Nanotechnology Perceptions
ISSN 1660-6795
www.nano-ntp.com

Enhancing Probiotic Efficacy through Progress in Polysaccharide-Based Oral Delivery Systems

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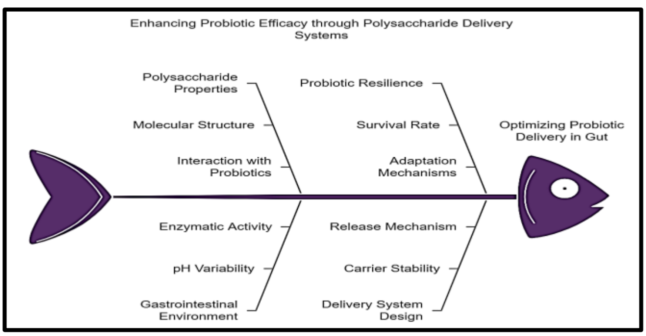
The recent developments in the use of polysaccharide-based oral delivery systems for improvement in the efficacy of probiotics have been organized under discussion within this review. The aspect of using polysaccharide as a carrier for probiotics seems to offer a particularly promising avenue for further stabilization and efficiency at the level of crossing the gastrointestinal tract. This paper covers some applications and current trends, along with future perspectives of using polysaccharide-based delivery systems for probiotics. This review explains and sheds light on how to develop novel strategies that could be used for optimizing probiotic delivery, thereby maximizing the health-promoting effects in the gut environment by discussing potential pros and cons related to the use of polysaccharides as a carrier for probiotics.

Keywords: Polysaccharide-based delivery systems, Probiotic efficacy, Gastrointestinal tract, Innovative strategies, Gut health

Graphical Abstract:



1. Introduction

Probiotics are live microorganisms that, provided in adequate amounts, confer health benefits. Beneficial bacteria in the gut have a big responsibility in the maintenance of gut health through creating a balanced microbial environment and supporting various functions of the body within the gastrointestinal tract. Over the past decade or two, significant interest has been generated in probiotics based on their proposed therapeutic utility for a variety of health conditions ranging from disturbances in the gastrointestinal tract and immune modulation to challenges of metabolic health. One of the most critical issues with probiotic supplementation is the survival and functionality of the probiotics once they are shielded from the hostile acidic environment of the stomach so that they arrive at the intestines where they exert beneficial effects. (1–4).

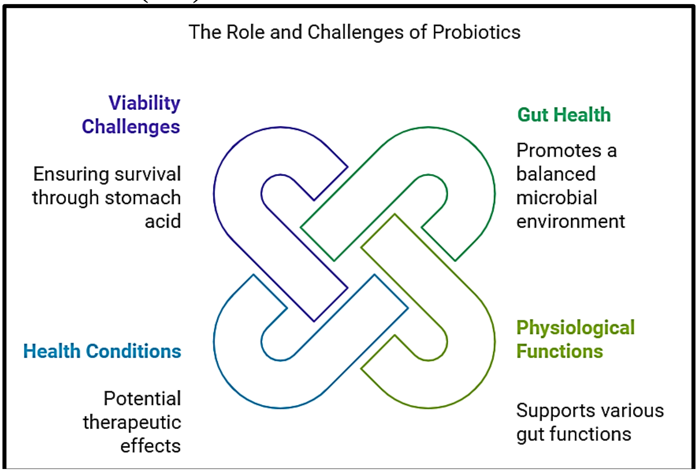


Fig. 01: The Role and Challenges of Probiotics

Many challenges limit the chances of survival and efficacy of the probiotic organisms from orally administered probiotics. These include low pH levels, bile salts, and enzymatic activity in the stomach, which leads to a very drastic reduction in viable counts of probiotic cells. This consequently dampens the probability of colonization potential of the bacteria in the gut and their health-promoting effect. To overcome these problems and increase the probiotic delivery of probiotics to the intestines, researchers have made attempts to find ingenious ways of protecting probiotic cells during their journey through the digestive system (5–7).

The concept recently reported regarding the application of polysaccharides as carriers for probiotics appears to develop as a promising route toward achieving better viability and therapeutic effects of probiotics. Polysaccharides are complex carbohydrates that occur in many natural sources such as plants, algae, or microorganisms. Such biocompatible and biodegradable materials offer several benefits as a carrier for probiotics, which include the encapsulation of protective barriers over probiotic cells, the protection of the probiotics against extreme environmental conditions, and targeting delivery to some site in the gut(8–11).

In efforts to enhance their survival, protect them from the acidic conditions of the stomach interior, and guarantee a better release and colonization in the intestines, scientists encapsulated the cells of probiotics using polysaccharide-based matrices. Since many of the polysaccharides demonstrated excellent carrier properties for probiotics, such as chitosan, alginate, pectin, cellulose derivatives, they soon represented ideal candidates for the development of new oral delivery systems that would make it possible to increase the efficacy of administered probiotic supplementation(12–15).

This review aims to explore the applications, current trends, and future prospects of polysaccharide-based oral delivery systems for enhancing the efficacy of probiotics. By investigating the potential benefits and challenges associated with the use of polysaccharides as carriers for probiotics, this review seeks to provide valuable insights into the development of innovative strategies that can optimize probiotic delivery and maximize their health-promoting effects in the gut(16,17).

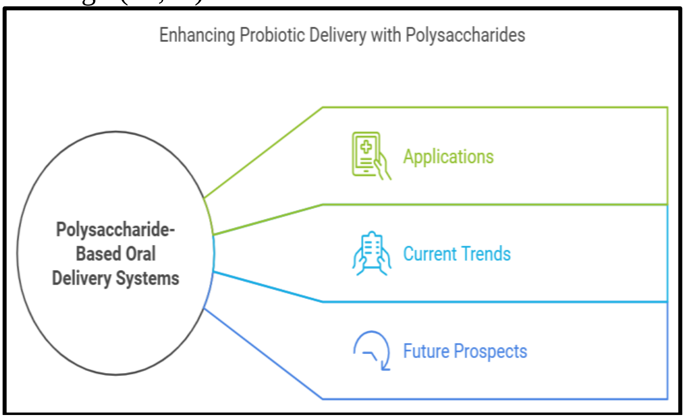


Fig.02: Enhancing Probiotic Delivery with Polysaccharides

2. Polysaccharide-Based Oral Delivery Systems:

Polysaccharides have garnered significant interest as carriers for probiotics in oral delivery systems due to their biocompatibility, biodegradability, and functional properties. Among the various polysaccharides used in probiotic delivery systems, chitosan, alginate, pectin, and cellulose derivatives have emerged as promising candidates for enhancing the survival and efficacy of probiotic cells in the gastrointestinal tract(18–22).

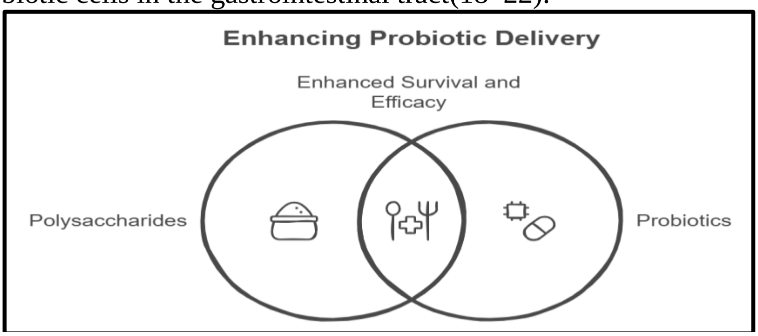


Fig. 03: Enhancing Probiotic Delivery

- **Chitosan:** Chitosan, a natural polysaccharide derived from chitin, has been extensively studied for its potential applications in probiotic delivery systems. Its cationic nature allows it to interact with negatively charged surfaces of probiotic cells, facilitating their adhesion and encapsulation. Chitosan forms mucoadhesive films that protect probiotic cells from the acidic environment of the stomach, thus promoting their survival during transit to the intestines(23–25).

- **Alginate:** Alginate, a biopolymer extracted from seaweed, is widely used in the encapsulation of probiotics due to its gel-forming properties. Alginate forms a protective barrier around probiotic cells, shielding them from gastric fluids and bile salts. The gel matrix created by alginate encapsulation enables controlled release of probiotics in the intestines, enhancing their viability and colonization in the gut(25,26).
- **Pectin:** Pectin, a soluble dietary fiber found in fruits, offers several advantages as a carrier for probiotics. Pectin-based delivery systems provide a protective microenvironment for probiotic cells, shielding them from adverse conditions in the stomach. Pectin encapsulation enhances the survival of probiotics by promoting their resistance to low pH and enzymatic degradation, thereby facilitating their targeted delivery to the intestines(27,28).
- **Cellulose Derivatives:** Cellulose derivatives, such as methylcellulose and hydroxypropyl cellulose, have been explored for their potential in probiotic delivery systems. These derivatives form hydrogels that can encapsulate probiotic cells, protecting them from acidic conditions and enzymatic degradation in the stomach. Cellulose-based matrices provide sustained release of probiotics in the intestines, ensuring prolonged exposure and improved colonization(29,30).

Mechanisms of Protection by Polysaccharides: Polysaccharides play a crucial role in protecting probiotic cells from harsh gastric conditions through various mechanisms. The mucoadhesive properties of polysaccharides enable them to adhere to the mucosal lining of the gastrointestinal tract, forming a protective barrier that shields probiotic cells from acidic pH and enzymatic activity. Polysaccharide encapsulation enhances the survivability of probiotics by maintaining a conducive microenvironment that supports their viability and functionality during transit(31–33).

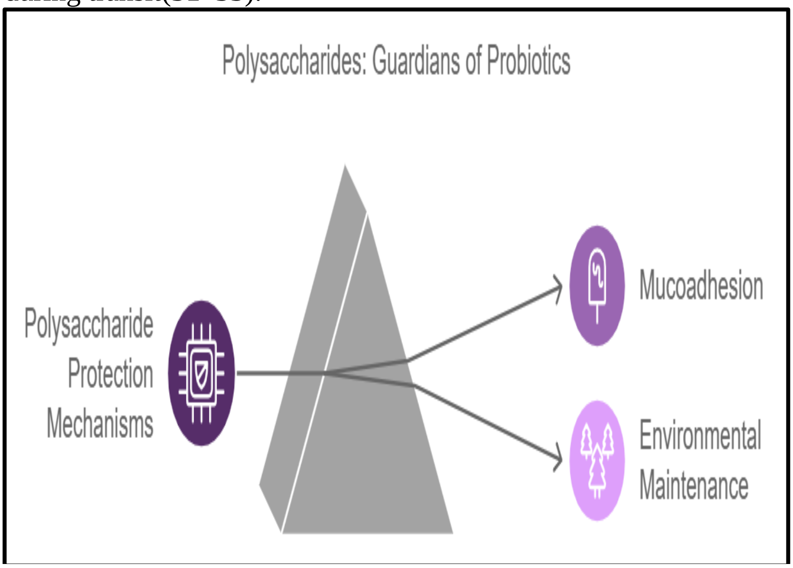


Fig.04: Polysaccharides: Guardians of Probiotics

- **Mechanisms of Protection by Polysaccharides in Probiotic Delivery:**

Polysaccharides serve as key players in safeguarding probiotic cells from the challenging conditions encountered in the gastrointestinal tract. Through a myriad of protective mechanisms, polysaccharides play a pivotal role in enhancing the survival and functionality of probiotics, ultimately maximizing their beneficial effects on gut health and overall well-being(34–37).

- **Mucoadhesive Properties of Polysaccharides:**

One of the primary mechanisms through which polysaccharides protect probiotic cells is via their mucoadhesive properties. Polysaccharides possess an inherent ability to adhere to the mucosal lining of the gastrointestinal tract, forming a bioadhesive barrier that shields probiotic cells from the hostile environment of the stomach. By adhering to the mucosal surface, polysaccharides create a protective shield that prevents direct exposure of probiotics to acidic pH levels and enzymatic degradation, thus improving their chances of survival as they navigate through the digestive system(38–41).

- **Formation of Protective Barrier:**

The formation of a protective barrier by polysaccharides is crucial in preventing probiotic cells from succumbing to the harsh conditions of the gastric environment. By creating a physical barrier between probiotics and the acidic gastric juices, polysaccharides offer a shield that helps maintain the viability and functionality of probiotic cells. This protective barrier not only safeguards probiotics during their passage through the stomach but also ensures their arrival in the intestines with their beneficial properties intact, ready to exert their health-promoting effects(42,43).

- **Maintaining a Conducive Microenvironment:**

Polysaccharide encapsulation provides probiotic cells with a conducive microenvironment that supports their survival and functionality throughout transit in the gastrointestinal tract. The encapsulated probiotics are ensconced within a protective matrix of polysaccharides, which helps create a stable environment for the probiotic cells. This protective matrix acts as a buffer against fluctuations in pH, temperature, and other environmental factors, safeguarding probiotics from external stressors and ensuring their viability until they reach the target site for colonization and activity(44,45).

- **Enhanced Survivability and Viability:**

By leveraging the protective mechanisms of polysaccharides, probiotic cells experience enhanced survivability and viability during their journey through the gut. The mucoadhesive properties of polysaccharides ensure prolonged contact between probiotics and the intestinal mucosa, increasing their retention time and bioavailability. This extended interaction allows probiotics to establish themselves more effectively in the gut environment, enhancing their chances of colonization and beneficial effects on gut microbiota and immune function(46–49).

- **Optimization of Probiotic Functionality:**

Moreover, polysaccharide encapsulation not only protects probiotic cells but also optimizes their functionality by providing a supportive microenvironment for their metabolic activities. The encapsulated probiotics are shielded from hostile conditions that could compromise their enzymatic functions, ensuring that they retain their ability to produce beneficial metabolites, modulate immune responses, and maintain gut homeostasis. This optimization of probiotic functionality through polysaccharide protection contributes to the overall efficacy of probiotic therapies in promoting gut health and well-being(50,51).

- The mechanisms of protection provided by polysaccharides in probiotic delivery systems are multifaceted and essential for ensuring the viability, functionality, and therapeutic efficacy of probiotic cells. Through their mucoadhesive properties, formation of protective barriers, maintenance of conducive microenvironments, and enhancement of survivability and functionality, polysaccharides play a crucial role in safeguarding probiotics through the challenging journey of the gastrointestinal tract. By understanding and harnessing these protective mechanisms, researchers can develop innovative probiotic delivery strategies that optimize the benefits of probiotics for gut health and overall wellness(51).

Encapsulation Techniques and Formulation Strategies: Various encapsulation techniques and formulation strategies are employed in developing polysaccharide-based delivery systems for probiotics. These include emulsion-based methods, ionotropic gelation, coacervation, and spray-drying. By optimizing the formulation parameters such as polymer concentration, crosslinking agents, and processing conditions, researchers can tailor the release kinetics and stability of probiotics within polysaccharide matrices. The choice of encapsulation technique influences the physicochemical properties and performance of the probiotic delivery system, ultimately impacting their survival and efficacy in the gut(52,53).

Polysaccharides serve as versatile carriers for probiotics in oral delivery systems, offering protection, targeted delivery, and controlled release mechanisms that enhance the viability and therapeutic effects of probiotic cells in the gastrointestinal tract. The selection of appropriate polysaccharides, encapsulation techniques, and formulation strategies plays a critical role in optimizing the performance of probiotic delivery systems, paving the way for the development of innovative solutions in gut health and functional foods(54,55).

3. Applications of Polysaccharide-Based Probiotic Delivery Systems:

Polysaccharides have shown immense potential in delivering various strains of probiotics to confer specific health benefits on the host. By utilizing polysaccharide carriers, researchers aim to target probiotics to specific sites in the gastrointestinal tract, optimizing their efficacy and therapeutic effects. The diverse applications of polysaccharide-based delivery systems span across functional foods, dietary supplements, and pharmaceutical products, offering innovative solutions for enhancing gut health and overall well-being(56–58).

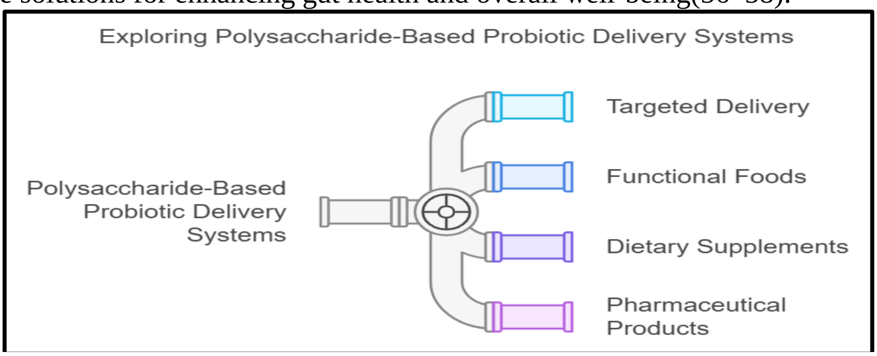


Fig.05: Exploring Polysaccharide-Based Probiotic Delivery Systems

- **Delivery of Different Probiotic Strains:** Polysaccharide carriers enable the encapsulation and targeted delivery of different strains of probiotics, each with unique health-promoting properties. By selecting specific strains known for their beneficial effects, such as Lactobacillus, Bifidobacterium, and Saccharomyces, researchers can tailor the probiotic formulation to address specific health concerns. Polysaccharide matrices provide a protective microenvironment for probiotic cells, ensuring their viability and functionality in the gut for delivering distinct health benefits(59).

- **Diversified Delivery of Probiotic Strains Using Polysaccharide Carriers:**

The delivery of various probiotic strains through polysaccharide carriers represents a significant advancement in personalized probiotic therapy, offering a tailored approach to addressing specific health concerns and optimizing health outcomes. By encapsulating and targeting different strains of probiotics known for their unique health-promoting properties, researchers can leverage the protective and stabilizing capabilities of polysaccharides to enhance the viability, functionality, and efficacy of probiotic delivery systems(60,61).

- **Tailoring Probiotic Formulations to Address Specific Health Concerns:**

The versatility of polysaccharide carriers allows for the encapsulation and delivery of diverse probiotic strains, each with distinct health benefits and therapeutic effects. Probiotic strains such as Lactobacillus, Bifidobacterium, and Saccharomyces are well-known for their roles in promoting gut health, immune function, and overall well-being. By selecting specific probiotic strains based on their documented effects, researchers can customize probiotic formulations to target specific health concerns, such as digestive disorders, immune system modulation, and metabolic health(62).

- **Utilizing the Protective Microenvironment of Polysaccharide Matrices:**

Polysaccharide matrices offer a protective microenvironment for probiotic cells, shielding them from harsh gastric conditions and ensuring their viability and functionality during transit through the gastrointestinal tract. The encapsulation of probiotic strains within polysaccharide carriers provides a stable and supportive environment that helps maintain the integrity of the probiotic cells and protects them from environmental stressors. This protective microenvironment facilitates the targeted delivery of probiotic strains to the intestines, where they can exert their health-promoting effects and contribute to overall gut health(63,64).

- **Enhancing Viability and Functionality of Probiotic Strains:**

The use of polysaccharide carriers in delivering different probiotic strains enhances the viability and functionality of these beneficial microorganisms. Polysaccharides act as protective barriers that shield probiotic cells from the acidic pH of the stomach and enzymatic degradation, increasing their chances of survival and colonization in the gut. By encapsulating probiotic strains within polysaccharide matrices, researchers can improve the stability and bioavailability of probiotics, ensuring that they reach the target site in the intestines with their health-promoting properties intact(65,66).

- **Promoting Distinct Health Benefits with Specific Probiotic Strains:**

Each probiotic strain offers unique health benefits and therapeutic effects, making the targeted delivery of specific strains crucial for addressing different health concerns. For example, Lactobacillus strains are known for their role in supporting digestive health and immune function, while Bifidobacterium strains contribute to gut microbiota balance and metabolic health. Saccharomyces strains have been studied for their potential in managing gastrointestinal disorders and promoting gut barrier function. By encapsulating and delivering these specific probiotic strains using polysaccharide carriers, researchers can tailor probiotic formulations to target specific health conditions and optimize therapeutic outcomes(67–70).

- **Innovative Approaches to Personalized Probiotic Therapy:**

The delivery of different probiotic strains through polysaccharide carriers represents an innovative approach to personalized probiotic therapy, allowing for the customization of probiotic formulations to meet individual health needs. By leveraging the protective and stabilizing properties of polysaccharides, researchers can develop tailored probiotic products that address specific health concerns and deliver distinct health benefits. This personalized approach to probiotic therapy holds great promise for optimizing gut health, immune function, and overall well-being, offering a targeted and effective solution to a wide range of health conditions(71,72).

The delivery of different probiotic strains through polysaccharide carriers enables a diversified and personalized approach to probiotic therapy, allowing for the targeted delivery of specific strains with unique health-promoting properties. By encapsulating probiotic strains within protective polysaccharide matrices, researchers can enhance the viability, functionality, and efficacy of probiotic delivery systems, providing tailored solutions to address individual health concerns and optimize health outcomes. This innovative approach to probiotic therapy harnesses the protective and stabilizing capabilities of polysaccharides to deliver distinct health benefits and promote overall well-being through the targeted delivery of probiotic strains known for their therapeutic effects(73,74).

- **Targeted Delivery to Specific Sites:** Polysaccharides play a crucial role in facilitating targeted delivery of probiotics to specific sites in the gastrointestinal tract, maximizing their efficacy and therapeutic outcomes. Through mucoadhesive interactions and controlled release mechanisms, polysaccharide carriers can guide probiotic cells to desired locations within the gut. This targeted delivery approach ensures that probiotics reach the colon or other regions where they can exert their health-promoting effects most effectively, such as modulating gut microbiota, enhancing immune function, and alleviating digestive disorders(75,76).
- **Applications in Functional Foods:** Polysaccharide-based delivery systems have found widespread applications in the development of functional foods enriched with probiotics. By incorporating probiotics into polysaccharide matrices, food products such as yogurt, fermented beverages, dairy products, and snack bars can be fortified with beneficial microorganisms. The use of polysaccharides ensures the stability and viability of probiotics in food matrices, enabling the creation of functional foods that offer enhanced nutritional value and potential health benefits to consumers(77,78).
- **Applications in Dietary Supplements:** Dietary supplements are another prominent area where polysaccharide-based probiotic delivery systems find extensive use. Formulating probiotics in polysaccharide capsules, tablets, or powders enhances their stability and shelf-life, ensuring optimal survival during storage and transit. Polysaccharide carriers provide a protective barrier that shields probiotic cells from external factors, maintaining their viability

until ingestion. Such dietary supplements offer a convenient and effective way to deliver probiotics for maintaining gut health and supporting overall well-being(79–81).

- **Applications in Pharmaceutical Products:** In the pharmaceutical industry, polysaccharide carriers are employed in the development of probiotic formulations for therapeutic purposes. Polysaccharide-based probiotic products can be designed to target specific health conditions, such as gastrointestinal disorders, immune modulation, or metabolic dysfunction. The controlled release properties of polysaccharides enable sustained delivery of probiotics, ensuring prolonged exposure and efficacy in the gut. Pharmaceutical products incorporating polysaccharide-based probiotic delivery systems offer a promising avenue for personalized medicine and targeted treatments tailored to individual health need(82)s.

The applications of polysaccharide carriers in probiotic delivery systems are vast and diverse, offering innovative solutions for enhancing gut health, immune function, and overall wellness. By utilizing polysaccharides for delivering different probiotic strains, targeting specific sites in the gastrointestinal tract, and developing functional foods, dietary supplements, and pharmaceutical products, researchers are unlocking the potential of probiotics to promote health and well-being through advanced delivery strategies(83,84).

4. Current Trends in Polysaccharide-Based Probiotic Delivery:

In recent years, significant progress has been made in the development of polysaccharide-based oral delivery systems for probiotics, aiming to enhance their efficacy and therapeutic benefits. This review explores the latest research and developments in this field, focusing on emerging trends such as nanotechnology-based delivery, bio-adhesive formulations, and personalized probiotic therapies utilizing polysaccharides. Additionally, the challenges and opportunities in commercializing polysaccharide-based probiotic delivery systems are examined to provide insights into the future of probiotic formulations(85,86).

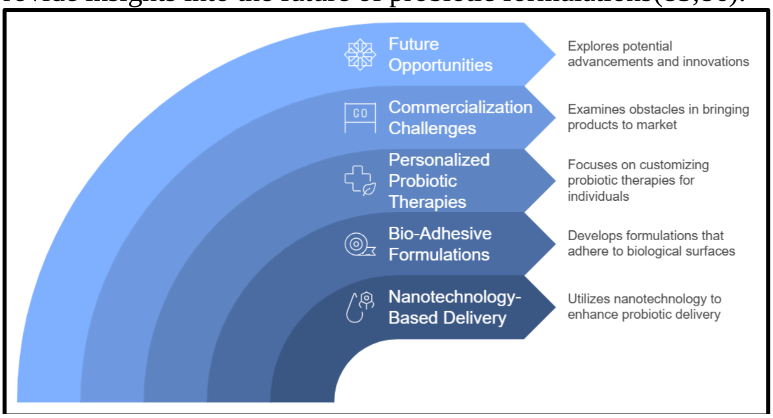


Fig.06: Advancements in Probiotic Delivery

Latest Research and Developments: Recent research has demonstrated the effectiveness of polysaccharide carriers in improving the viability and functionality of probiotics during transit through the gastrointestinal tract. Studies have investigated novel encapsulation techniques, such as microencapsulation and nanoencapsulation, using polysaccharides to protect probiotic cells from harsh environmental conditions. These advancements have shown promising results in enhancing the survival rates and colonization of probiotics in the gut, leading to improved health outcomes(85–88).

Emerging Trends in Polysaccharide-Based Probiotic Delivery(88–92)**:**

1. **Nanotechnology-Based Delivery:** Nanotechnology has revolutionized the field of probiotic delivery by enabling the development of nano-sized carriers for enhanced protection and targeted release of probiotics. Polysaccharide-based nanoparticles offer controlled delivery of probiotic cells to specific sites in the gut, ensuring optimal bioavailability and efficacy. Nanoencapsulation using polysaccharides allows for precise modulation of probiotic release kinetics, offering a customizable approach to probiotic therapy.
2. **Bio-Adhesive Formulations:** Bio-adhesive polysaccharide formulations have garnered attention for their ability to improve the adhesion of probiotics to the intestinal mucosa, enhancing their retention and bioavailability. By exploiting the mucoadhesive properties of polysaccharides, researchers have developed formulations that prolong the residence time of probiotics in the gut, increasing their interaction with the host epithelium and maximizing their therapeutic effects.
3. **Personalized Probiotic Therapies:** Personalized medicine approaches have extended to probiotic therapies, with polysaccharides playing a key role in tailoring treatment strategies to individual health needs. By incorporating probiotics into polysaccharide-based formulations customized for specific health conditions, personalized probiotic therapies offer targeted solutions for gut health, immune modulation, and disease management. Polysaccharide carriers enable the design of probiotic products that address unique health concerns, providing personalized benefits to users.

Challenges and Opportunities in Commercialization(93–95)**:**

1. **Regulatory Hurdles:** The commercialization of polysaccharide-based probiotic delivery systems faces regulatory challenges related to safety, efficacy, and labeling requirements. Ensuring compliance with regulatory standards and obtaining approval for novel probiotic formulations can be a barrier to market entry.
2. **Scale-Up Challenges:** Scaling up production processes for polysaccharide-based probiotic formulations can pose technical challenges, especially in maintaining consistency, quality control, and cost-effectiveness at industrial scales. Optimizing manufacturing processes and ensuring product stability are essential for commercial success.
3. **Market Competition:** The probiotics market is highly competitive, with numerous products available to consumers. Differentiating polysaccharide-based probiotic formulations from existing products and communicating their unique benefits to consumers present marketing challenges but also opportunities for innovation and market growth.
4. **Consumer Education:** Educating consumers about the benefits of polysaccharide-based probiotic delivery systems and their role in improving gut health and overall well-being is crucial for market acceptance. Clear communication of the science behind these formulations and their advantages over traditional probiotic products can help drive consumer interest and adoption.

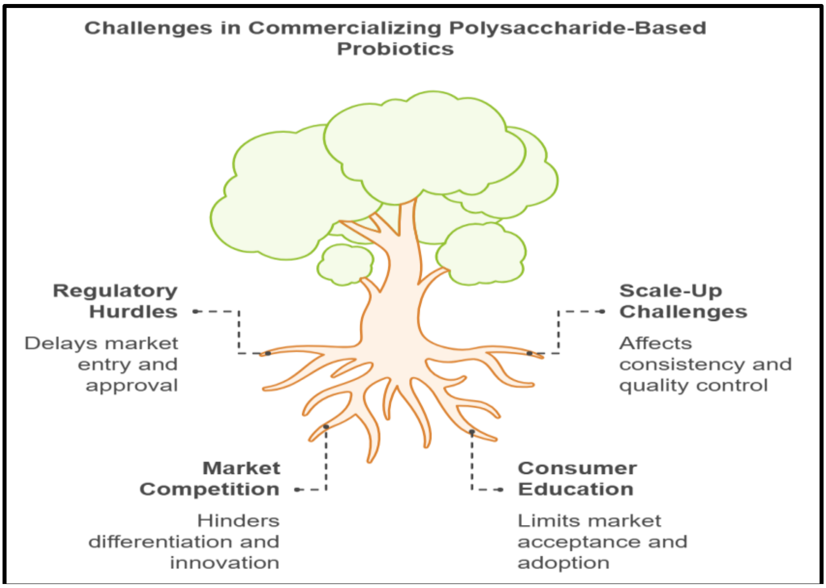


Fig.07: Challenges in Commercializing Polysaccharide-Based Probiotics

The advancements in polysaccharide-based oral delivery systems for probiotics offer promising prospects for improving gut health and personalized therapy options. Leveraging nanotechnology-based delivery, bio-adhesive formulations, and personalized probiotic therapies using polysaccharides opens up new avenues for enhancing probiotic efficacy and commercial viability. While challenges in regulatory compliance, scale-up, market competition, and consumer education exist, the opportunities for innovation and growth in the polysaccharide-based probiotic market are substantial, paving the way for a future of tailored probiotic solutions that cater to individual health needs(95–98).

5. Conclusion:

In conclusion, the review underscores the transformative potential of polysaccharide-based oral delivery systems in revolutionizing probiotic supplementation. The effectiveness of polysaccharides as carriers for probiotics has been demonstrated through their ability to enhance survival rates, improve functionality, and deliver therapeutic benefits to consumers. By emphasizing the vital role of polysaccharides in probiotic delivery, this review sets the stage for future research directions and innovation in leveraging polysaccharides for optimizing probiotic efficacy and promoting gut health.

Through ongoing advancements in polysaccharide-based probiotic delivery systems, the potential for innovation and improvement in probiotic therapies remains vast, promising a future of enhanced health outcomes and personalized probiotic solutions tailored to individual needs.

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