Research on the Application of Probiotic Products Based on New Processing Technologies

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Abstract. Probiotics are beneficial to human health. However, traditional processing methods are highly likely to destroy the viability of probiotics, so there is an urgent need for new processing technologies to handle probiotics. Currently, there are relatively few review articles on new processing technologies in probiotic products. This article conducts a systematic evaluation of the relevant literature on the application of new processing technologies in probiotic products. During the retrieval process, keywords closely related to the theme, such as "probiotics", "processing technology", "viability", and "high - temperature sterilization", are focused on, and the retrieval is carried out with the help of databases such as Web of Science, Google Scholar, and PubMed. This paper deeply explores the application of new processing technologies in probiotic products from dimensions such as principles, advantages, challenges and improvements, and applications. The research finds that new processing technologies are expected to promote the expansion of probiotic products into more fields, which is of great significance for the further development of the probiotic industry.

Keywords: Probiotics, Processing Technology, Biological Activity, Application.

1. Introduction

Probiotics are live microorganisms that confer health benefits on the host[1]. Their core function lies in regulating the balance of the gut microbiota to maintain intestinal health .In the intestine, probiotics, on one hand, promote the growth of beneficial bacteria and inhibit pathogenic microorganisms[2]; on the other hand, they maintain the stability of the microbiota by competing with harmful bacteria for nutrients and attachment sites[3]. Additionally, they optimize the intestinal microecology by increasing butyric acid secretion and fortifying tight junction proteins.

In terms of immune regulation, probiotics activate the lymphoid tissue , the lymphoid organ of the human gastrointestinal system , and interact dynamically with immune cells and symbiotic microorganisms to achieve systemic immune homeostasis and enhance specific immune responses [4]. Meanwhile, by regulating the secretion of cytokines, probiotics help balance the immune response by inhibiting the secretion of proinflammatory cytokines and enhance the synthesis of anti-inflammatory cytokines such as interleukin-10 (IL-10).For example, *Lactobacillus casei* can improve colitis symptoms in mice by regulating T-cell responses [5].

Clinical research has confirmed that probiotics show great potential in disease prevention and treatment. Regarding the dysregulation of the *Firmicutes*/*Bacteroidetes* ratio of obese patients [6], probiotics can increase the proportion of *Bacteroidete*s and also control appetite by regulating the secretion of gut hormones such as glucagon-like peptide-1 (GLP-1) and peptide YY (PYY). *Lactobacillus acidophilus* JYLA-126 can improve hepatic glycogen metabolism and reduce oxidative stress [7], while short bioactive peptides produced by the metabolism of milk proteins by *Lactobacillus* contribute to the regulation of hypertension [8].

The probiotic market has experienced a remarkable upswing in recent years. Probiotic products cover a wide range of fields, including food, health products, and pharmaceuticals. The demand for probiotic products for infants and young children is particularly strong, and strains such as *Bifidobacterium lactis* - 12 and *Lactobacillus rhamnosus* LGG are widely used. However, adding probiotics to food poses multiple challenges: high-temperature processing (such as pasteurization) ensures product safety but leads to a significant decrease in the viability of probiotic strains due to their thermosensitivity [9]; freeze processing is prone to cell damage caused by ice crystals [10]; although spray drying has cost advantages, it may damage the cell structure. For example, the viability of *Lactobacillus rhamnosus* decreases when spray drying [11]. Traditional processing methods damage the value of products by reducing microbial viability and degrading heat-sensitive components. Therefore, the development of innovative processing technologies has become a key issue in the industry. This article focuses on new processing technologies, and its innovations are reflected in the following aspects: a systematic comparison of technologies such as microencapsulation technology, nanotechnology, and high-pressure processing technology; a detailed description of the application principles of each technology and the latest progress in improving the performance of probiotics; a forward-looking analysis of the application prospects of cutting-edge technologies such as intelligent release systems, nanoparticle encapsulation, and genetic engineering technology, providing new ideas for industry development.

2. Microencapsulation Technology

2.1. Emulsification Method

The principle of the emulsification method is to encapsulate probiotics in tiny droplets of the oil - phase or water - phase to form a stable emulsified system, thus protecting probiotics from damage by the external environment. It can protect probiotics from the damage of gastric acid, bile, and oxygen, improve their survival rate in the gastrointestinal tract, and extend the product's shelf life. Moreover, through modifying the variety and dosage of emulsifiers, the controlled release of probiotics can be achieved, improving their targeting and effectiveness [12]. However, safe and non - toxic emulsifiers need to be selected to ensure product safety. In practical applications, coating probiotics with corn flour and applying them to yogurt helps to improve the yogurt's consistency [13]. Alginate microparticles are recognized for their biocompatibility and for food, pharmaceutical purposesand cosmetic applications, hydrophilic active ingredients are encapsulated by biodegradable, non-toxic carriers [14].

2.2. Coacervation Method

The coacervation method utilizes electrostatic interactions between oppositely charged polymers to form insoluble polyelectrolyte complexes, which precipitate and encapsulate probiotic cells. The advantage of this technology is that no toxic organic solvents are used during the encapsulation process [15]. However, during the production process, the activity of probiotics may decrease due to mechanical stress, high temperature, or chemical cross - linkers. In practical applications, encapsulating *Lactobacillus plantarum* with this technology improves the thermal stability of probiotics at 60°C and 70°C [16].

3. Nanotechnology

3.1. Nanofiber Technology

The principle of nanofiber technology is to encapsulate probiotics in nanofibers through methods such as electrospinning. The advantage is that the electrospinning technology enhances the thermal stability and targeted delivery of probiotics, significantly improving their survival rate in harsh gastrointestinal conditions. However, the high production cost and scalability challenges of nanofiber-based encapsulation may limit its commercial viability for widespread probiotic applications. It can be applied in many other ways. For example, a new double - layer carrier fabricated by a one-phase coaxial electrospinning process has been used to envelope probiotics. Probiotic cells are successfully incorporated in the fibers (10^7 CFU/mg).[17].

3.2. Nanocoating Technology

Nano microcapsule technology not only provides protection for functional foods but also enhances their solubility, dispersibility, and bioavailability by encapsulating bioactive substances in the wall materials of nano microcapsules [18]. It can effectively protect probiotics from damage by the external environment. However, during the application process, uneven or overly thick coatings may lead to diminish in the activity of probiotics or poor release performance. It has many uses, for example, self-assembly of silk fibroin occurs on bacterial surfaces. Coating *Escherichia coli* Nissle with silk fibroin has the effect of improving intestinal mucosal inflammation in mice [19].

4. High-pressure Processing Technology

4.1. High-pressure Sterilization Technology

The principle of high-pressure sterilization technology is to destroy the cell membrane and cell wall of microorganisms through high pressure, leading to the leakage of cell contents and the death of cells. As an emerging technology, high-pressure sterilization technology offers benefits that can be utilized to enhance the comprehensive quality of foods. It will not destroy nutrients such as vitamins, proteins, and enzymes in food. However, it is very easy to kill probiotics, which is not conducive to the synthesis of live bacteria formulations. It has been applied in many aspects of food production, such as using high-pressure sterilization technology to treat two spore strains in baby food puree, which can ensure food safety while reducing the generation of harmful substances and improving food quality [20].

4.2. High-pressure Freeze-drying Technology

When high pressure is applied to the probiotic's suspension, the gas solubility in the cells increases, and the cell permeability is improved. High-pressure treatment makes the freeze-dried probiotics form a loose and porous sponge-like structure. The rehydration speed is 30%-50% faster than that of ordinary freeze-dried products, and it can almost immediately restore the original properties. However, inappropriate pressure parameters in the application may damage the cell structure of probiotics, resulting in a decrease in the viable bacteria rate. It is applied to probiotic powder and milk powder, which not only avoiding the problem of chemical residues, but also not destroy nutrients such as vitamins, proteins, and enzymes in food [21].

4.3. High-pressure Assisted Extraction Technology

High-pressure assisted extraction is an environmentally friendly extraction technology. By applying a high pressure of 100-1000 MPa, it can destroy the cell wall, membrane, and organelles of plant tissues, and can also optimize the mass transfer process, improve the efficiency of extraction, shorten the extraction time, and reduce the solvent consumption. Nevertheless, it is only suitable for strains with strong pressure resistance (such as *Lactobacillus*), and may have a negative impact on the survival rate of fragile strains (such as *Bifidobacterium*). Research has shown that high-pressure extracted active substances from *Bifidobacterium longum* exhibit antibacterial activity against harmful bacteria such as *Listeria monocytogenes* [22].

5. 3D Printing Technology

5.1. Precise Encapsulation Technology

The 3D printing technology achieves precise encapsulation of probiotics through pH-sensitive materials (such as alginate-pectin microgel beads). One drawback associated with precise encapsulation technology is certain variables will affect the survival of probiotic microorganisms, such as oxygen exposure amount, and printing temperature. A series of recent studies has indicated that a 3D printing technology based on the food structure of grains, pureed potatoes and cream has been formulated and applied in probiotic products [23].

5.2. Stereolithography Technology

Its principle is that the liquid photosensitive material rapidly solidifies under the irradiation of a laser beam to form a cross-sectional thin layer of the part. The advantage of this technology is that it can be used to manufacture cellulose scaffolds with complex structures, prolonging theinhabitation period of probiotics in the intestine. However, its disadvantage is the high cost. Previous studies have shown that 3D printed cellulose derived spiral tube scaffolds can be used for oral probiotic delivery [24].

6. 6. Intelligent Release System

6.1. Intelligent Release Based on pH Response

The principle is that, aiming at the pH differences in different segments of the gastrointestinal tract, pH-sensitive polymers (such as chitosan) are used, which dissolve at the intestinal pH to protect probiotics from being damaged by gastric acid. It enables precise targeted release, improves the survival rate of probiotics, enhances the intestinal colonization effect. As an intelligent architecture designed for medicament delivery, the pH-responsive drug delivery system can deliver drugs in a controllable manner at specific locations and times [25]. However, the main weakness of this protocol is that it has a high cost. Previous studies have emphasized the gastric acid passage rate of ordinary probiotic products is usually lower than 20%, while pH-responsive embedding (such as enteric-coated capsules) can increase the survival rate to more than 80% [26].

6.2. Enzyme-triggered Intelligent Release

The principle is to select biopolymers that can be degraded by specific enzymes to coat probiotics, enabling the release of probiotics at specific sites. The advantage is that enzyme triggering can achieve more precise release in the colon. Moreover, prebiotics can be selected as carrier materials, which not only serve as substrates for enzymatic hydrolysis but also promote the proliferation of probiotics. However, enzyme-triggered intelligent release suffers from the shortcoming of the purification and embedding processes of enzyme-sensitive materials are complex, resulting in high production costs. The majority of prior research has applied VSL#3 (a high-concentration probiotic mixture) is coated with an azo polymer and is released after being degraded by azoreductase in the colon [27].

7. Genetic Engineering Technology

7.1. Gene Editing Technology

The principle is to precisely modify the genome of probiotics through means such as functional gene insertion, gene knockout and regulation, and stress resistance modification, endowing them with specific functions or optimizing their original characteristics [28]. It can precisely modify the genome of probiotics and enhance the safety of probiotics. One of the major drawbacks of Gene Editing Technology is there are significant differences in the application regulations of gene-edited microorganisms among various countries. Gene-edited Bacteroides can increase the content of butyric acid it secretes.

7.2. Metabolic Engineering

The principle is to regulate the carbon source utilization, energy metabolism, or secondary metabolite synthesis pathways of probiotics to increase the production of target products (such as vitamins, SCFAs) [29]. It can optimize the metabolic efficiency of strains and improve the stress resistance of probiotics. A significant disadvantage of this technology lies in the overexpression of certain metabolites may cause intestinal inflammation or metabolic disorders.

New processing technologies are facing numerous challenges and opportunities in the development process. On the one hand, due to large equipment investments and high technical requirements, the costs of some new processing technologies are extremely high, which limits their large-scale promotion and application. At the same time, different probiotic strains have varying tolerances to the processing environment, and it is necessary to continuously Refine the manufacturing procedure parameters to ensure the activity of the strains. Looking to the future, developing new processing technologies with low costs and high efficiency has become the key to industry breakthroughs. In-depth research on the compatibility between probiotic strains and processing technologies and the construction of precise process optimization models will help improve production efficiency and product quality. In addition, in-depth exploration of the influence mechanism of new processing technologies on the functional characteristics of probiotics will provide theoretical support for the development of functional probiotic products with specific effects, promoting the industry to move towards a higher level.

8. Conclusions

This review comprehensively and deeply compares and analyzes new processing technologies such as microencapsulation technology, nanotechnology, high-pressure treatment technology, intelligent release systems, and genetic engineering technology for the first time. It not only elaborates in detail the application principles of each technology in probiotic products but also highlights the latest progress in functionality. However, the disadvantage is that the exploration of functional details is limited. Since it is necessary to cover various processing technologies, the description of each technology may only scratch the surface. Although this review has certain timeliness advantages, the process from research, writing to publication may prevent some of the latest technologies from being reflected in a timely manner. In conclusion, we have summarized the new processing technologies applied in probiotic products and comprehensively analyzed their principles, advantages, disadvantages, and applications, providing a comprehensive reference for researchers and the industry.

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