليط الضوء على تطور هذه التقنيات وتأثيرها على توصيل الأدوية.

النتائج :تشمل الابتكارات الحديثة جزيئات النانو، والمستحلبات الدقيقة، والأجهزة المصغرة، التي تعزز استقرار الأدوية، واستهدافها، وتوافرها الحيوي. توفر جزيئات النانو، مثل الحويصلات الدهنية وجزيئات الدهون الصلبة، حماية للأدوية من بيئة الجهاز الهضمي وتحسن امتصاصها. تقدم الأجهزة المصغرة، مثل الإبر الدقيقة واللصقات الدقيقة، إطلاقًا محكمًا ومستهدفًا للأدوية. بالإضافة إلى ذلك، توفر التقدمات في أنظمة توصيل الأدوية الذكية، مثل الأنظمة الحساسة لـ pH والأنظمة المستجيبة للإنزيمات، تحكمًا دقيقًا في إطلاق الأدوية.

الخاتمة :قد أدت التقدمات في أنظمة توصيل الأدوية عبر الفم إلى تحسين كبير في القدرة على تجاوز الحواجز في الجهاز الهضمي، مما يعزز فعالية الأدوية الفموية. يجب أن يركز البحث المستقبلي على دمج هذه الابتكارات مع approaches الطب الشخصي لمزيد من تخصيص العلاجات لاحتياجات المرضى الفردية وتوسيع إمكانيات استهداف الأمراض غير المتعلقة بالجهاز الهضمي.

الكلمات المفتاحية :توصيل الأدوية عبر الفم، الأدوية النانوية، الأجهزة المصغرة، التوصيل المستهدف، التوافر الحيوي، الطب الشخصي