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Encapsulation of probiotics by Electrospinning: Advances, Challenges and future prospects

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Abstract

Electrospinning, a cutting-edge nanofabrication technique, holds the potential to significantly enhance the survival and efficacy of probiotics, offering innovative solutions to address challenges associated with their delivery and viability. This review abstract explores the application of electrospinning in improving probiotic viability by encapsulating them within protective nanofiber matrices. The technique allows precise control over fiber morphology, diameter, and composition, tailoring encapsulation systems to safeguard probiotics from harsh gastrointestinal conditions. Electrospun nanofibers provide a protective barrier that shields probiotics from gastric acids and digestive enzymes, enabling their controlled release within the targeted gastrointestinal segments. This controlled release not only enhances probiotic survival but also facilitates sustained colonization and interactions with the host microbiota. Challenges such as optimal polymer selection, uniform probiotic distribution, and long-term stability are discussed, along with emerging applications and future prospects. Electrospinning's potential to revolutionize probiotic delivery and efficacy marks a pivotal advancement at the intersection of nanotechnology and microbiology, promising to unlock new avenues for personalized and effective health interventions.

Keywords

Encapsulation; probiotic; Electrospinning; Nanofibers

1. Introduction

The encapsulation of probiotics through electrospinning has emerged as a promising approach to enhance the viability, stability, and targeted delivery of these beneficial microorganisms. Probiotics are live microorganisms that confer health benefits to the host when administered in adequate amounts(1). However, their delicate nature and susceptibility to environmental stresses challenge their effective delivery to the desired sites within the human body(2). Electrospinning, a versatile technique capable of producing nanofiber-based structures, presents a novel platform to address these challenges and expand the potential of probiotics in various applications.(3)

1.1. Probiotics

Probiotics are live microorganisms that, when administered in adequate amounts, confer health benefits to the host. These beneficial bacteria, yeasts, or other microorganisms are often associated with improving gut health, enhancing digestion, supporting immune function, and potentially alleviating certain health conditions. The term "probiotic" was initially defined by the World Health Organization (WHO) and the Food and Agriculture Organization of the United Nations (FAO) in 2001.(4)

1.1.1. common types of probiotics

- *Lactobacillus species*: *Lactobacillus acidophilus*, *Lactobacillus rhamnosus*, *Lactobacillus casei*, and *Lactobacillus plantarum* are well-known strains. They are often used in dairy products and supplements to support gut health and immune function.(5)
- *Bifidobacterium species*: *Bifidobacterium bifidum*, *Bifidobacterium longum*, and *Bifidobacterium breve* are commonly used strains. They are known for their ability to promote gut health, support digestion, and modulate the immune system.(6)
- *Saccharomyces boulardii*: This yeast strain is used as a probiotic to support gut health and alleviate symptoms of gastrointestinal issues like diarrhea.(7)
- *Streptococcus thermophiles*: This strain is commonly found in fermented dairy products and is known for its potential to support gut health and lactose digestion.(8)
- *Escherichia coli Nissle 1917*: This strain, also known as Mutaflor, has been studied for its potential to support gut health and modulate the immune system.(9)
- *Bacillus coagulans*: This spore-forming strain is studied for its potential digestive health benefits and immune modulation.(10)

1.1.2. History of Probiotics

The concept of probiotics dates back to the early 20th century when Nobel laureate Elie Metchnikoff proposed the idea that consuming live microorganisms could have health benefits. The term "probiotic" was coined in the 1960s, and since then, research has grown significantly to understand the potential benefits and applications of these beneficial microorganisms.(11)

1.1.3. Advantages of Probiotics

- Gut Health: Probiotics play a crucial role in maintaining a balanced gut microbiota, supporting digestion, and preventing gastrointestinal issues.
- Immune System Support: Certain probiotic strains can modulate the immune system, enhancing its function and responsiveness to infections.
- Nutrient Absorption: Probiotics aid in nutrient absorption by promoting the breakdown of food compounds and synthesizing certain vitamins.
- Mental Health: Emerging research suggests a connection between gut health and mental health, with probiotics potentially contributing to improved mood and cognitive function.
- Allergy and Inflammation: Probiotics may help alleviate symptoms of allergies and reduce inflammation in conditions like inflammatory bowel disease.(12,13)

1.1.4. Disadvantages of Probiotics

- Strain-Specificity: Different probiotic strains have different effects, and not all strains are equally beneficial for every individual or condition.
- Regulation and Quality: The quality and efficacy of probiotics can vary widely, making it important to choose products from reputable manufacturers.
- Potential Side Effects: Some individuals may experience gastrointestinal discomfort or gas when initially introducing probiotics.(14)

1.1.5. Applications of Probiotics

Probiotics are commonly available as dietary supplements, providing a convenient way to introduce beneficial microorganisms into the diet. They are added to various food products such as yogurt, kefir, and fermented vegetables to enhance their nutritional value.(15)

Probiotics are used to address digestive issues, irritable bowel syndrome (IBS), constipation, and diarrhea. They can help maintain vaginal health and prevent recurring infections. In addition, Certain probiotic strains are explored for their potential to boost immune responses and prevent infections.(16)

1.1.6. Challenges with Probiotics

Probiotic bacteria face challenges like surviving stomach acid, reaching the intestines, and adhering to the gut lining. They also need to compete with existing gut microbes and remain stable during storage and distribution. Additionally, ensuring consistent efficacy across diverse individuals and addressing regulatory requirements are ongoing challenges in the field of probiotics. In general, the following points should be considered:

- *Survival and Viability: Probiotics must survive harsh stomach acids to reach the intestines, where they exert their benefits.*
- Specificity: Not all probiotic strains have the same effects, making it important to match strains to intended health outcomes.

- Dosage and Duration: Optimal dosages and treatment durations for different probiotics are still being determined.

- Regulatory Issues: The lack of consistent regulation in the probiotic market can lead to variability in product quality and efficacy.(17,18)

2. Electrospinning Technique and process

Electrospinning involves the use of an electric field to transform polymer solutions into ultrafine fibers with diameters ranging from nanometers to micrometers. The process begins with the preparation of a polymer solution containing the probiotic microorganisms. The solution is then electrospun, resulting in the formation of nanofiber mats or particles that encapsulate the probiotics. Parameters such as polymer type, solution concentration, flow rate, voltage, and distance between the spinneret and collector influence the morphology and properties of the encapsulated probiotics.(19,20)

2.1.1. Advantages of Electrospun Encapsulation

- Enhanced Viability: The controlled release of probiotics from electrospun nanofibers can shield these microorganisms from harsh environmental conditions, thereby improving their survival rates during storage and gastrointestinal transit.

- Targeted Delivery: Electrospun matrices can be designed to release probiotics at specific locations within the body, such as the gastrointestinal tract. This targeted delivery ensures that probiotics reach their intended site of action, increasing their efficacy.

- Sustained Release: The porous structure of electrospun fibers facilitates the controlled and sustained release of probiotics, maintaining a consistent supply of beneficial microorganisms over time.

- Protection from Oxygen and Moisture: Electrospun materials can act as barriers against oxygen and moisture, reducing the oxidative stress and degradation that probiotics may experience.(21,22)

2.1.2. Application

The encapsulation of probiotics via electrospinning holds potential across various fields:

- Functional Foods: Electrospun fibers can be incorporated into food products, delivering probiotics with improved stability and bioavailability.

- Pharmaceuticals: Electrospun probiotic delivery systems can be developed as pharmaceutical formulations for targeted therapies, especially in gastrointestinal disorders.

- Nutraceuticals: Electrospun nanofibers can be utilized to create nutraceutical formulations that combine probiotics with other bioactive compounds.

- Biomedical Devices: Electrospun probiotic-loaded scaffolds can promote wound healing and tissue regeneration by delivering beneficial microorganisms directly to the site of interest.(23,24,25)

2.1.3. Challenges and Future Directions:

Despite the promising potential of electrospun encapsulation, challenges such as optimizing the encapsulation efficiency, minimizing probiotic loss during the electrospinning process, and ensuring long-term stability need to be addressed. Additionally, investigating the impact of electrospinning process parameters on probiotic viability and the interaction between probiotics and polymer matrices is crucial.(26)

2.1.4. Characteristics of nanofibers:

Nanofibers have captured significant research and commercial interest due to their versatility and unique characteristics, opening up new avenues for innovation and technological advancement. for example:

- High Surface Area: Nanofibers have an exceptionally high surface area-to-volume ratio. This property is particularly advantageous for applications that involve interactions at the surface, such as filtration, adsorption, and sensing.

- Mechanical Properties: Despite their small size, nanofibers can exhibit remarkable mechanical properties. Their tensile strength can be impressive due to the alignment of polymer chains along the fiber axis during formation.

- Porosity and Pore Size Control: Nanofiber mats can be engineered to have controlled porosity and pore sizes. This tunability makes them useful for applications where controlled fluid flow, gas permeability, or surface interactions are important.

- Biocompatibility: Many nanofibers are biocompatible and can mimic the extracellular matrix, making them suitable for tissue engineering scaffolds, wound healing, and drug delivery systems.

- Electrical Conductivity: Certain nanofibers, such as those incorporating conductive materials like carbon nanotubes or metallic nanoparticles, can exhibit electrical conductivity. This property is exploited in electronic devices, sensors, and energy storage applications.

- Chemical Functionalization: Nanofibers' large surface area allows for easy chemical functionalization, enabling the attachment of various molecules or nanoparticles to modify their properties.(27,28,29,30)

2.1.5. Applications

Nanofibers find applications in diverse fields, including:

- Medical and Healthcare: Tissue engineering scaffolds, wound dressings, drug delivery carriers, and medical textiles.
- Environmental: Air and water filtration, oil spill cleanup, and water purification.
- Textiles: Clothing with enhanced properties like moisture wicking, UV protection, and antibacterial properties.
- Electronics: Flexible electronics, sensors, and wearable devices.
- Energy: Battery and supercapacitor electrodes, fuel cells, and photovoltaics.(31)

2.1.6. Challenges

Despite their many advantages, producing nanofibers with consistent diameter and alignment, as well as scaling up the production process, can be challenging. Additionally, some applications require specific material properties that might not be achievable with all types of nanofibers.(32)

3. Encapsulation Techniques

Researchers have been exploring various techniques to encapsulate probiotic bacteria within electrospun nanofibers. These techniques include coaxial electrospinning, where a core-shell structure is formed, with the probiotics in the core and the polymer shell protecting them. Coaxial electrospinning allows for better control over the release kinetics and protection of probiotics from external factors.(33,34)

3.1.1. Viability Enhancement:

One of the primary goals of encapsulating probiotics with electrospinning is to enhance their viability. Electrospun nanofibers can create a protective barrier around the probiotics, shielding them from environmental stresses such as oxygen, moisture, and temperature fluctuations. This improved protection can lead to higher survival rates of probiotics during storage and delivery.(35)

3.1.2. Controlled Release and Targeted Delivery

Electrospun nanofibers provide a platform for controlled release of probiotics. By adjusting the properties of the polymer matrix and the electrospinning parameters, researchers can tailor the release kinetics of probiotics. This controlled release is particularly useful for achieving targeted delivery to specific sites within the body, such as the intestines, where probiotics exert their beneficial effects.(36)

3.1.3. Biocompatibility and Biodegradability

The selection of biocompatible and biodegradable polymers is essential for creating electrospun matrices that are suitable for probiotic encapsulation. Researchers are investigating various polymer materials to ensure that the encapsulated probiotics are safe for consumption and can degrade over time in the body.(37)

3.1.4. Multifunctional Matrices

In addition to providing protection and controlled release, researchers are exploring ways to create multifunctional electrospun matrices. These matrices can be designed to not only encapsulate probiotics but also deliver other bioactive compounds, such as prebiotics or antimicrobial agents. This approach aims to create synergistic effects that enhance the overall health benefits.(38)

3.1.5. Application Diversification

Research into electrospun encapsulation of probiotics spans various applications, including food and beverages, pharmaceuticals, nutraceuticals, wound healing, and more. For instance, in food applications, electrospun probiotic-containing fibers can be added to products like yogurt, enhancing both texture and nutritional value.(39)

3.1.6. Clinical and In Vivo Studies

While much of the research has been conducted in vitro, there is growing interest in conducting clinical and in vivo studies to validate the effectiveness of electrospun encapsulated probiotics. These studies involve evaluating factors such as probiotic colonization in the gastrointestinal tract, health benefits, and overall impact on the host.(40)

3.1.7. Challenges and Future Directions

Despite the promising outcomes, challenges remain. Optimizing encapsulation efficiency, ensuring probiotic viability throughout the electrospinning process, and achieving long-term stability are areas of ongoing research. Additionally, investigating the effects of encapsulated probiotics on the host's health and microbiome composition will be crucial for further advancing this field.(41)

3.2. some of the materials commonly used for nanofiber encapsulation of probiotics:

3.2.1. Alginate

Alginate is a natural polysaccharide derived from brown seaweeds. It forms hydrogels that are biocompatible, biodegradable, and exhibit excellent water-holding capacity. Alginate nanofibers can protect probiotics during encapsulation and offer controlled release. They are particularly effective in protecting probiotics from harsh gastric conditions.(42)

3.2.2. Chitosan

Chitosan is a biopolymer derived from chitin, found in crustacean shells. It possesses antibacterial properties, making it beneficial for probiotic encapsulation. Chitosan nanofibers can enhance probiotic viability, adhesion to intestinal cells, and resistance to gastric conditions.(43)

3.2.3. Poly(lactic-co-glycolic acid) (PLGA)

PLGA is a biodegradable synthetic polymer widely used for drug delivery. It offers tunable degradation rates and release profiles.PLGA nanofibers can protect probiotics, control release, and provide sustained delivery. It's commonly used in core-shell structures for enhanced encapsulation.(44)

3.2.4. Gelatin:

Gelatin is a natural protein derived from collagen, commonly used in food and pharmaceutical applications. It supports cell adhesion and can enhance probiotic survival. Gelatin nanofibers can improve probiotic viability, adhesion, and controlled release.(45)

4. Nanofiber Modification for Enhanced Encapsulation

4.1. Functionalization with Bioactive Compounds

Nanofibers can be functionalized with bioactive compounds such as antimicrobial peptides, growth factors, and immune modulators. These functional nanofibers can create synergistic effects with encapsulated probiotics, enhancing their overall health benefits.(46)

4.2. Surface Modification for Targeted Delivery

Surface modifications of nanofibers, such as ligand conjugation or coating with bioadhesive molecules, can enable targeted delivery of probiotics to specific sites in the gastrointestinal tract, improving their adhesion and colonization.(47)

4.3. Responsive Nanofibers

Responsive nanofibers that can change properties in response to specific triggers (pH, temperature, enzymes) are being explored. These nanofibers can release probiotics in a controlled manner under specific physiological conditions.(48)

4.4. Skin Health Applications

Nanofiber encapsulation is being explored for delivering probiotics to the skin. Skin-friendly nanofibers can provide a controlled release of probiotics to support skin health, wound healing, and treatment of dermatological conditions.(49)

*4.5. Oral Health Applications:***

Nanofiber-encapsulated probiotics can be incorporated into oral care products, such as toothpaste and mouthwash, to promote oral health by enhancing the balance of oral microbiota.(50)

5. Conclusion

In conclusion, electrospun encapsulation of probiotic bacteria represents a groundbreaking approach at the intersection of nanotechnology and microbiology, with significant implications for health and wellness. This innovative technique harnesses the power of nanofibers to shield probiotics from harsh environmental conditions, including pH variations and digestive enzymes, during their journey through the gastrointestinal tract. By entrapping probiotics within nanofibers, researchers aim to enhance their viability, targeted delivery, and therapeutic efficacy.(51)

The electrospinning process allows for precise control over fiber morphology, diameter, and composition, enabling the creation of tailored encapsulation systems for different probiotic strains. These encapsulation systems not only protect probiotics but also offer controlled release mechanisms that ensure a sustained supply of beneficial bacteria in the gut. The incorporation of probiotics within nanofibers opens new avenues for personalized therapies, where specific probiotic strains can be delivered to targeted regions of the gastrointestinal tract based on an individual's health needs.

The challenges associated with electrospun encapsulation of probiotics include optimizing polymer selection, achieving uniform distribution of probiotics within the nanofibers, and ensuring long-term stability during storage. However, as evidenced by a growing body of research, innovative solutions and novel materials are continually being explored to overcome these hurdles.(52)

The potential applications of electrospun encapsulation of probiotics are vast and promising. From promoting gut health and modulating the microbiome to addressing chronic gastrointestinal disorders, the controlled delivery of probiotics through nanofibers holds immense potential for enhancing human health. Furthermore, the field is not limited to gastrointestinal delivery alone; researchers are investigating applications in oral health, skin health, and beyond.

As the field continues to evolve, collaborations between microbiologists, material scientists, and clinicians are likely to propel electrospun encapsulation of probiotics toward practical implementation. While challenges remain, the innovative combination of nanotechnology and microbiology holds the promise of revolutionizing the way probiotics are delivered, unlocking their full therapeutic potential for improved well-being.(53)

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